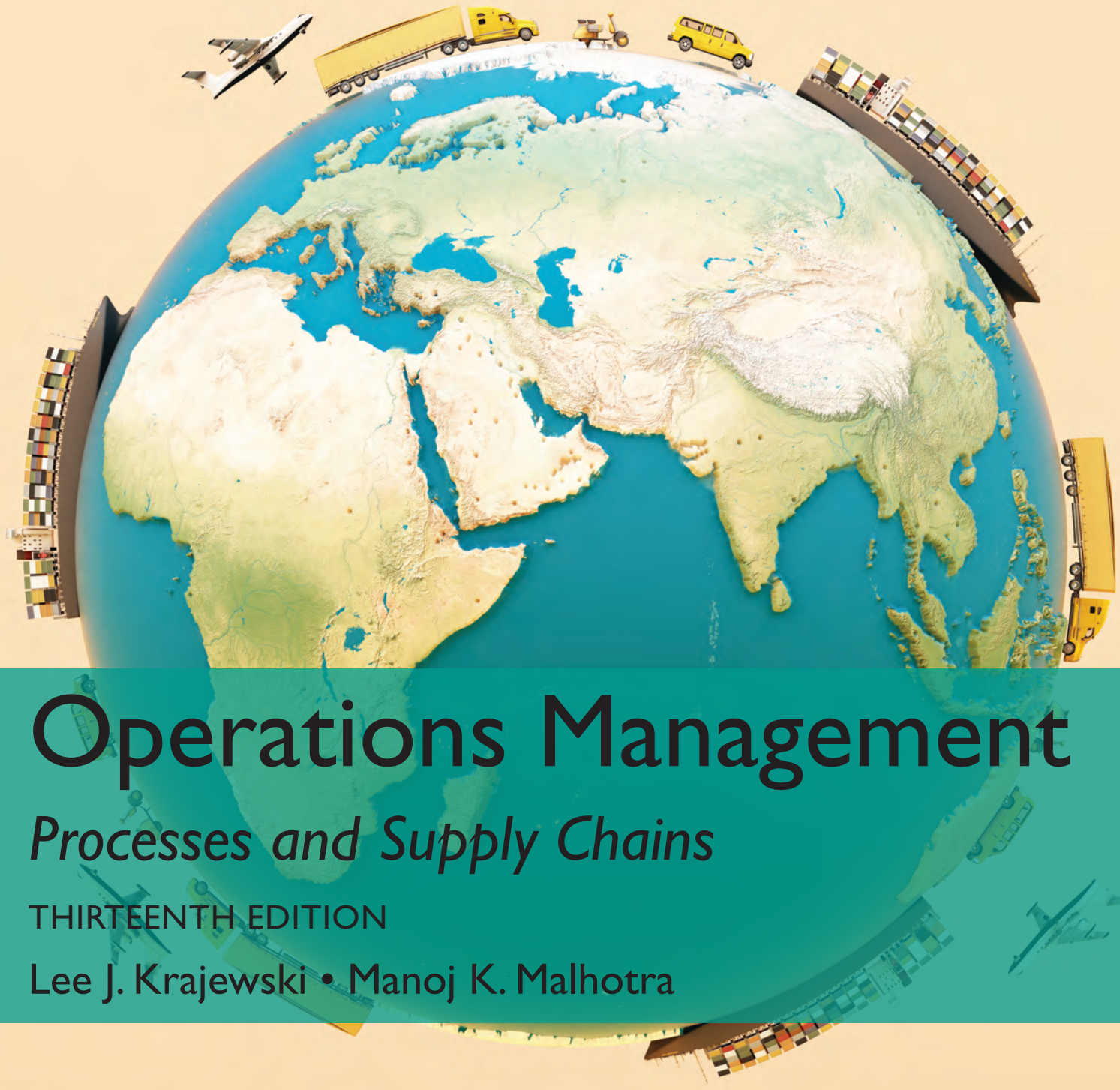
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Operations Management

Processes and Supply Chains

THIRTEENTH EDITION

Lee J. Krajewski • Manoj K. Malhotra

Operations Management

PROCESSES AND SUPPLY CHAINS

Thirteenth Edition

Global Edition

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Dedicated with love to our families.

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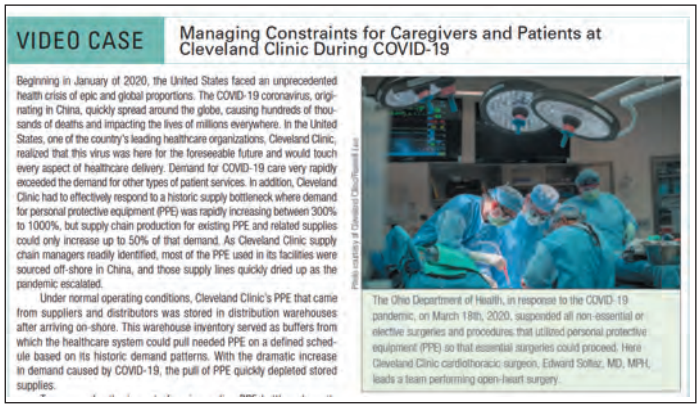
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Preface

It does not take a genius to know that the world, in particular the business world, is changing. Although the Twelfth Edition was successful at bringing current practice in operations management, in an easy-to-understand format, to a broad brush of business students, it became clear that much has happened since it was published. We began the Thirteenth Edition by obtaining feedback from instructors, reviewers, practicing managers, and students and diligently wove these inputs into the fabric of each chapter. However, before we could actually start the revision, the COVID-19 coronavirus pandemic struck the world. While it brought economic ruin to hundreds of millions of people worldwide, and death to many across the globe, it afforded an extraordinary opportunity to demonstrate how business operations can respond when an unexpected disaster presents itself. In the Thirteenth Edition you will see many examples of the effects of the coronavirus on business operations and how they were handled. We offer one final thought: If you are a business major taking operations management as a required course but you are not an operations major, we have made a special effort to show you how the principles of operations management *will* be useful to you regardless of your chosen career path.

New to This Edition

Video Cases—Cleveland Clinic In addition to the existing selection of real-world video cases throughout the text, this edition features the world-renowned Cleveland Clinic, headquartered in Cleveland, Ohio. Cleveland Clinic is a global-leading U.S.-based hospital group whose expertise is in specialized medical care. In addition to its 165-acre campus near downtown Cleveland, it has 11 regional hospitals throughout Northeast Ohio; 5 hospitals in Florida; a hospital in Abu Dhabi, UAE; and facilities in Las Vegas, Nevada, and Toronto, Canada. We have added four videos and cases that demonstrate the outstanding level of operations at Cleveland Clinic and how the coronavirus pandemic has affected them. You will first learn how Cleveland Clinic has addressed process-design challenges in Chapter 2, "Process Strategy and Analysis," to set the stage. Then, in subsequent chapters, you will see managerial responses to operations issues related to managing constraints in Chapter 6, "Constraint Management," planning for resources in Chapter 11, "Resource Planning," and the coordination of supply chain activities and information flows throughout the organization in Chapter 14, "Supply Chain Integration." It's the first time we have woven a single organizational focus into the text. After reading the cases and watching the videos, we hope you will agree that such an emphasis provides the opportunity to really appreciate how broad the brush of operations management reaches in supporting the success of world-class organizations.


VIDEO CASE

Managing Constraints for Caregivers and Patients at Cleveland Clinic During COVID-19

Beginning in January of 2020, the United States faced an unprecedented health crisis of epic and global proportions. The COVID-19 coronavirus, originating in China, quickly spread around the globe, causing hundreds of thousands of deaths and impacting the lives of millions everywhere. In the United States, one of the country's leading healthcare organizations, Cleveland Clinic, realized that this virus was here for the foreseeable future and would touch every aspect of healthcare delivery. Demand for COVID-19 care very rapidly exceeded the demand for other types of patient services. In addition, Cleveland Clinic had to effectively respond to a historic supply bottleneck where demand for personal protective equipment (PPE) was rapidly increasing between 300% to 1000%, but supply chain production for existing PPE and related supplies could only increase up to 50% of that demand. As Cleveland Clinic supply chain managers readily identified, most of the PPE used in its facilities were sourced off-shore in China, and those supply lines quickly dried up as the pandemic escalated.

Under normal operating conditions, Cleveland Clinic's PPE that came from suppliers and distributors was stored in distribution warehouses after arriving on-shore. This warehouse inventory served as buffers from which the healthcare system could pull needed PPE on a defined schedule based on its historic demand patterns. With the dramatic increase in demand caused by COVID-19, the pull of PPE quickly depleted stored supplies.

The Ohio Department of Health, in response to the COVID-19 pandemic, on March 18th, 2020, suspended all non-essential or elective surgeries and procedures that utilized personal protective equipment (PPE) so that essential surgeries could proceed. Here Cleveland Clinic cardiothoracic surgeon, Edward Soltesz, MD, MPH, leads a team performing open-heart surgery.

Chapter Opening Vignettes Each chapter opens with a real-world example of a company addressing the topic of that chapter. In this edition, we have introduced seven new vignettes highlighting the operations at Apple, Lego, Nike, 3M, Starbucks, Oasis of the Seas, and Coca-Cola, Inc.

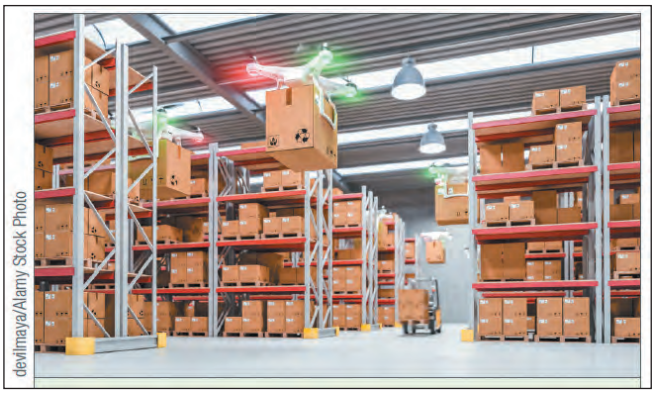

3M

Minnesota Mining and Manufacturing (3M) company is a diversified conglomerate that has operations in more than 70 countries. It manufactures over 60,000 products, such as adhesives, window films, paint protection films, laminates, and consumer products like Scotch tape and Post-its, among others, that are used in the health care, manufacturing, and construction industries, as well as several others. With nearly $33 billion in sales and 93,500 employees in 2018, 3M has been an icon of innovation and steady growth since its founding as a mining company in Minnesota in 1902.

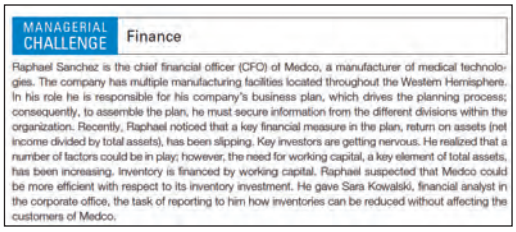
New Technologies In the Thirteenth Edition, we have taken care to include the latest technologies being used to improve business operations. Here are some of those technologies you can look forward to:

- **Fourth Industrial Revolution (Industry 4.0).** Chapter 1, "Using Operations to Create Value," describes Industry 4.0, which is the ongoing automation of traditional manufacturing and industrial practices using modern smart technology. The discussion categorizes the Industry 4.0 technologies into four groups: Smart Manufacturing, Smart Products, Smart Supply, and Base Technologies.
- **Autonomous Supply Chains.** Chapter 12, "Supply Chain Design," discusses the concept of autonomous supply chains, which is a digital transformation in which the latest in digital technology is used to facilitate and automate decision making up and down the supply chain and thereby transform the way supply chains operate.

- **Autonomous Warehouse Operations.** Chapter 13, "Supply Chain Logistics Networks," addresses the use of automated guided vehicles, automated mobile robots, and aerial drones in warehouse operations.
- **Blockchains.** Chapter 14, "Supply Chain Integration," defines the concept of blockchain, differentiates it from cloud computing, and shows an example of its use in supply chains.


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Managerial Challenges We believe that the principles of operations management are useful to managers of all disciplines. To demonstrate, we have added Managerial Challenges to each chapter, starting with Chapter 2, "Process Strategy and Analysis." These challenges are realistic scenarios, based on extensive research, that describe meaningful operations decision problems in which managers of various disciplines find themselves taking a leading role. The featured disciplines include accounting, finance, human resources, information systems, logistics, marketing, and operations, and cover both manufacturing and service companies.


MANAGERIAL CHALLENGE Finance

Raphael Sanchez is the chief financial officer (CFO) of Medco, a manufacturer of medical technologies. The company has multiple manufacturing facilities located throughout the Western Hemisphere. In his role he is responsible for his company's business plan, which drives the planning process; consequently, to assemble the plan, he must secure information from the different divisions within the organization. Recently, Raphael noticed that a key financial measure in the plan, return on assets (net income divided by total assets), has been slipping. Key investors are getting nervous. He realized that a number of factors could be in play; however, the need for working capital, a key element of total assets, has been increasing. Inventory is financed by working capital. Raphael suspected that Medco could be more efficient with respect to its inventory investment. He gave Sara Kowalski, financial analyst in the corporate office, the task of reporting to him how inventories can be reduced without affecting the customers of Medco.

Managerial Practices It is important for the understanding of operations management to provide many examples of current practices. In this edition, we have added four new Managerial Practices, ranging from the inventory system at IKEA to the shortage of toilet paper due to the coronavirus pandemic.


MANAGERIAL PRACTICE 14.1 Coronavirus and the Supply Chain: Where Is the Toilet Paper?

What do you fear the most? Falling into a pit of spiders? Getting eaten by a zombie? Running out of toilet paper? If it is the latter, you are not alone. The coronavirus pandemic of 2020 has caused shortages of many products, but running out of toilet paper causes nightmares. What could be worse than walking into your local supermarket, armed with your mask and maintaining social distancing, and seeing the paper products aisle as barren as the Grand Canyon in January? Asking a stock clerk about the toilet paper gets you a shrug of the shoulders and a promise that an order has been placed with the distributor; relief will take a week or two.

Before we get into theories of why this has happened, let's take a peek at the supply chain for toilet paper. Toilet paper is made from one of two sources: virgin pulp from trees in Canada and the United States, or recycled pulp obtained from materials like discarded copy paper that is reprocessed and turned into pulp. The pulp is delivered to paper mills that turn it into large rolls of paper over 100 inches wide. The rolls are then shipped to a paper converting facility, which then cuts and packages them into the designated end product like toilet paper or kitchen towels, depending on the quality of the paper. Packaging and shipping are the final steps in the chain. The mills typically run 24 hours, 7 days a week—in other words, fixed capacity. However, with the pandemic, mills have adjusted their work hours for the safety of their employees, eroding their capacity to respond to demand increases. Retailers have a set amount of toilet paper inventory that is determined on the basis of historic demand levels; however, a shock to demand can exceed the safety stocks in their warehouses.

Large rolls of toilet paper are shipped to a paper converting facility to produce the product you buy in the store. Here the rolls have been cut to the proper size and are conveyed to the packaging process.

more often, but because they are using more of it at home. It is estimated that the demand for consumer toilet paper increased 40 percent, a huge increase for a supply chain designed for constant demand. That leaves a lot of com-

Detailed Chapter-by-Chapter Changes

We have meticulously revised the text to enhance its readability and update all the references and business examples. Here are the major changes in each chapter.

Chapter 1: Using Operations to Create Value We added a new opening vignette featuring Apple that explains how its superior operations and supply chain capabilities are the reasons for its success. The 10 decision areas of operations management that Apple uses to maximize its operational efficiency and build strategic capabilities provide a nice entrée to the remainder of the text. We added a new section titled "Fourth Industrial Revolution (Industry 4.0)," which defines the four distinct categories of modern technologies: Smart Manufacturing, Smart Products, Smart Supply, and Base Technologies. We also put the Internet of Things (IoT) and additive manufacturing under this umbrella to make a succinct, but comprehensive, overview of modern technologies for improved operations. A new learning objective was added to cover this important material.

PART 1: Managing Processes The first part of the text lays the foundation for why a process view is critical for utilizing operations management as a strategic weapon by showing how to design and manage the internal processes in a firm, regardless of the functional area.

Chapter 2: Process Strategy and Analysis In addition to updating the opening vignette on CVS and the Managerial Practice on Ford Camacari, we added a Managerial Challenge focusing on the vice president of marketing and sales for Templeton's Packaging Products Division, who must figure out why machine repair requests coming into her department from customers are

experiencing lengthy delays. Finally, a new video case featuring the Cleveland Clinic shows how management used the Six Sigma Improvement Model to resolve a workflow problem involving skilled and licensed staff.

Chapter 3: Quality and Performance We added a new opening vignette describing the precise quality standards of Lego, which produces 36 billion plastic bricks a year with a process that produces only 18 defects per million bricks. We also added a Managerial Challenge involving the corporate controller of Star Industries, who last year initiated a major overhaul of their payroll and customer billing processes and now has to determine if significant improvements were made. We updated the Managerial Practice on Santa Cruz Guitar Company and changed Figure 3.2 to be more consistent with the ISO 9001:2015 terminology.

Chapter 4: Lean Systems We moved this chapter, which was Chapter 6 in the Twelfth Edition, to next in line because the content and techniques strongly support the methods we describe in Chapter 3, "Quality and Performance." We added a new opening vignette on Nike, Inc., that tells the engaging story of how Nike, Inc., applied the principles of lean systems to its factories and supply chain to become a leader in the industry. We updated the Managerial Practice on Alcoa and completely revamped the illustration of the Kanban system, including a new Figure 4.6 with multiple subparts, eliminating the two-card system and simplifying the discussion. Finally, we added a Managerial Challenge in which the VP of finance for Oak Grove Health System was given the assignment of figuring out how to combat the rising cost of patient care and declining revenues.

Chapter 5: Capacity Planning In keeping with the currency of the topics in the Thirteenth Edition, the new opening vignette on 3M shows how a top-notch company can cope with an unexpected capacity crunch brought on by the coronavirus pandemic. We also added a Managerial Challenge in which the facility manager for Tower Medical Center must determine how to cope with dramatically increased visits to the emergency department and a surge in surgery requests. The Managerial Practice on PacifiCorp was also updated.

Chapter 6: Constraint Management We created a new Managerial Practice on Steelo Limited that illustrates the application of the theory of constraints and the drum-buffer-rope system. A Managerial Challenge was also added that features the marketing manager at Schmidt Industries, who found out that his sales process was a bottleneck to the sales of the company's winch product. Finally, we added a Video Case on constraint management at the Cleveland Clinic that shows how management analyzed and solved a personal protective equipment (PPE) bottleneck due to the COVID-19 virus pandemic.

Chapter 7: Project Management Cleveland Clinic, a main attraction of the Thirteenth Edition, is featured in a new Managerial Practice that discusses a project to build a new hospital in London, England. Also added to this chapter is a Managerial Challenge that involves the head of the marketing department for a large financial services firm who is tasked with overseeing a project within her department to design and implement a new process to deal with requests for creative ads, innovative communications, printed brochures, new web content, and continual sales support from units all over the company. Finally, we added a section addressing project risk caused by changing requirements. It describes an approach called *scrum*, which is an "Agile" project management framework that focuses on allowing teams to respond rapidly, efficiently, and effectively to change.

PART 2: Managing Customer Demand The second part of the text shows how to estimate customer demands and satisfy those demands through inventory management, operations planning and scheduling, and resource planning.

Chapter 8: Forecasting We begin this chapter with a new opening vignette describing how Starbucks uses big data for managing demands. We also added a Managerial Challenge featuring a recent information system graduate who was assigned the task of reviewing the forecasting system and software at Kramer Health Clinic because staffing levels of critical employees have been too low due to excessive forecast errors.

Chapter 9: Inventory Management The opening vignette on Ford's Smart Inventory Management System was revised to include CarStory, which uses predictive analytics to determine how long used vehicles will remain on the lot. We added a new Managerial Practice describing how IKEA manages its large inventories at retail outlets. Finally, a Managerial Challenge presents a scenario in which the chief financial officer (CFO) of Medco, a manufacturer of medical technologies, is concerned about declining return on assets (ROA) and assigns his financial analyst in the corporate office the task of reporting to him how inventory investment can be reduced without affecting the customers of Medco.

Chapter 10: Operations Planning and Scheduling We updated the opening vignette on Cooper Tire and revised the Managerial Practice on umpire scheduling to include the 2019 World Series. We added a Managerial Challenge in which the director of human resources for Redwood Hotel, faced with staffing problems, must find a staffing plan that meets the hotel's revenue targets.

Chapter 11: Resource Planning We updated the opening vignette on Philips and the Managerial Practice on Valle del Lili Foundation Hospital for recent events. We also added a Managerial Challenge in which the VP of manufacturing and her staff at Rennselar Industries, Inc., an original equipment manufacturer (OEM) of automotive parts, was tasked with recommending changes to the current master production scheduling process and resolving a problem in delivery performance. Finally, there is a new Video Case that reveals how Cleveland Clinic ensures that the required resources are available for the large number of complicated surgeries and procedures performed daily.

PART 3: Managing Supply Chains The third part of the text builds upon the tools for managing processes and customer demands at the level of the firm and provides the tools and perspectives to manage the flows of materials, information, and funds between suppliers, the firm, and its customers.

Chapter 12: Supply Chain Design We added a Managerial Challenge in which the supply chain manager of Adorn, a leading manufacturer of women's apparel, must analyze the supply chain to see how Adorn can get its products to market faster. We simplified the discussion of what a supply chain is by removing the distinction between service supply chains and manufacturing supply chains and instead focusing on the structure of a supply chain with its tiers of suppliers and distribution channels. Finally, we added a new section titled "Autonomous Supply Chains," which describes the trend toward automating elements of supply chains and the advantages it can have.

Chapter 13: Supply Chain Logistics Networks We added a Managerial Challenge involving the director of human resources for EuroTran AG, a producer of transmissions, steering and axle systems, and driver assistance features for the automobile industry; this director was assigned to a committee analyzing the location for a new plant and finds that she must argue for the inclusion of key factors associated with labor climate and quality of life at the potential sites. We also added a major section titled "Warehouse Strategy in Logistics Networks," in which we discuss inventory placement and autonomous warehouse operations, such as automated guided vehicles, autonomous mobile robots, and aerial drones.

Chapter 14: Supply Chain Integration This chapter underwent a major revision to drive home the importance of supply chain integration. The new opening vignette describes the Oasis of the Seas and the need for an integrated supply chain, especially when faced with unexpected disruptions such as the coronavirus pandemic. We added a Managerial Challenge in which the director of information technology for Crestview Food, Inc., whose stores were experiencing severe stock outages, had to devise a plan to facilitate information exchanges up and down the supply chain. We moved the section on additive manufacturing to Chapter 1, "Using Operations to Create Value," and moved the section "Supply Chain Risk Management" to just after the section "Supply Chain Disruptions" to reinforce the tactics used to cope with disruptions in supply chains. We added a new Managerial Practice on the coronavirus and its effect on the supply of toilet paper. We also incorporated a major section titled "Cloud Computing and Blockchains," which provides a thorough discussion of new technologies for integrating supply chains. The concept of a blockchain in a supply chain is explained with examples and two new figures. We discuss how it works, its benefits, and its uses. We also added a discussion question on cloud computing and blockchains. Finally, there is a new Video Case at Cleveland Clinic that shows the advantage of having an integrated supply chain to support the goal of a patient first enterprise in light of the COVID-19 pandemic.

Chapter 15: Supply Chain Sustainability A new opening vignette describes how Coca-Cola has worked on decreasing its water footprint in an industry that uses 69 percent of the world's freshwater supply. We also added a Managerial Challenge at Eagle Trucking Company, a transportation company serving the oil and gas, health care, and food industries, in which the CEO has tasked his vice presidents to devise a plan to reduce the company's carbon footprint. We expanded the section on transportation mode to include a discussion of electric trucks.

Solving Teaching and Learning Challenges

Many students who take the introduction to operations management course have difficulty seeing the relevance of a process view of a business or the concepts of competitive priorities, throughput, and sustainability to their lives and their careers. Teaching can be a challenge when students are not motivated and get little reinforcement in what they have learned. We have found that students get motivated when they study concepts, techniques, and methods that are actually

used in practice, and they get reinforcement when they can apply what they have learned. As for motivation, the Thirteenth Edition has four pillars:

Four Pillars of Motivational Learning

- ***Practical.*** This text is written from a managerial perspective. The Managerial Challenges show how students of any business major can find usefulness in the topics of this text. Further, there are many examples of problems typically experienced in practice and the decision tools used to analyze them. The explanations are intuitive and provide a basis for students to apply the concepts and techniques in practice.
- ***Current.*** The chapter opening vignettes, Managerial Practices, videos, and photos connect the topics covered in the text to present-day practice and issues.
- ***Comprehensive.*** The Thirteenth Edition covers all of the new and traditional topics managers need to know to make their processes competitive weapons in a dynamic environment. Regardless of the functional area, *processes* are the means to get work done.
- ***Understandable.*** The Thirteenth Edition has numerous diagrams clearly showing the concepts or techniques being discussed. We took care to avoid unnecessary jargon. Key terms are defined in the margins of the paragraph where they are used, and key equations are listed at the end of the chapter. Further, each learning objective for a chapter is repeated at the end of the chapter with guidelines for review. All of these features are in the Thirteenth Edition to enhance clarity and make the text much more accessible to students of all majors.

As for reinforcement by applying what they have learned, the Thirteenth Edition provides ample opportunity for students to engage with the content.

EXAMPLE 4.2 **Determining the Value Stream Map, Takt Time, and Total Capacity**

Jensen Bearings Incorporated, a ball-bearing manufacturing company located in Lexington, South Carolina, receives raw material sheets from Kline Steel Company every Monday for a product family of retainers (casings in which ball bearings are held), and then ships its finished product on a daily basis to a second-tier automotive manufacturing customer named GNK Enterprises. The product family of the bearing manufacturing company under consideration consists of two types of retainers—large (L) and small (S)—that are packaged for shipping in returnable trays with 40 retainers in each tray. The manufacturing process consists of a value stream containing pressing operation; a piercing and forming cell, and a finish grind operation, after which the two types of retainers are staged for shipping. The information collected by the operations manager at Jensen Bearings Inc. is shown in Table 4.3.

Solved Problem 2

Metcalf, Inc., manufactures engine assembly brackets for two major automotive customers. The manufacturing process for the brackets consists of a cell containing a forming operation, a drilling operation, a finish grinding operation, and packaging, after which the brackets are staged for shipping. The information collected by the operations manager at Metcalf, Inc., is shown in Table 4.4.

Learning by Example

Many students struggle with quantitative problem solving. To help students who have difficulty, in the Thirteenth Edition each technique or interim calculation has an associated *example problem* in the chapter where it is discussed and a *solved problem* showing the entire technique for another problem at the end. In each case, the problem and all the steps toward solution are clearly demonstrated.

Developing Critical Problem-Solving Skills

Instructors can use the thought-provoking *discussion questions* in class to spark dialog of various issues and managerial situations. The *problems* are grouped under learning objectives to make it easier for instructors to assign problems that cover all objectives.

Discussion Questions

1. Figure 8.9 shows summer air visibility measurements for Denver, Colorado. The acceptable visibility standard is 100, with readings above 100 indicating clean air and good visibility, and readings below 100 indicating temperature inversions caused by forest fires, volcanic eruptions, or collisions with comets.
   a. Is a trend evident in the data? Which time-series techniques might be appropriate for estimating the average of these data?
   b. A medical center for asthma and respiratory diseases located in Denver has great demand for its services when air quality is poor. If you were in charge of developing a short-term (say, 3-day) forecast of visibility, which causal factor(s) would you analyze? In other words, which external factors hold the potential to significantly affect visibility in the *short term*?
   c. Tourism, an important factor in Denver's economy, is affected by the city's image. Air quality, as measured by visibility, affects the city's image. If you were responsible for development of tourism, which causal factor(s) would you analyze to forecast visibility for the *medium term* (say, the next two summers)?
   d. The federal government threatens to withhold several hundred million dollars in Department of Transportation funds unless Denver meets visibility standards within 8 years. How would you proceed to generate a *long-term* judgment forecast of technologies that will be available to improve visibility in the next 10 years?
2. Kay and Michael Passe publish *What's Happening?*—a biweekly newspaper to publicize local events. *What's Happening?* has few subscribers; it typically is sold at checkout stands. Much of the revenue comes from advertisers of garage sales and supermarket specials. In an effort to reduce costs associated with printing too many papers or delivering them to the wrong location, Michael implemented a computerized system to collect sales data. Sales-counter scanners accurately record sales data for each location. Since the system was implemented, total sales volume has steadily declined. Selling advertising space and maintaining shelf space at supermarkets are getting more difficult.

Helping Students Apply Their Skills

Students can test their understanding of the content using *cases* in two ways. First, the Thirteenth Edition has 14 *video cases*, 4 of which are new to this edition. Each video case has two parts: a written case describing a problem experienced by a real company, along with several questions asking how the student might resolve the issue at hand, and a video showing the actual setting for the case and discussions with managers regarding the problem. Each format provides a rich environment in which to discuss the topic of the chapter. The second way instructors can engage students is to use any of the 13 written cases in the text. These cases often provide data that students can use with techniques in the text to analyze and resolve an issue.



CASE Wolverine, Inc.

Wolverine is a medium-sized firm employing 900 persons and 125 managerial and administrative personnel. The firm produces a line of automotive electrical components. It supplies about 95 auto parts stores and several car dealers in its region. Johnny Bennett, who serves as the president, founded the company by producing cable assemblies in his garage. By working hard, delivering consistent product quality, and by providing good customer service, he expanded his business to produce a variety of electrical components. Bennett's commitment to customer service is so strong that his company motto, "Love Thy Customers as Thyself," is etched on a big cast-iron plaque under his giant oil portrait in the building's front lobby.

The company's two most profitable products are the automotive front sidelamp and the headlamp. With the rising popularity of Eurosport sedans, Wolverine has enjoyed substantial demand for these two lamp items.

Last year, Kathryn Marley, the vice president of operations and supply chain management, approved the installation of a new MRP system. It is a first important step toward the eventual goal of a full-fledged ERP system. Marley worked closely with the task force that was created to bring MRP online. She frequently attended the training sessions for selected employees, emphasizing how MRP should help Wolverine secure a better competitive edge.

A year later, the MRP system is working fairly well. However, Marley believes that there is always a better way and seeks to continually improve the company's processes. To get a better sense for potential improvements, she met with the production and inventory control manager, the shop supervisor, and the purchasing manager. Here are some of their observations.

can be just the opposite—so many new orders with short fuses that almost everyone needed to work overtime or else the scheduled receipt quantities are reduced to cover immediate needs. It is feast or famine, unless they make things work on the shop floor! They do make inventory transactions to report deviations from plan for the scheduled receipts, but these "overrides" make the scheduled receipt information in the MRP records more uncertain for the planners. A particular concern is to make sure that the bottleneck workstations are kept busy.

Purchasing

Buyers are putting out too many fires, leaving little time for creative buying. In such cases, their time is spent following up on orders that are required in the very near future or that are even late. Sometimes, the MRP plan shows planned order releases for purchased items that that are needed almost immediately, not allowing for the planned lead time. In checking the MRP records, the planned lead times are realistic and what the suppliers expect. Last week, things were fine for an item, and this week a rush order needs to be placed. What is the problem?

Marley tried to assimilate all this information. She decided to collect all the required information about the sidelamps and headlamps (shown in Tables 11.23 through 11.26 and in Figure 11.49) to gain further insight into possible problems and identify areas for improvement.



VIDEO CASE Quality at Axon

Protect life. Protect truth. That's the mission of Axon, the company that produces public safety technologies such as Taser electrical smart weapons and body cameras for law enforcement around the globe. In business since 1993, the company manufactures three weapons lines inside its high-tech headquarters in Scottsdale, Arizona. Ninety-nine percent of its customers are in law enforcement, military, correctional, and professional security organizations.

Designing and manufacturing smart weapons technologies requires precise engineering and production processes that can ensure both accuracy and operational safety for its organizational customers and personal protection buyers. This attention to detail is evidenced in the company's commitment to quality, and can be seen in the way the manufacturing operation is organized. Axon's manufacturing operations are ISO 9001:2008 certified.

All finished goods are produced to stock, so that the company can be responsive when an order is received. Sales history data help dictate which items to make to stock, and which could sit in inventory between 6 and 12 weeks before being sold. Most employees have undergone voluntary exposure to the weapons, including the founders.

Axon's work cells are arranged by product. At the start of the week, each cell is given a "production order" document that lists the bill of materials for the finished goods that cell must produce during the week. The production order is released by Axon's Enterprise Resource Planning (ERP) system, with raw materials required for assembly pulled and staged at each cell weekly. In addition to supporting the informational needs of all the functional areas of a firm, ERP systems support the manufacture of a firm's products by scheduling the fabrication of components and the arrival of purchased materials in support of the overall production plan.

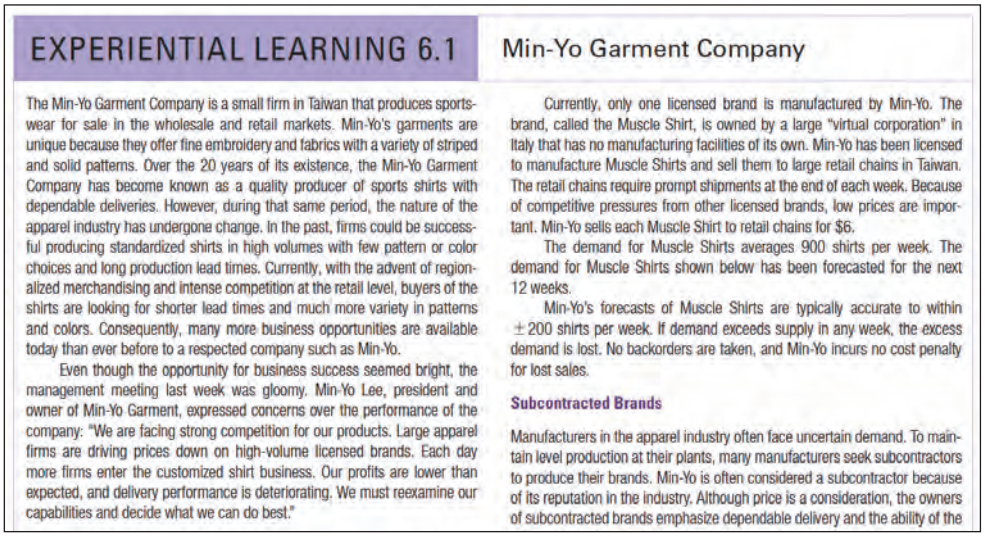
Axon's attention to quality is embedded throughout its manufacturing processes. Raw materials are tested and inspected for quality conformance at the supplier to be certain no faulty components are shipped. Circuit boards, which are assembled domestically, are each tested prior to shipment, and then acceptance sampling at Axon's receiving dock confirms shipment conformance. The same process occurs for the supplier of injection molded components, such as weapons casings. Testing includes functionality checks, drop tests to ensure the product can withstand being dropped, and temperature checks to make sure the weapons will work between a temperature range

Bill's project sought to engage manufacturing engineering in the automation of test data collection to develop baselines for processes and establish upper and lower control limits. Line workers were given explicit parameters for processes, and they immediately took ownership of those processes. As a result, it quickly became evident when something in the work cell was trending out of control so the issue could be resolved within hours. A formal escalation process further ensured that the right individuals were notified to get action.

In 2013, Axon installed computer monitors above each work cell so that all manufacturing employees could see the data related to how they were doing. The data include scrap dollars as a percentage of total production, process yield (units produced), average labor cost per unit compared to expected labor cost, average material costs per unit compared to expected material costs, daily/monthly/quarterly production output compared to planned output, throughput times compared to standards, and more.

ATHENA PICTURE AGENCY LTD/Alamy Stock Photo

The AXON bodycams on their charge and download cradle. Body worn video cameras are being introduced into the South Wales Police force as part of operational equipment and will be rolled out over the next few months.



EXPERIENTIAL LEARNING 6.1 Min-Yo Garment Company

The Min-Yo Garment Company is a small firm in Taiwan that produces sportswear for sale in the wholesale and retail markets. Min-Yo's garments are unique because they offer fine embroidery and fabrics with a variety of striped and solid patterns. Over the 20 years of its existence, the Min-Yo Garment Company has become known as a quality producer of sports shirts with dependable deliveries. However, during that same period, the nature of the apparel industry has undergone change. In the past, firms could be successful producing standardized shirts in high volumes with few pattern or color choices and long production lead times. Currently, with the advent of regionalized merchandising and intense competition at the retail level, buyers of the shirts are looking for shorter lead times and much more variety in patterns and colors. Consequently, many more business opportunities are available today than ever before to a respected company such as Min-Yo.

Even though the opportunity for business success seemed bright, the management meeting last week was gloomy. Min-Yo Lee, president and owner of Min-Yo Garment, expressed concerns over the performance of the company: "We are facing strong competition for our products. Large apparel firms are driving prices down on high-volume licensed brands. Each day more firms enter the customized shirt business. Our profits are lower than expected, and delivery performance is deteriorating. We must reexamine our capabilities and decide what we can do best."

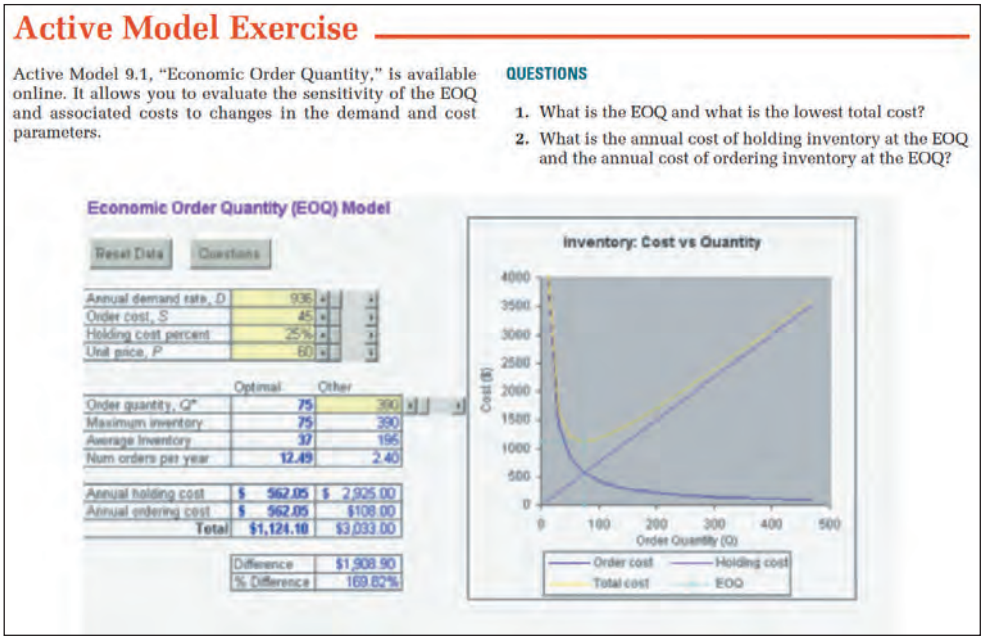
Currently, only one licensed brand is manufactured by Min-Yo. The brand, called the Muscle Shirt, is owned by a large "virtual corporation" in Italy that has no manufacturing facilities of its own. Min-Yo has been licensed to manufacture Muscle Shirts and sell them to large retail chains in Taiwan. The retail chains require prompt shipments at the end of each week. Because of competitive pressures from other licensed brands, low prices are important. Min-Yo sells each Muscle Shirt to retail chains for $6.

The demand for Muscle Shirts averages 900 shirts per week. The demand for Muscle Shirts shown below has been forecasted for the next 12 weeks.

Min-Yo's forecasts of Muscle Shirts are typically accurate to within ±200 shirts per week. If demand exceeds supply in any week, the excess demand is lost. No backorders are taken, and Min-Yo incurs no cost penalty for lost sales.

Subcontracted Brands

Manufacturers in the apparel industry often face uncertain demand. To maintain level production at their plants, many manufacturers seek subcontractors to produce their brands. Min-Yo is often considered a subcontractor because of its reputation in the industry. Although price is a consideration, the owners of subcontracted brands emphasize dependable delivery and the ability of the



Active Model Exercise

Active Model 9.1, "Economic Order Quantity," is available online. It allows you to evaluate the sensitivity of the EOQ and associated costs to changes in the demand and cost parameters.

QUESTIONS

1. What is the EOQ and what is the lowest total cost?
2. What is the annual cost of holding inventory at the EOQ and the annual cost of ordering inventory at the EOQ?

Working in Teams and Gaining Valuable Decision-Making Experience

Perhaps the most engaging and fun activities in the Thirteenth Edition are the *experiential learning* and *active model* exercises. There are five time-tested experiential learning exercises that require students to form teams for work both in and out of class on exercises that involve them in team-based discussion questions and decisions. Two of these experiences are competitive decision simulations that often generate intense interest in the students. In addition, there are 29 active model spreadsheets that require students to evaluate different situations based on problem scenarios. These models are perfect for asking "what if" questions and learning from the results. The Active Models assignments are supported by online tools that are available to all students.

All told, the Thirteenth Edition has the elements to support student motivation and reinforcement and, along with a host of Instructor Resources, it solves most of the teaching and learning challenges involved in the introduction to operations management course.

Developing Employability Skills

For students to succeed in a rapidly changing job market, they need to develop a variety of skills. We have identified seven critical skills that recruiters look for in students seeking a career in business. The matrix shows how major elements of the Thirteenth Edition map into those essential skills.

Employability Skills in the 13e

Text Elements	Communication	Critical Thinking	Collaboration	Knowledge Application and Analysis	Business Ethics and Social Responsibility	Information Technology Application and Computing Skills	Data Literacy
Active Model Exercises				✓		✓	✓
Cases	✓	✓	✓	✓			✓
Chapter Opening Vignettes				✓	✓		
Discussion Questions	✓				✓		
Experiential Learning	✓	✓	✓	✓			
Managerial Challenges	✓	✓	✓				
Managerial Practices				✓	✓		
Numerical Examples		✓					✓
OM Explorer and POM for Windows						✓	
Photo Illustrations				✓			
Problems		✓		✓		✓	✓
Solved Problems		✓					✓

Additional Resources

Resources available to instructors and students at www.pearsonglobaleditions.com	Features of the Resource
Online Supplements	Supplement Sections E through K provide students and instructors with additional content on important topics such as Simulation, Financial Analysis, Acceptance Sampling, Measuring Output Rates, Learning Curve Analysis, Operations Scheduling, and Layout.
OM Explorer	This text-specific software consists of Excel worksheets and includes tutors and solvers. • **Tutors** provide coaching for more than 60 analytical techniques presented in the text. The tutors also provide additional examples for learning and practice. • **Solvers** provide powerful general-purpose routines often encountered in practice. These are great for experiential exercises and homework problems.
POM for Windows	An easy-to-use software program that covers over 25 common OM techniques.
Active Models	These 29 spreadsheets require students to evaluate different situations based on problem scenarios. They are excellent for doing "what-if" analyses.
SimQuick	An Excel spreadsheet (with macros) for building simulation models of processes: waiting lines, supply chains, manufacturing facilities, and project scheduling. SimQuick is easy to learn, easy to use, and flexible in its modeling capability.
SmartDraw	Draw diagrams, flowcharts, organization charts, and more in minutes with SmartDraw's diagram software. Thousands of included diagram templates and symbols.

Detailed information and additional resources are available at **www.pearsonglobaleditions.com**.

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Manoj K. Malhotra

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1

USING OPERATIONS TO CREATE VALUE

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

1.1 Describe the role of operations in an organization and its historical evolution over time.

1.2 Describe the process view of operations in terms of inputs, processes, outputs, information flows, suppliers, and customers.

1.3 Describe the supply chain view of operations in terms of linkages between core and support processes.

1.4 Define an operations strategy and its linkage to corporate strategy and market analysis.

1.5 Identify nine competitive priorities used in operations strategy, and explain how a consistent pattern of decisions can develop organizational capabilities.

1.6 Identify the latest trends in operations management and understand how firms can address the challenges facing operations and supply chain managers in a firm.

1.7 Define the fourth industrial revolution (Industry 4.0) and understand how its embedded technologies and automation are transforming the practice of operations and supply chain management.

1.8 Understand how to develop skills for your career using this textbook.

Apple Inc.



SOPA Images Limited/Alamy Stock Photo

The brand new Apple Store at Central World during the first day opening event, Bangkok, Thailand.

Apple Incorporated is the world's largest multinational technology company: It has over 137,000 employees and 510 retail stores in 25 countries. Robust sales of consumer electronics, computer software, and online

services have made it the most valued company in the world, with a market capitalization of $1.953 trillion as of August 12, 2020. Apple's brand loyalty is legendary, with a cult-like following of customers who often stand in long lines to buy new products when they are launched. Even though its stellar reputation has been built on innovative designs and trendsetting new products like the iPhone, few realize that Apple's distinctiveness and competitive superiority arise just as strongly, if not more so, from its outstanding manufacturing, operations, and supply chain management practices.

The 10 decision areas of operations management that Apple measures to maximize its operational efficiency and build strategic capabilities are (i) design of goods and services, (ii) quality management, (iii) process and capacity design, (iv) location strategy for stores, (v) layout design and strategy, (vi) job design and human resources, (vii) supply chain management, (viii) inventory management, (ix) scheduling, and (x) maintenance. A dedicated team of senior managers establish and implement a well-calibrated set of metrics that establish different standards, benchmarks, and criteria for productivity in different decision areas.

So, what drives Apple's operational excellence? It is not any single decision area mentioned above that stands out in particular, but how well operations and supply chain decisions are intertwined into every other decision that the company makes in its fairly well-controlled ecosystem, ranging from product design to component sourcing, manufacturing, distribution, and retail store design and location. By focusing on a narrow product line, Apple can make each product in larger volumes and get quantity discounts from suppliers. By investing in advanced component material and manufacturing process technologies, coupled with a superior understanding of the markets, Apple can anticipate customer needs ahead of time and give customers what they want through innovative products that competitors cannot easily copy or reproduce.

Apple's long-term investments in its processes, supply chains, and human resource practices also make it very resilient in managing its complex multinational supply chains. Even in the midst of the coronavirus pandemic, Foxconn, Apple's contract manufacturer, was running night shifts at its iPhone factory in Zhengzhou, Henan Province, China. While it will not escape completely unscathed, Apple has built contingency plans and managed disruptions in its supply chains better than many of its competitors. Its launch of potential new products like iPhone 12, Apple TV, and an Apple Watch will not occur within the usual time frame of September 2020, but are on track to show up a few weeks later. Despite store closures and inventory shortages, Apple reported on July 30, 2020, that its revenue was the highest that the company has ever reported in its third quarter, up 11 percent year-over-year. And so the juggernaut continues, powered by its vaunted world-class skills and capabilities in operations and supply chain management.[1]

[1] *Sources:* Christine Rowland, "Apple Inc. Operations Management: 10 Decisions, Productivity," *Panmore Institute* (February 19, 2019), http://panmore.com/apple-inc-operations-management-10-decisions-areas-productivity (August 10, 2020); Jonny Evans, "Apple's Operations Teams Must Be Struggling to Pull Things Together," *Computerworld* (March 2, 2020), https://www.computerworld.com/article/3530037/apples-operations-teams-must-be-struggling-to-pull-things-together.html (August 10, 2020); Kif Leswing, "Apple Posts Blowout Third Quarter, with Sales up 11% Despite Coronavirus Disruptions," cnbc.com (July 30, 2020), https://www.cnbc.com/2020/07/30/apple-aapl-earnings-q3-2020.html (August 10, 2020); Marty Lativiere, "Operations: Apple's Secret Sauce?" The Operations Room (November 4, 2011), https://operationsroom.wordpress.com/2011/11/04/operations-apples-secret-sauce/ (August 10, 2010); https://en.wikipedia.org/wiki/Apple_Inc. (August 10, 2020).

Operations management refers to the systematic design, direction, and control of processes that transform inputs into services and products for both internal and external customers. As exemplified by Apple, it can be a source of competitive advantage for firms in both service and manufacturing sectors.

This book deals with managing those fundamental activities and processes that organizations use to produce goods and services that people use every day. A **process** is any activity or group of activities that takes one or more inputs, transforms them, and provides one or more outputs for its customers. For organizational purposes, processes tend to be clustered together into operations. An **operation** is a group of resources performing all or part of one or more processes. Processes can be linked together to form a **supply chain**, which is the interrelated series of processes within a firm and across different firms that produce a service or product to the satisfaction of customers.[2] A firm can have multiple supply chains, which vary by the product or service provided. **Supply chain management** is the synchronization of a firm's processes with those of its suppliers and customers to match the flow of materials, services, and information with customer demand. As we will learn throughout this book, all firms have processes and supply chains. Sound operational planning and design of these processes, along with internal and external coordination within its supply chain, can create wealth and value for a firm's diverse stakeholders.

operations management
The systematic design, direction, and control of processes that transform inputs into services and products for internal, as well as external, customers.

process
Any activity or group of activities that takes one or more inputs, transforms them, and provides one or more outputs for its customers.

operation
A group of resources performing all or part of one or more processes.

supply chain
An interrelated series of processes within and across firms that produces a service or product to the satisfaction of customers.

supply chain management
The synchronization of a firm's processes with those of its suppliers and customers to match the flow of materials, services, and information with customer demand.

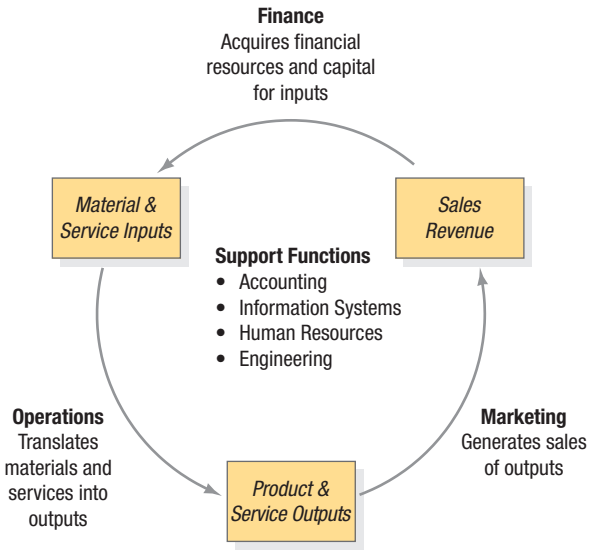
Role of Operations in an Organization

Broadly speaking, operations and supply chain management underlie all departments and functions in a business. Whether you aspire to manage a department or a particular process within it, or you just want to understand how the process you are a part of fits into the overall fabric of the business, you need to understand the principles of operations and supply chain management.

Operations serve as an excellent career path to upper management positions in many organizations. The reason is that operations managers are responsible for key decisions that affect the success of the organization. In manufacturing firms, the head of operations usually holds the title chief operations officer (COO) or vice president of manufacturing (or of production or operations). The corresponding title in a service organization might be COO or vice president (or director) of operations. Reporting to the head of operations are the managers of departments such as customer service, production and inventory control, and quality assurance.

Figure 1.1 shows operations as one of the key functions within an organization. The circular relationships that are shown highlight the importance of the coordination among the three mainline functions of any business: (1) operations, (2) marketing, and (3) finance. Each function is unique and has its own knowledge and skill areas, primary responsibilities, processes, and decision domains. From an external perspective, finance generates resources, capital, and funds from investors and sales of its goods and services in the marketplace. Based on business strategy, the finance and operations functions then decide how to invest these resources and convert them into physical assets and material inputs. Operations subsequently transforms these material and service inputs into product and service outputs. These outputs must match the characteristics that can be sold in the selected markets by marketing. Marketing is responsible for producing sales revenue of the outputs, which become returns to investors and capital for supporting operations. Functions such as accounting, information systems, human resources, and engineering make the firm complete by providing essential information, services, and other managerial support.

▼ **FIGURE 1.1**
Integration Between Different Functional Areas of a Business



These relationships provide direction for the business as a whole and are aligned to the same strategic intent. It is important to understand the entire circle, and not just the individual functional areas. How well these functions work together determines the effectiveness of the organization. Functions should be integrated and should pursue a common strategy. Success depends on how well they are able to do so. No part of this circle can be dismissed or minimized without loss of effectiveness, and regardless of how departments and functions are individually managed; they are always linked together through processes. Thus, a firm competes not only by offering new services and products, creative marketing, and skillful finance but also through its unique competencies in operations and sound management of core processes.

[2]The terms *supply chain* and *value chain* are sometimes used interchangeably.



Philip Arno Photography/Shutterstock

The Ford Motor Company, founded in 1903, produced about 1 million Model T's in 1921 alone.

Historical Evolution and Perspectives

The history of modern operations and supply chain management is rich and over 200 years old, even though its practice has been around in one form or another for centuries. James Watt invented the steam engine in 1785. The subsequent establishment of railroads facilitated efficient movement of goods throughout Europe, and eventually even in distant colonies such as India. With the invention of the cotton gin in 1794, Eli Whitney introduced the concept of interchangeable parts. It revolutionized the art of machine-based manufacturing and, coupled with the invention of the steam engine, led to the great industrial revolution in England and the rest of Europe. The textile industry was one of the earliest industries to be mechanized. The industrial revolution gradually spread to the United States and the rest of the world in the 19th century and was accompanied by such great innovations as the internal combustion engine, steam-powered ships, metallurgy of iron making, large-scale production of chemicals, and invention of machine tools, among others. The foundations of modern manufacturing and technological breakthroughs were also inspired by the creation of a mechanical computer by Charles Babbage in the early part of the 19th century. He also pioneered the concept of division of labor, which laid the foundation for scientific management of operations and supply chain management that was further improved upon by Frederick Taylor in 1911.

Three other landmark events from the 20th century define the history of operations and supply chain management. First is the invention of the assembly line for the Model T car by Henry Ford in 1909. The era of mass production was born, in which complex products like automobiles could be manufactured in large numbers at affordable prices through repetitive manufacturing. Second, Alfred Sloan in the 1930s introduced the idea of strategic planning for achieving product proliferation and variety, with the newly founded General Motors Corporation offering "a car for every purse and purpose." Finally, with the publication of the Toyota Production System book in Japanese in 1978, Taiichi Ohno laid the groundwork for removing wasteful activities from an organization, a concept that we explore further in this book while learning about lean systems.

The recent history of operations and supply chains over the past three decades has been steeped in technological advances. The 1980s were characterized by wide availability of computer-aided design (CAD), computer-aided manufacturing (CAM), and automation. Information technology applications started playing an increasingly important role in the 1990s and started connecting the firm with its extended enterprise through Enterprise Resource Planning Systems and outsourced technology hosting for supply chain solutions. Service organizations like Amazon, Federal Express, United Parcel Service (UPS), and Walmart also became sophisticated users of information technology in operations, logistics, and management of supply chains. The new millennium has seen an acceleration of this trend, along with an increased focus on modern smart technologies, sustainability and the natural environment. We cover all these ideas and topical areas in greater detail throughout this book.

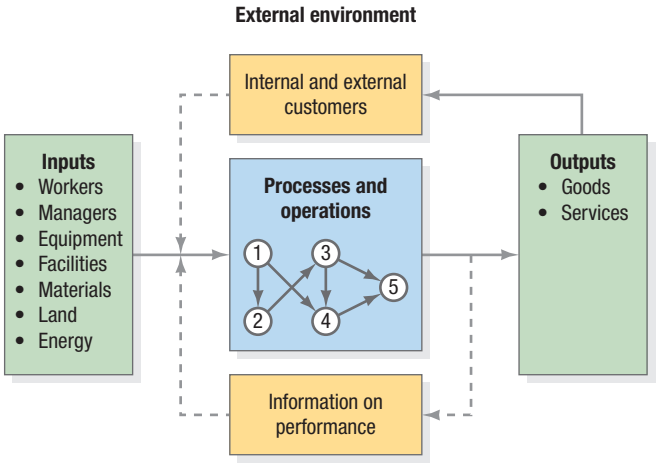
A Process View

You might wonder why we begin by looking at processes rather than at departments or even the firm. The reason is that a process view of the firm provides a much more relevant picture of the way firms actually work. Departments typically have their own set of objectives, a set of resources with capabilities to achieve those objectives, and managers and employees responsible for performance. Some processes, such as billing, may be so specific that they are contained wholly within a single department, such as accounting.

The concept of a process, however, can be much broader. A process can have its own set of objectives, involve a workflow that cuts across departmental boundaries, and require resources from several departments. You will see examples throughout this text of companies that discovered how to use their processes to gain a competitive advantage. You will notice that the key to success in many organizations is a keen understanding of how their processes work, since an organization is only as effective as its processes. Therefore, operations management is relevant and important for all students, regardless of major, because all departments have processes that must be managed effectively to gain a competitive advantage.

How Processes Work

Figure 1.2 shows how processes work in an organization. Any process has inputs and outputs. Inputs can include a combination of human resources (workers and managers), capital (equipment and facilities), purchased materials and services, land, and energy. The numbered circles represent operations through which services, products, or customers pass and where processes are performed. The arrows represent flows and can cross because one job or customer can have different requirements (and thus a different flow pattern) than the next job or customer.



▲ **FIGURE 1.2**
Processes and Operations

Processes provide outputs to customers. These outputs may often be services (that can take the form of information) or tangible products. Every process and every person in an organization has customers. Some are **external customers**, who may be end users or intermediaries (e.g., manufacturers, financial institutions, or retailers) buying the firm's finished services or products. Others are **internal customers**, who may be employees in the firm whose process inputs are actually the outputs of earlier processes managed within the firm. Either way, processes must be managed with the customer in mind.

In a similar fashion, every process and every person in an organization relies on suppliers. **External suppliers** may be other businesses or individuals who provide the resources, services, products, and materials for the firm's short-term and long-term needs. Processes also have **internal suppliers**, who may be employees or processes that supply important information or materials.

Inputs and outputs vary depending on the service or product provided. For example, inputs at a jewelry store include merchandise, the store building, registers, the jeweler, and customers; outputs to external customers are services and sold merchandise. Inputs to a factory manufacturing blue jeans include denim, machines, the plant, workers, managers, and services provided by outside consultants; outputs are clothing and supporting services. The fundamental role of inputs, processes, and customer outputs holds true for processes at all organizations.

Figure 1.2 can represent a whole firm, a department, a small group, or even a single individual. Each one has inputs and uses processes at various operations to provide outputs. The dashed lines represent two special types of input: participation by customers and information on performance from both internal and external sources. Participation by customers occurs not only when they receive outputs but also when they take an active part in the processes, such as when students participate in a class discussion. Information on performance includes internal reports on customer service or inventory levels and external information from market research, government reports, or telephone calls from suppliers. Managers need all types of information to manage processes most effectively.

external customers
A customer who is either an end user or an intermediary (e.g., manufacturers, financial institutions, or retailers) buying the firm's finished services or products.

internal customers
One or more employees or processes that rely on inputs from other employees or processes to perform their work.

external suppliers
The businesses or individuals who provide the resources, services, products, and materials for the firm's short-term and long-term needs.

internal suppliers
The employees or processes that supply important information or materials to a firm's processes.

nested process
The concept of a process within a process.

Nested Processes

Processes can be broken down into subprocesses, which in turn can be broken down further into still more subprocesses. We refer to this concept of a process within a process as a **nested process**. It may be helpful to separate one part of a process from another for several reasons. One person or one department may be unable to perform all parts of the process, or different parts of the process may require different skills. Some parts of the process may be designed for routine work, whereas other parts may be geared for customized work. The concept of nested processes is illustrated in greater detail in Chapter 2, "Process Strategy and Analysis," where we reinforce the need to understand and improve activities within a business and each process's inputs and outputs.

Service and Manufacturing Processes

Two major types of processes are (1) service and (2) manufacturing. Service processes pervade the business world and have a prominent place in our discussion of operations management. Manufacturing processes are also important; without them the products we enjoy as part of our daily lives would not exist. In addition, manufacturing gives rise to service opportunities.

Differences Why do we distinguish between service and manufacturing processes? The answer lies at the heart of the design of competitive processes. While Figure 1.3 shows several distinctions between service and manufacturing processes along a continuum, the two key differences that we discuss in detail are (1) the nature of their output and (2) the degree of customer contact. In general, manufacturing processes also have longer response times, they are more capital intensive, and their quality can be measured more easily than those of service processes.



- Physical, durable output
- Output can be inventoried
- Low customer contact
- Long response time
- Capital intensive
- Quality easily measured

- Intangible, perishable output
- Output cannot be inventoried
- High customer contact
- Short response time
- Labor intensive
- Quality not easily measured

▲ **FIGURE 1.3**
Continuum of Characteristics of Manufacturing and Service Processes

Manufacturing processes convert materials into goods that have a physical form we call products. For example, an assembly line produces a 370 Z sports car, and a tailor produces an outfit for the rack of an upscale clothing store. The transformation processes change the materials on one or more of the following dimensions:

1. Physical properties
2. Shape
3. Size (e.g., length, breadth, and height of a rectangular block of wood)
4. Surface finish
5. Joining parts and materials

The outputs from manufacturing processes can be produced, stored, and transported in anticipation of future demand.

If a process does not change the properties of materials on at least one of these five dimensions, it is considered a service (or nonmanufacturing) process. Service processes tend to produce intangible, perishable outputs. For example, the output from the auto loan process of a bank would be a car loan, and an output of the order fulfillment process of the U.S. Postal Service is the delivery of your letter. The outputs of service processes typically cannot be held in a finished goods inventory to insulate the process from erratic customer demands.

A second key difference between service processes and manufacturing processes is degree of customer contact. Service processes tend to have a higher degree of customer contact. Customers may take an active role in the process itself, as in the case of shopping in a supermarket, or they may be in close contact with the service provider to communicate specific needs, as in the case of a medical clinic. Manufacturing processes tend to have less customer contact. For example, washing machines are ultimately produced to meet retail forecasts. The process requires little information from the ultimate consumers (you and me), except indirectly through market surveys and market focus groups. Even though the distinction between service and manufacturing processes on the basis of customer contact is not perfect, the important point is that managers must recognize the degree of customer contact required when designing processes.



Image Source/Alamy Stock Photo



Iakov Filimonov/Shutterstock

(a) A manufacturing process showing workers on a production line in a factory. (b) A service process showing a hospitable cheerful server helping customers with the menu and taking their orders in a restaurant.

Similarities At the level of the firm, service providers do not just offer services and manufacturers do not just offer products. Patrons of a restaurant expect good service and good food. A customer purchasing a new computer expects a good product as well as a good warranty, maintenance, replacement, and financial services.

Further, even though service processes do not keep finished goods inventories, they do inventory their inputs. For example, hospitals keep inventories of medical supplies and materials needed for day-to-day operations. Some manufacturing processes, in contrast, do not inventory their outputs because they are too costly. Such would be the case with low-volume customized products (e.g., tailored suits) or products with short shelf lives (e.g., daily newspapers).

When you look at what is being done at the process level, it is much easier to see whether the *process* is providing a service or manufacturing a product. However, this clarity is lost when the whole company is classified as either a manufacturer or a service provider because it often performs both types of processes. For example, the process of cooking a hamburger at a McDonald's is a manufacturing process because it changes the material's physical properties (dimension 1), as is the process of assembling the hamburger with the bun (dimension 5). However, most of the other processes visible or invisible to McDonald's customers are service processes. You can debate whether to call the whole McDonald's organization a service provider or a manufacturer, whereas classifications at the process level are much less ambiguous.

A Supply Chain View

Most services or products are produced through a series of interrelated business activities. Each activity in a process should add value to the preceding activities; waste and unnecessary cost should be eliminated. Our process view of a firm is helpful for understanding how services or products are produced and why cross-functional coordination is important, but it does not shed any light on the strategic benefits of the processes. The missing strategic insight is that processes must add value for customers throughout the supply chain. The concept of supply chains reinforces the link between processes and performance, which includes a firm's internal processes as well as those of its external customers and suppliers. It also focuses attention on the two main types of processes in the supply chain, namely, (1) core processes and (2) support processes. Figure 1.4 shows the links between the core and support processes in a firm and a firm's external customers and suppliers within its supply chain.

Core Processes

A **core process** is a set of activities that delivers value to external customers. Managers of these processes and their employees interact with external customers and build relationships with them, develop new services and products, interact with external suppliers, and produce the service or product for the external customer. Examples include a hotel's reservation handling, a new car design for an auto manufacturer, or Web-based purchasing for an online retailer like Amazon.com. Of course, each of the core processes has nested processes within it.

In this text we focus on four core processes:

1. *Supplier Relationship Process.* Employees in the **supplier relationship process** select the suppliers of services, materials, and information and facilitate the timely and efficient flow of these items into the firm. Working effectively with suppliers can add significant value to the services or products of the firm. For example, negotiating fair prices, scheduling on-time deliveries, and gaining ideas and insights from critical suppliers are just a few of the ways to create value.
2. *New Service/Product Development Process.* Employees in the **new service/product development process** design and develop new services or products. The services or products may be developed to external customer specifications or conceived from inputs received from the market in general.
3. *Order Fulfillment Process.* The **order fulfillment process** includes the activities required to produce and deliver the service or product to the external customer.
4. *Customer Relationship Process,* sometimes referred to as *customer relationship management.* Employees involved in the **customer relationship process** identify, attract, and build relationships with external customers and facilitate the placement of orders by customers. Traditional functions, such as marketing and sales, may be a part of this process.

core process
A set of activities that delivers value to external customers.

supplier relationship process
A process that selects the suppliers of services, materials, and information and facilitates the timely and efficient flow of these items into the firm.

new service/product development process
A process that designs and develops new services or products from inputs received from external customer specifications or from the market in general through the customer relationship process.

order fulfillment process
A process that includes the activities required to produce and deliver the service or product to the external customer.

customer relationship process
A process that identifies, attracts, and builds relationships with external customers and facilitates the placement of orders by customers, sometimes referred to as *customer relationship management.*

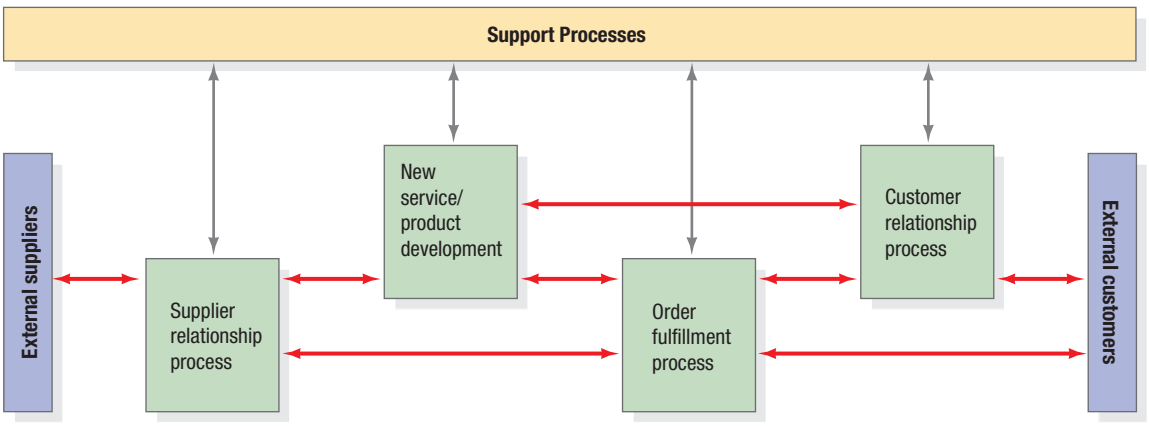


FIGURE 1.4
Supply Chain Linkages Showing Work and Information Flows

Support Processes

A **support process** provides vital resources and inputs to the core processes and is essential to the management of the business. Processes as such are not just in operations but are found in accounting, finance, human resources, management information systems, and marketing. The human resources function in an organization provides many support processes, such as recruiting and hiring workers who are needed at different levels of the organization, training the workers for skills and knowledge needed to properly execute their assigned responsibilities, and establishing incentive and compensation plans that reward employees for their performance. The legal department

support process
A process that provides vital resources and inputs to the core processes and therefore is essential to the management of the business.

puts in place support processes ensuring that the firm is in compliance with the rules and regulations under which the business operates. The accounting function supports processes that track how the firm's financial resources are being created and allocated over time, while the information systems function is responsible for the movement and processing of data and information needed to make business decisions. Organizational structure throughout the many diverse industries varies, but for the most part, all organizations perform similar business processes. Table 1.1 lists a sample of them that are outside the operations area.

TABLE 1.1 | ILLUSTRATIVE BUSINESS PROCESSES OUTSIDE OPERATIONS

Activity-based costing	Employee benefits	Help desks
Asset management	Employee compensation	IT networks
Billing budget	Employee development	Payroll
Complaint handling	Employee recruiting	Records management
Credit management	Employee training	Research and development
Customer satisfaction	Engineering	Sales
Data warehousing	Environment	Security management
Data mining	External communications	Waste management
Disaster recovery	Finance	Warranty

All of these support processes must be managed to create as much value for the firm and its customers as possible, and are therefore vital to the execution of core processes highlighted in Figure 1.4. Managers of these processes must understand that they cut across the organization, regardless of whether the firm is organized along functional, product, regional, or process lines.

Supply Chain Processes

supply chain processes
Business processes that have external customers or suppliers.

Supply chain processes are business processes that have external customers or suppliers. Table 1.2 illustrates some common supply chain processes.

These supply chain processes should be documented and analyzed for improvement, examined for quality improvement and control, and assessed in terms of capacity and bottlenecks. Supply chain processes will be only as good as the processes within the organization that have only internal suppliers and customers. Each process in the chain, from suppliers to customers, must be designed and managed to add value to the work performed.

TABLE 1.2 | SUPPLY CHAIN PROCESS EXAMPLES

Process	Description	Process	Description
Outsourcing	Exploring available suppliers for the best options to perform processes in terms of price, quality, delivery time, and environmental issues	**Customer Service**	Providing information to answer questions or resolve problems using automated information services as well as voice-to-voice contact with customers
Warehousing	Receiving shipments from suppliers, verifying quality, placing in inventory, and reporting receipt for inventory records	**Logistics**	Selecting transportation mode (train, ship, truck, airplane, or pipeline), scheduling both inbound and outbound shipments, and providing intermediate inventory storage
Sourcing	Selecting, certifying, and evaluating suppliers and managing supplier contracts	**Cross-docking**	Packing of products of incoming shipments so they can be easily sorted more economically at intermediate warehouses for outgoing shipments to their final destination

Operations Strategy

operations strategy
The means by which operations implements the firm's corporate strategy and helps to build a customer-driven firm.

Operations strategy specifies the means by which operations implements corporate strategy and helps to build a customer-driven firm. It links long-term and short-term operations decisions to corporate strategy and develops the capabilities the firm needs to be competitive. It is at the heart of managing processes and supply chains. A firm's internal processes are only building blocks:

They need to be organized to ultimately be effective in a competitive environment. Operations strategy is the linchpin that brings these processes together to form supply chains that extend beyond the walls of the firm, encompassing suppliers as well as customers. Since customers constantly desire change, the firm's operations strategy must be driven by the needs of its customers.

Developing a customer-driven operations strategy is a process that begins with *corporate strategy*, which, as shown in Figure 1.5, coordinates the firm's overall goals with its core processes. It determines the markets the firm will serve and the responses the firm will make to changes in the environment. It provides the resources to develop the firm's core competencies and core processes, and it identifies the strategy the firm will employ in international markets. Based on corporate strategy, a *market analysis* categorizes the firm's customers, identifies their needs, and assesses competitors' strengths. This information is used to develop *competitive priorities*. These priorities help managers develop the services or products and the processes needed to be competitive in the marketplace. Competitive priorities are important to the design of existing as well as new services or products, the processes that will deliver them, and the operations strategy that will develop the firm's capabilities to fulfill them. Developing a firm's operations strategy is a continuous process because the firm's capabilities to meet the competitive priorities must be periodically checked, and any gaps in performance must be addressed in the operations strategy.

Corporate Strategy

Corporate strategy provides an overall direction that serves as the framework for carrying out all the organization's functions. It specifies the business or businesses the company will pursue, isolates new opportunities and threats in the environment, and identifies growth objectives.

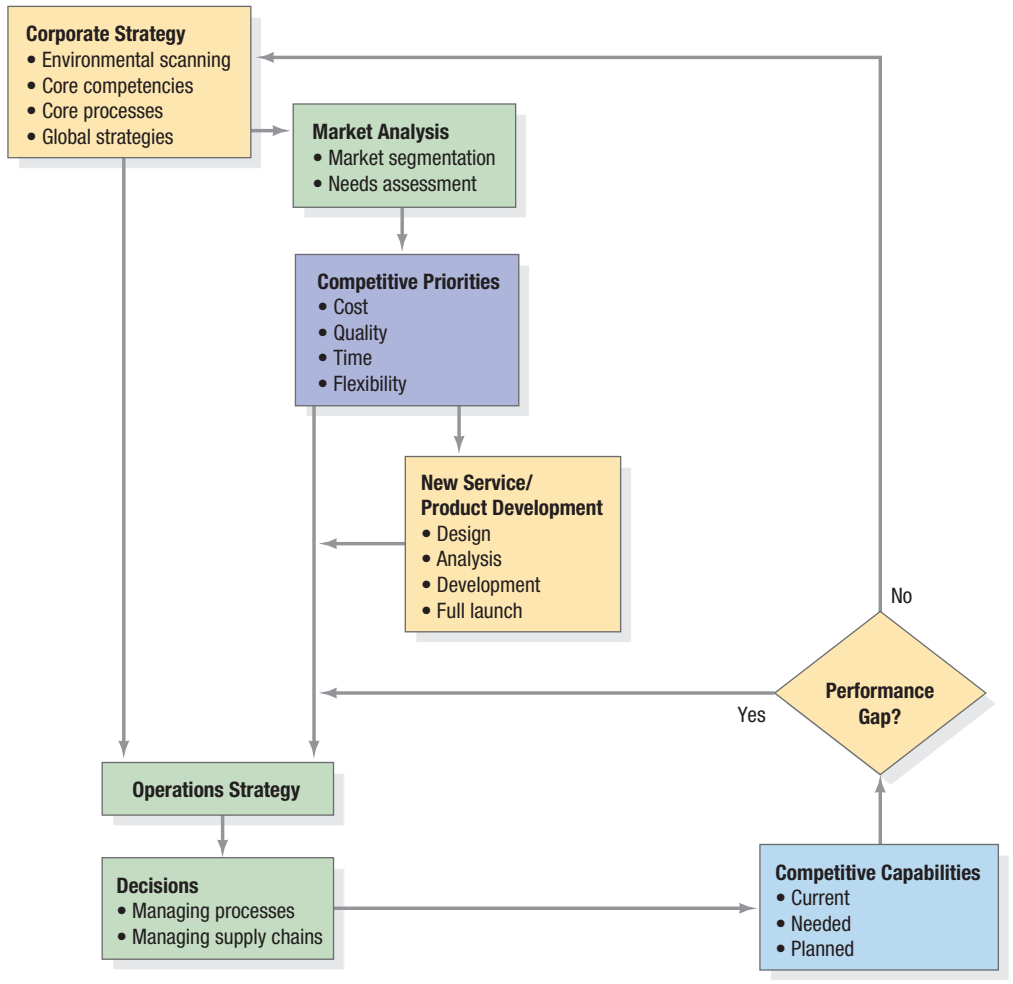


FIGURE 1.5
Connection Between Corporate Strategy and Key Operations Management Decisions

Developing a corporate strategy involves four considerations: (1) environmental scanning: monitoring and adjusting to changes in the business environment, (2) identifying and developing the firm's core competencies, (3) developing the firm's core processes, and (4) developing the firm's global strategies.

Environmental Scanning The external business environment in which a firm competes changes continually, and an organization needs to adapt to those changes. Adaptation begins with *environmental scanning*, the process by which managers monitor trends in the environment (e.g., the industry, the marketplace, and society) for potential opportunities or threats. A crucial reason for environmental scanning is to stay ahead of the competition. Competitors may be gaining an edge by broadening service or product lines, improving quality, or lowering costs. New entrants into the market or competitors that offer substitutes for a firm's service or product may threaten continued profitability. Other important environmental concerns include economic trends, technological changes, political conditions, social changes (i.e., attitudes toward work), and the availability of vital resources. For example, car manufacturers recognize that dwindling oil reserves will eventually require alternative fuels for their cars. Consequently, they have designed prototype cars that use hydrogen or electric power as supplements to gasoline as a fuel.

Developing Core Competencies Good managerial skill alone cannot overcome environmental changes. Firms succeed by taking advantage of what they do particularly well—that is, the organization's unique strengths. **Core competencies** are the unique resources and strengths that an organization's management considers when formulating strategy. They reflect the collective learning of the organization, especially in how to coordinate processes and integrate technologies. These competencies include the following:

core competencies
The unique resources and strengths that an organization's management considers when formulating strategy.

lead time
The elapsed time between the receipt of a customer order and filling it.

1. *Workforce.* A well-trained and flexible workforce allows organizations to respond to market needs in a timely fashion. This competency is particularly important in service organizations, where customers come in direct contact with employees.
2. *Facilities.* Having well-located facilities (offices, stores, and plants) is a primary advantage because of the long **lead time** needed to build new ones. In addition, flexible facilities that can handle a variety of services or products at different levels of volume provide a competitive advantage.
3. *Market and Financial Know-How.* An organization that can easily attract capital from stock sales, market and distribute its services or products, or differentiate them from similar services or products on the market has a competitive edge.
4. *Systems and Technology.* Organizations with expertise in information systems have an edge in industries that are data intensive, such as banking. Particularly advantageous is expertise in Internet technologies and applications, such as business-to-consumer and business-to-business systems. Having the patents on a new technology is also a big advantage.



Peter Foley/Bloomberg/Getty Images

Capital One Financial Corp. is a U.S.-based bank holding company specializing in credit cards, home loans, auto loans, banking, and savings products.

Developing Core Processes A firm's core competencies should drive its core processes: customer relationship, new service or product development, order fulfillment, and supplier relationship. Many companies have all four processes, whereas others focus on a subset of them to better match their core competencies, since they find it difficult to be good at all four processes and still be competitive. For instance, in the credit card business within the banking industry, some companies primarily specialize in finding customers and maintaining relationships with them. American Airlines' credit card program reaches out and achieves a special affinity with customers through its marketing database. In contrast, specialized credit card companies, such as Capital One, focus on service innovation by creating new features and pricing programs. Finally, many companies are taking over the order fulfillment process by managing the processing of credit card transactions and call centers. The important point is that every firm must evaluate its core competencies and choose to focus on those processes that provide it the greatest competitive strength.

Developing Global Strategies Identifying opportunities and threats today requires a global perspective. A global strategy may include buying foreign services or parts, combating threats from foreign competitors, or planning ways to enter markets beyond traditional national boundaries. Although warding off threats from global competitors is

necessary, firms should also actively seek to penetrate foreign markets. Two effective global strategies are (1) strategic alliances and (2) locating abroad.

One way for a firm to open foreign markets is to create a *strategic alliance*. A strategic alliance is an agreement with another firm in which each firm maintains its autonomy, while gaining new opportunities. It may take one of two forms. One form of strategic alliance is the *collaborative effort*, which often arises when one firm has core competencies that another needs but is unwilling (or unable) to duplicate. Such arrangements commonly arise out of buyer–supplier relationships. Another form of strategic alliance is technology licensing in which one company licenses its service or production methods to another. Licenses may be used to gain access to foreign markets. Such access to foreign and domestic markets can also be gained through forming a joint venture, in which two companies typically pool resources to create a separate business entity. A joint venture is typically more involved and longer lasting than a strategic alliance.

Another way to enter global markets is to locate operations in a foreign country. However, managers must recognize that what works well in their home country might not work well elsewhere. The economic and political environment or customers' needs may be significantly different. For example, the family-owned chain Jollibee Foods Corporation became the dominant fast-food chain in the Philippines by catering to a local preference for sweet and spicy flavors, which it incorporates into its fried chicken, spaghetti, and burgers. Jollibee's strengths are its creative marketing programs and an understanding of local tastes; it claims that its burger is similar to the one a Filipino would cook at home. McDonald's responded by introducing its own Filipino-style spicy burger, but competition is stiff. This example shows that to be successful, corporate strategies must recognize customs, preferences, and economic conditions in other countries.

Locating abroad is a key decision in the design of supply chains because it affects the flow of materials, information, and employees in support of the firm's core processes. Chapter 12, "Supply Chain Design," and Chapter 13, "Supply Chain Logistic Networks," offer more in-depth discussion of these other implications.

Market Analysis

One key to successfully formulating a customer-driven operations strategy for both service and manufacturing firms is to understand what the customer wants and how to provide it. A *market analysis* first divides the firm's customers into market segments and then identifies the needs of each segment. In this section, we examine the process of market analysis, and we define and discuss the concepts of market segmentation and needs assessment.

Market Segmentation *Market segmentation* is the process of identifying groups of customers with enough in common to warrant the design and provision of services or products that the group wants and needs. To identify market segments, the analyst must determine the characteristics that clearly differentiate each segment. The company can then develop a sound marketing program and an effective operating strategy to support it. For instance, The Gap, Inc., a major provider of casual clothes, targets teenagers and young adults, while the parents or guardians of infants to 12-year-olds are the primary targets for its GapKids stores. At one time, managers thought of customers as a homogeneous mass market but now realize that two customers may use the same product for different reasons. Identifying the key factors in each market segment is the starting point in devising a customer-driven operations strategy.

Needs Assessment The second step in market analysis is to make a *needs assessment*, which identifies the needs of each segment and assesses how well competitors are addressing those needs. Each market segment's needs can be related to the service or product and its supply chain. Market needs should include both the tangible and intangible attributes and features of products and services that a customer desires. Market needs may be grouped as follows:

- *Service or Product Needs.* Attributes of the service or product, such as price, quality, and degree of customization.
- *Delivery System Needs.* Attributes of the processes and the supporting systems, and resources needed to deliver the service or product, such as availability, convenience, courtesy, safety, accuracy, reliability, delivery speed, and delivery dependability.
- *Volume Needs.* Attributes of the demand for the service or product, such as high or low volume, degree of variability in volume, and degree of predictability in volume.
- *Other Needs.* Other attributes, such as reputation and number of years in business, after-sale technical support, ability to invest in international financial markets, and competent legal services.

Once it makes this assessment, the firm can incorporate the needs of customers into the design of the service or product and the supply chain that must deliver it. We further discuss these new service and product development-related issues in Chapter 14, "Supply Chain Integration."

Competitive Priorities and Capabilities

A customer-driven operations strategy requires a cross-functional effort by all areas of the firm to understand the needs of the firm's external customers and to specify the operating capabilities the firm requires to outperform its competitors. Such a strategy also addresses the needs of internal customers because the overall performance of the firm depends upon the performance of its core and supporting processes, which must be coordinated to provide the overall desirable outcome for the external customer.

competitive priorities
The critical dimensions that a process or supply chain must possess to satisfy its internal or external customers, both now and in the future.

competitive capabilities
The cost, quality, time, and flexibility dimensions that a process or supply chain actually possesses and is able to deliver.

Competitive priorities are the critical operational dimensions a process or supply chain must possess to satisfy internal or external customers, both now and in the future. Competitive priorities are planned for processes and the supply chain created from them. They must be present to maintain or build market share or to allow other internal processes to be successful. Not all competitive priorities are critical for a given process; management selects those that are most important. **Competitive capabilities** are the cost, quality, time, and flexibility dimensions that a process or supply chain actually possesses and is able to deliver. When the capability falls short of the priority attached to it, management must find ways to either close the gap or revise the priority.

We focus on nine broad competitive priorities that fall into the four capability groups of cost, quality, time, and flexibility. Table 1.3 provides definitions and examples of these competitive priorities, as well as how firms achieve them at the process level.

TABLE 1.3 | DEFINITIONS, PROCESS CONSIDERATIONS, AND EXAMPLES OF COMPETITIVE PRIORITIES

Cost	Definition	Processes Considerations	Example
1. **Low-cost operations**	Delivering a service or a product at the lowest possible cost to the satisfaction of external or internal customers of the process or supply chain	To reduce costs, processes must be designed and operated to make them efficient, using rigorous process analysis that addresses workforce, methods, scrap or rework, overhead, and other factors, such as investments in new automated facilities or technologies to lower the cost per unit of the service or product.	**Costco** achieves low costs by designing all processes for efficiency, stacking products on pallets in warehouse-type stores, and negotiating aggressively with their suppliers. Costco can provide low prices to its customers because they have designed operations for low cost.
Quality			
2. **Top quality**	Delivering an outstanding service or product	To deliver top quality, a service process may require a high level of customer contact, and high levels of helpfulness, courtesy, and availability of servers. It may require superior product features, close tolerances, and greater durability from a manufacturing process.	**Rolex** is known globally for creating precision timepieces.
3. **Consistent quality**	Producing services or products that meet design specifications on a consistent basis	Processes must be designed and monitored to reduce errors, prevent defects, and achieve similar outcomes over time, regardless of the "level" of quality.	**McDonald's** standardizes work methods, staff training processes, and procurement of raw materials to achieve the same consistent product and process quality from one store to the next.
Time			
4. **Delivery speed**	Quickly filling a customer's order	Design processes to reduce lead time (elapsed time between the receipt of a customer order and filling it) through keeping backup capacity cushions, storing inventory, and using premier transportation options.	**Netflix** engineered its customer relationship, order fulfillment, and supplier relationship processes to create an integrated Web-based system that allows its customers to watch multiple episodes of a TV program or movies in rapid succession.
5. **On-time delivery**	Meeting delivery-time promises	Along with processes that reduce lead time, planning processes (forecasting, appointments, order promising, scheduling, and capacity planning) are used to increase percent of customer orders shipped when promised (95% is often a typical goal).	**United Parcel Service (UPS)** uses its expertise in logistics and warehousing processes to deliver a very large volume of shipments on-time across the globe.
6. **Development speed**	Quickly introducing a new service or a product	Processes aim to achieve cross-functional integration and involvement of critical external suppliers in the service or product development process.	**Zara** is known for its ability to bring fashionable clothing designs from the runway to market quickly.

Flexibility	Definition	Processes Considerations	Example
7. **Customization**	Satisfying the unique needs of each customer by changing service or product designs	Processes with a customization strategy typically have low volume, close customer contact, and an ability to reconfigure processes to meet diverse types of customer needs.	**Ritz Carlton** customizes services to individual guest preferences.
8. **Variety**	Handling a wide assortment of services or products efficiently	Processes supporting variety must be capable of larger volumes than processes supporting customization. Services or products are not necessarily unique to specific customers and may have repetitive demands.	**Amazon.com** uses information technology and streamlined customer relationship and order fulfillment processes to reliably deliver a vast variety of items to its customers.
9. **Volume flexibility**	Accelerating or decelerating the rate of production of services or products quickly to handle large fluctuations in demand	Processes must be designed for excess capacity and excess inventory to handle demand fluctuations that can vary in cycles from days to months. This priority could also be met with a strategy that adjusts capacity without accumulation of inventory or excess capacity.	The **United States Post Office (USPS)** can have severe demand peak fluctuations at large postal facilities where processes are flexibly designed for receiving, sorting, and dispatching mail to numerous branch locations.

At times, management may emphasize a cluster of competitive priorities together. For example, many companies focus on the competitive priorities of delivery speed and development speed for their processes, a strategy called **time-based competition**. To implement the strategy, managers carefully define the steps and time needed to deliver a service or produce a product and then critically analyze each step to determine whether they can save time without hurting quality. Zara is an example of a firm that follows time-based competition. Managerial Practice 1.1 illustrates how Zara used development speed and quick delivery time to carve out a unique and profitable niche for itself in the fast-fashion industry.



Bogdan Glisik/Shutterstock

Netflix, an American media-services provider headquartered in Los Gatos, California, USA, has proven to be a major source of entertainment during the coronavirus pandemic due to its rapidly delivered video-on-demand streaming service.

To link to corporate strategy, management assigns selected competitive priorities to each process (and the supply chains created from them) that are consistent with the needs of external as well as internal customers. Competitive priorities may change over time. For example, consider a high-volume standardized product, such as color ink-jet desktop printers. In the early stages of the ramp-up period when the printers had just entered the mass market, the manufacturing processes required consistent quality, delivery speed, and volume flexibility. In the later stages of the ramp-up when demand was high, the competitive priorities became low-cost operations, consistent quality, and on-time delivery. Competitive priorities must change and evolve over time along with changing business conditions and customer preferences.

time-based competition
A strategy that focuses on the competitive priorities of delivery speed and development speed.

MANAGERIAL PRACTICE 1.1 Zara

Zara is a clothing and accessories company that was founded in Galicia, Spain, in 1975. With 2,259 stores located worldwide in 96 countries, Zara has emerged as a leader in the fashion industry that is known for tough operations challenges. The product life cycle is extremely short and hard to forecast. Retailers chronically suffer from steep price discounts for remaining inventory (markdowns) and stockouts. For some retailers, the estimated costs of markdowns can be as high as 33 percent of sales. However, a new trend known as fast fashion is changing the way these fashion brands operate. The Spanish fast-fashion leader Zara is proving to be a tough competition for U.S. retailers such as Abercrombie & Fitch, American Eagle Outfitters, and Aeropostale. Compared to the 50 to 70 percent average markdown cost of fashion retailers, Zara's markdowns are only around 15 percent. Fast-fashion companies like Zara focus on competitive priorities of product development speed, which allows them to respond quickly to changing consumer trends without inflating costs. For example, Zara's Spanish company headquarters, in the small industrial city of Arteixo, took 5 days to design the prototype of a loose-fitting winter coat. Design ideas and market insights were collected from discussions with store managers. Next, pattern makers, cutters, and



Sorbis/Shutterstock

Zara store at Singapore Changi Airport, which is the primary civilian airport for Singapore and one of the largest transportation hubs in Southeast Asia.

tailors worked 13 days to produce 8,000 coats. Ironing, labeling, tagging, and quality inspection took another 6 days. The finished coats were trucked in to Zara's logistics center and exported through the Barcelona airport. The next day, the clothes were displayed at Fifth Avenue stores and sold for $189. Now, Zara introduces new products twice per week to its 1,670 stores around the world. Moreover, it takes only 10 to 15 days from the design to sales. How is Zara able to achieve such surprising results?

First, Zara has all nonvalue-adding activities eliminated from its processes. Every creative decision is made quickly in an open workspace at Zara's headquarters. Designers and sales staff hold impromptu communications with Zara store managers around the world, who are often flown in to consult, view a few mockups, and provide additional design ideas. There are no formal meetings in this entire process. Second, most other retailers maintain sophisticated distribution networks, which increase the chance of losing track of inventories. In contrast, Zara relies on a centralized distribution system where 60 percent of the production takes place in Spain and nearby countries, and which in turn improves inventory accuracy. Rather than partnering with Asian subcontractors, Zara has built 14 highly automated Spanish factories that produce "gray goods," the foundations of their final products. These gray goods are then sent to Zara's partner network of more than 300 small shops in Portugal and Galicia for finishing. This final step is done after Zara becomes confident about the upcoming fashion trends and demand. Zara can also quickly ramp up manufacturing for popular products and get items to their stores in a matter of days.

The estimated financial benefit of fast fashion to reduce markdowns and stockouts adds up to a profit increase of as much as 28 percent. Zara is four times more profitable than most of its competitors, which is achieved through lower inventory costs. Over the past couple of decades, fashion brands have aggressively experimented with various sourcing and distribution strategies to cut costs and inventories. Zara has been very successful by focusing on what customers want, and how to meet their needs by rapidly developing and bringing new products to the market rather than just emphasizing inward-looking cost savings in parts of their supply chain. With these efforts paying off, Zara's parent company Inditex has now become the world's largest clothing retailer.[3]

Order Winners and Qualifiers

order winner

A criterion customers use to differentiate the services or products of one firm from those of another.

Competitive priorities focus on what operations can do to help a firm be more competitive and are in response to what the market wants. Another useful way to examine a firm's ability to be successful in the marketplace is to identify the order winners and order qualifiers. An **order winner** is a criterion that customers use to differentiate the services or products of one firm from those of another. Order winners can include price (which is supported by low-cost operations) and other dimensions of quality, time, and flexibility. However, order winners also include criteria not directly related to the firm's operations, such as after-sale support (Are maintenance service contracts available? Is there a return policy?); technical support (What help do I get if something goes wrong? How knowledgeable are the technicians?); and reputation (How long has this company been in business? Have other customers been satisfied with the service or product?). It may take good performance on a subset of the order-winner criteria, cutting across operational as well as nonoperational criteria, to make a sale.

order qualifier

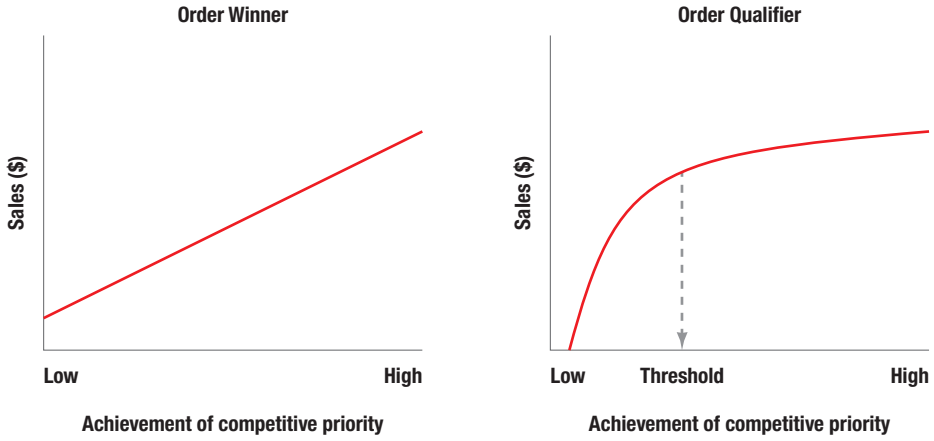
Minimal level required from a set of criteria for a firm to do business in a particular market segment.

Order winners are derived from the considerations customers use when deciding which firm to purchase a service or product from in a given market segment. Sometimes customers demand a certain level of demonstrated performance before even contemplating a service or product. Minimal level required from a set of criteria for a firm to do business in a particular market segment is called an **order qualifier**. Fulfilling the order qualifier will not ensure competitive success; it will only position the firm to compete in the market. From an operations perspective, understanding which competitive priorities are order qualifiers and which ones are order winners is important for the investments made in the design and management of processes and supply chains.

Figure 1.6 shows how order winners and qualifiers are related to achieving the competitive priorities of a firm. If a minimum threshold level is not met for an order-qualifying dimension (consistent quality, for example) by a firm, then it would get disqualified from even being considered further by its customers. For example, there is a level of quality consistency that is minimally tolerable by customers in the auto industry. When the subcompact car Yugo built by Zastava Corporation could not sustain the minimal level of quality, consistency, and reliability expected by customers, it had to exit the U.S. car market in 1991 despite offering very low prices (order winner) of under $4,000. However, once the firm qualifies by attaining consistent quality beyond the threshold, it

[3] *Sources:* Steve Denning, "How Agile and Zara Are Transforming the US Fashion Industry," *Forbes* (March 13, 2015); Greg Petro, "The Future of Fashion Retailing: The Zara Approach," *Forbes* (Oct. 25, 2012); Patricia Kowsmann, "Fast Fashion: How a Zara Coat Went from Design to Fifth Avenue in 25 Days," *Wall Street Journal* (Dec. 6, 2016); https://en.wikipedia.org/wiki/Zara_(retailer), (August 11, 2020).

may only gain additional sales at a very low rate by investing further in improving that order-qualifying dimension. In contrast, for an order-winning dimension (i.e., low price driven by low-cost operations), a firm can reasonably expect to gain appreciably greater sales and market share by continuously lowering its prices as long as the order qualifier (i.e., consistent quality) is being adequately met. Toyota Corolla and Honda Civic have successfully followed this route in the marketplace to become leaders in their target market segment.



▲ **FIGURE 1.6**
Relationship of Order Winners and Order Qualifiers to Competitive Priorities

Order winners and qualifiers are often used in competitive bidding. For example, before a buyer considers a bid, suppliers may be required to document their ability to provide consistent quality as measured by adherence to the design specifications for the service or component they are supplying (order qualifier). Once qualified, the supplier may eventually be selected by the buyer on the basis of low prices (order winner) and the reputation of the supplier (order winner).

Using Competitive Priorities: An Airline Example

To gain a better understanding of how companies use competitive priorities, let us look at a major airline. We will consider two market segments: (1) first-class passengers and (2) coach passengers. Core services for both market segments are ticketing and seat selection, baggage handling, and transportation to the customer's destination. The peripheral services are quite different across the two market segments. First-class passengers require separate airport lounges; preferred treatment during check-in, boarding, and deplaning; more comfortable seats; better meals and beverages; more personal attention (cabin attendants who refer to customers by name); more frequent service from attendants; high levels of courtesy; and low volumes of passengers (adding to the feeling of being special). Coach passengers are satisfied with standardized services (no surprises), courteous flight attendants, and low prices. Both market segments expect the airline to hold to its schedule. Consequently, we can say that the competitive priorities for the first-class segment are *top quality* and *on-time delivery*, whereas the competitive priorities for the coach segment are *low-cost operations*, *consistent quality*, and *on-time delivery*.


caia image/Alamy Stock Photo

Flight attendant greeting passengers boarding an airplane.

The airline knows what its collective capabilities must be as a firm, but how does that get communicated to each of its core processes? Let us focus on the four core processes: (1) customer relationship, (2) new service or product development, (3) order fulfillment, and (4) supplier relationship. Competitive priorities are assigned to each core process to achieve the service required to provide complete customer satisfaction. Table 1.4 shows some possible assignments just to give you an idea of how this works.

Identifying Gaps Between Competitive Priorities and Capabilities

Operations strategy translates service or product plans and competitive priorities for each market segment into decisions affecting the supply chains that support those market segments. Even if it is not formally stated, the current operations strategy for any firm is really the pattern of decisions that have been made for its processes and supply chains. As we have previously seen in Figure 1.5, corporate strategy provides the umbrella for key operations management decisions that contribute to the development of the firm's ability to compete successfully in the marketplace. Once managers determine the competitive priorities for a process, it is necessary to assess the *competitive capabilities* of the process. Any gap between a competitive priority and the capability to achieve that competitive priority must be closed by an effective operations strategy.

TABLE 1.4 | COMPETITIVE PRIORITIES ACROSS DIFFERENT CORE PROCESSES FOR AN AIRLINE

	CORE PROCESSES			
Priority	**Supplier Relationship**	**New Service Development**	**Order Fulfillment**	**Customer Relationship**
Low-Cost Operations	Costs of acquiring inputs must be kept to a minimum to allow for competitive pricing.		Airlines compete on price and must keep operating costs in check.	
Top Quality		New services must be carefully designed because the future of the airline industry depends on them.	High-quality meal and beverage service delivered by experienced cabin attendants ensures that the service provided to first-class passengers is kept top notch.	High levels of customer contact and lounge service for the first-class passengers.
Consistent Quality	Quality of the inputs must adhere to the required specifications. In addition, information provided to suppliers must be accurate.		Once the quality level is set, it is important to achieve it every time.	The information and service must be error free.
Delivery Speed				Customers want immediate information regarding flight schedules and other ticketing information.
On-Time Delivery	Inputs must be delivered to tight schedules.		The airline strives to arrive at destinations on schedule; otherwise, passengers might miss connections to other flights.	
Development Speed		It is important to get to the market fast to preempt the competition.		
Customization		The process must be able to create unique services.		
Variety	Many different inputs must be acquired, including maintenance items, meals, and beverages.		Maintenance operations are required for a variety of aircraft models.	The process must be capable of handling the service needs of all market segments and promotional programs.
Volume Flexibility	The process must be able to handle variations in supply quantities efficiently.			

Developing capabilities and closing gaps is the thrust of operations strategy. To demonstrate how this works, suppose the management of a bank's credit card division decides to embark on a marketing campaign to significantly increase its business, while keeping costs low. A key process in this division is billing and payments. The division receives credit transactions from the merchants, pays the merchants, assembles and sends the bills to the credit card holders, and processes payments. The new marketing effort is expected to significantly increase the volume of bills and payments. In assessing the capabilities, the process must have to serve the bank's customers and to meet the challenges of the new market campaign; management assigns the following competitive priorities for the billing and payments process:

- *Low-Cost Operations.* It is important to maintain low costs in the processing of the bills because profit margins are tight.
- *Consistent Quality.* The process must consistently produce bills, make payments to the merchants, and record payments from the credit card holders accurately.
- *Delivery Speed.* Merchants want to be paid for the credit purchases quickly.
- *Volume Flexibility.* The marketing campaign is expected to generate many more transactions in a shorter period of time.

Management assumed that customers would avoid doing business with a bank that could not produce accurate bills or payments. Consequently, consistent quality is an order qualifier for this process.

TABLE 1.5 | OPERATIONS STRATEGY ASSESSMENT OF THE BILLING AND PAYMENT PROCESS

Competitive Priority	Measure	Capability	Gap	Action
Low-cost operations	■ Cost per billing statement ■ Weekly postage	■ $0.0813 ■ $17,000	■ Target is $0.06 ■ Target is $14,000	■ Eliminate microfilming and storage of billing statements ■ Develop Web-based process for posting bills
Consistent quality	■ Percent errors in bill information ■ Percent errors in posting payments	■ 90% ■ 74%	■ Acceptable ■ Acceptable	■ No action ■ No action
Delivery speed	■ Lead time to process merchant payments	■ 48 hours	■ Acceptable	■ No action
Volume flexibility	■ Utilization	■ 98%	■ Too high to support rapid increase in volumes	■ Acquire temporary employees ■ Improve work methods

Is the billing and payment process up to the competitive challenge? Table 1.5 shows how to match capabilities to priorities and uncover any gaps in the credit card division's operations strategy. The procedure for assessing an operations strategy begins with identifying good measures for each priority. The more quantitative the measures are, the better. Data are gathered for each measure to determine the current capabilities of the process. Gaps are identified by comparing each capability to management's target values for the measures, and unacceptable gaps are closed by appropriate actions.

The credit card division shows significant gaps in the process's capability for low-cost operations. Management's remedy is to redesign the process in ways that reduce costs but will not impair the other competitive priorities. Likewise, for volume flexibility, management realized that a high level of utilization is not conducive for processing quick surges in volumes while maintaining delivery speed. The recommended actions will help build a capability for meeting more volatile demands.

Trends and Challenges in Operations Management

Several trends are currently having a great impact on operations management: productivity improvement; global competition; and ethical, workforce diversity, and environmental issues. In this section, we look at these trends and their challenges for operations managers.

Productivity Improvement

Productivity is a basic measure of performance for economies, industries, firms, and processes. Improving productivity is a major trend in operations management because all firms face pressures to improve their processes and supply chains so as to compete with their domestic and foreign competitors. **Productivity** is the value of outputs (services and products) produced divided by the values of input resources (wages, cost of equipment, etc.) used:

productivity
The value of outputs (services and products) produced divided by the values of input resources (wages, costs of equipment, etc.).

$$\text{Productivity} = \frac{\text{Output}}{\text{Input}}$$

Manufacturing employment peaked at just below 20 million in mid-1979, and shrank by nearly 8 million from 1979 to 2011.[4] However, the manufacturing productivity in the United States has climbed steadily, as more manufacturing capacity and output has been achieved efficiently with a leaner workforce. It is interesting and even surprising to compare productivity improvements in the service and manufacturing sectors. In the United States, employment in the service sector has grown rapidly, outstripping the manufacturing sector. It now employs about 90 percent of the workforce. But service-sector productivity gains have been much lower. If productivity growth in the service sector stagnates, so does the overall standard of living regardless of which part of the world you live in. Other major industrial countries, such as Japan and Germany, are experiencing the same problem. Yet signs of improvement are appearing. The surge of investment across national boundaries can stimulate productivity gains by exposing firms to

[4]Paul Wiseman, "Despite China's Might, US Factories Maintain Edge," *The State* and *The Associated Press* (January 31, 2011).

greater competition. Increased investment in information technology by service providers also increases productivity.

Measuring Productivity As a manager, how do you measure the productivity of your processes? Many measures are available. For example, value of output can be measured by what the customer pays or simply by the number of units produced or customers served. The value of inputs can be judged by their cost or simply by the number of hours worked.

Managers usually pick several reasonable measures and monitor trends to spot areas needing improvement. For example, a manager at an insurance firm might measure office productivity as the number of insurance policies processed per employee per week. A manager at a carpet company might measure the productivity of installers as the number of square yards of carpet installed per hour. Both measures reflect *labor productivity*, which is an index of the output per person or per hour worked. Similar measures may be used for *machine productivity*, where the denominator is the number of machines. Accounting for several inputs simultaneously is also possible. *Multifactor productivity* is an index of the output provided by more than one of the resources used in production; it may be the value of the output divided by the sum of labor, materials, and overhead costs. Example 1.1 shows how to calculate the labor productivity and multifactor productivity measures.

EXAMPLE 1.1 Productivity Calculations

Online Resource
Tutor 1.1 in OM Explorer provides a new example for calculating productivity.

Calculate the productivity for the following operations:

a. Three employees process 600 insurance policies in a week. They work 8 hours per day, 5 days per week.

b. A team of workers makes 400 units of a product, which is sold in the market for $10 each. The accounting department reports that for this job the actual costs are $400 for labor, $1,000 for materials, and $300 for overhead.

SOLUTION

a. $$\text{Labor productivity} = \frac{\text{Policies processed}}{\text{Employee hours}}$$

$$= \frac{600 \text{ policies}}{(3 \text{ employees})(40 \text{ hours/employee})} = \mathbf{5} \text{ policies/hour}$$

b. $$\text{Multifactor productivity} = \frac{\text{Value of output}}{\text{Labor cost} + \text{Materials cost} + \text{Overhead cost}}$$

$$= \frac{(400 \text{ units})(\$10/\text{unit})}{\$400 + \$1{,}000 + \$300} = \frac{\$4{,}000}{\$1{,}700} = \mathbf{2.35}$$

DECISION POINT

We want multifactor productivity to be as high as possible. These measures must be compared with performance levels in prior periods and with future goals. If they do not live up to expectations, the process should be investigated for improvement opportunities.

The Role of Management The way processes are managed plays a key role in productivity improvement. Managers must examine productivity from the level of the supply chain because it is the collective performance of individual processes that makes the difference. The challenge is to increase the value of output relative to the cost of input. If processes can generate more output or output of better quality using the same amount of input, productivity increases. If they can maintain the same level of output while reducing the use of resources, productivity also increases.

Global Competition

Most businesses realize that, to prosper, they must view customers, suppliers, facility locations, and competitors in global terms. Firms have found that they can increase their market penetration by locating their production facilities in foreign countries because it gives them a local presence that reduces customer aversion to buying imports. Globalization also allows firms to balance cash flows from other regions of the world when economic conditions are less robust in the home country. Sonoco, a $5-billion-a-year industrial and consumer packaging company in Hartsville, South Carolina, has nearly 19,900 employees in 335 locations worldwide spread

across 33 countries.[5] These global operations resulted in international sales and income growth even as domestic sales were stumbling during 2007. How did Sonoco do it?[6] Locating operations in countries with favorable tax laws is one reason. Lower tax rates in Italy and Canada helped in padding the earnings margin. Another reason was a weak dollar, whereby a $46 million boost came from turning foreign currencies into dollars as Sonoco exported such items as snack bag packaging, and tubes and cores used to hold tape and textiles, to operations it owned in foreign countries. The exchange rate difference was more than enough to counter the added expense of increased raw materials, shipping, and energy costs in the United States.

Most products today are composites of materials and services from all over the world. Your t-shirt is sewn in Honduras from cloth cut in the United States. Sitting in a Cineplex theater (Canadian), you munch a Nestle's Crunch bar (Swiss) while watching a Columbia Pictures movie (Japanese). Five developments spurred the need for sound global strategies: (1) improved transportation and communications technologies; (2) loosened regulations on financial institutions; (3) increased demand for imported services and goods; (4) reduced import quotas and other international trade barriers due to the formation of regional trading blocks, such as the European Union (EU) and the United States–Mexico–Canada Agreement (USMCA); and (5) comparative cost advantages.



wsr/Alamy Stock Photo

Sonoco is a global supplier of innovative packaging solutions, including packages for Chips Ahoy cookies, M&M's, Pringles Potato Crisps, flexible brick packs for coffee, and many other products.

Comparative Cost Advantages China and India have traditionally been the sources for low-cost, but skilled, labor, even though the cost advantage is diminishing as these countries become economically stronger. In the late 1990s, companies manufactured products in China to grab a foothold in a huge market, or to get cheap labor to produce low-tech products despite doubts about the quality of the workforce and poor roads and rail systems. Today, however, China's new factories, such as those in the Pudong industrial zone in Shanghai, produce a wide variety of products that are sold overseas in the United States and other regions of the world. U.S. manufacturers have increasingly abandoned low profit margin sectors like consumer electronics, shoes, and toys to emerging nations such as China and Indonesia. Instead, they are focusing on making expensive goods like computer chips, advanced machinery, and health care products that are complex and require specialized labor.

Foreign companies have opened tens of thousands of new facilities in China over the past decade. A major reason is the so-called "landed cost" of the product, or the cost of getting the product to the ultimate consumer. If a firm is interested in selling products in Southeast Asia, it may be less expensive to use Chinese labor and suppliers, ship major components to China, and then deliver the final product to customers in China and Southeast Asia, than it is to produce the product at home with Chinese components and then ship the completed product to Southeast Asia. The same argument on landed costs may sometimes make it cheaper for U.S.-based firms to locate facilities here, especially if the major markets for the product are in the United States and transportation costs are high.

Alternatively, it may be less expensive to import products made abroad if labor is a significant component of product costs. Many goods the United States imports from China now come from foreign-owned companies with operations there. These companies include cell phone makers such as Apple, and nearly all of the big footwear and clothing brands. Many more major manufacturers are there as well. The implications for competition are enormous. Companies that do not have operations in China are finding it difficult to compete on the basis of low prices with companies that do. Instead, they must focus on speed and small production runs.

[5]https://en.wikipedia.org/wiki/Sonoco (August 7, 2020).

[6]Ben Werner, "Sonoco Holding Its Own," *The State* (February 7, 2008); http://www.sonoco.com, 2008.

What China is to manufacturing, India is to service. As with the manufacturing companies, the cost of labor is a key factor. Indian software companies have grown sophisticated in their applications and offer a big advantage in cost. The computer services industry is also affected. Back-office operations are affected for the same reason. Many firms are using Indian companies for accounting and bookkeeping, research and development, preparing tax returns, and processing insurance claims. Many tech companies, such as Intel and Microsoft, are opening significant research and development (R&D) operations in India.

Disadvantages of Globalization Of course, operations in other countries can have disadvantages. A firm may have to relinquish proprietary technology if it turns over some of its component manufacturing to offshore suppliers or if suppliers need the firm's technology to achieve desired quality and cost goals. Political risks may also be involved. Each nation can exercise its sovereignty over the people and property within its borders. The extreme case is nationalization, in which a government may take over a firm's assets without paying compensation. Exxon and other large multinational oil firms are scaling back operations in Venezuela due to nationalization concerns. Further, a firm may actually alienate customers back home if jobs are lost to offshore operations.



JO YONG-HAK/REUTERS/Alamy Stock Photo

A firefighter walks around rubble near a burning factory damaged by an earthquake and tsunami in Sendai, northeastern Japan, on March 13, 2011. The impact of the earthquake was particularly acute on industries that rely on batteries, LCD panels, automotive sensors, and cutting-edge electronic component and parts sourced from Japan.

Employee skills may be lower in foreign countries, requiring additional training time. South Korean firms moved much of their sports shoe production to low-wage Indonesia and China, but they still manufacture hiking shoes and inline roller skates in South Korea because of the greater skills required. In addition, when a firm's operations are scattered globally, customer response times can be longer. We discuss these issues in more depth in Chapter 12, "Supply Chain Design," because they should be considered when making decisions about outsourcing. Coordinating components from a wide array of suppliers can be challenging. In addition, catastrophic events, such as the earthquake in Japan in 2011 or the coronavirus pandemic crisis in 2020, can affect production and operations globally because interconnected supply chains can spread disruptions rapidly across international borders.

Strong global competition affects industries everywhere. For example, U.S. manufacturers of steel, appliances, household durable goods, machinery, and chemicals have seen their market share decline in both domestic and international markets. With the value of world trade in commercial services now in trillions of dollars per year, banking, data processing, airlines, and consulting services are beginning to face many of the same international pressures. Regional trading blocs, such as EU and USMCA, further change the competitive landscape in both services and manufacturing. Regardless of which area of the world you live in, the challenge is to produce services or products that can compete in a global market and to design the processes that can make it happen.

Ethical, Workforce Diversity, and Environmental Issues

Businesses face more ethical quandaries than ever before, intensified by an increasing global presence and rapid technological change. As companies locate new operations and acquire more suppliers and customers in other countries, potential ethical dilemmas arise when business is conducted by different rules. Some countries are more sensitive than others about conflicts of interest, bribery, discrimination against minorities and women, minimum-wage levels, and unsafe workplaces. Managers must decide whether to design and operate processes that do more than just meet local standards. In addition, technological change brings debates about data protection and customer privacy. In an electronic world, businesses are geographically far from their customers, so a reputation of trust is paramount.

In the past, many people viewed environmental problems, such as toxic waste, poisoned drinking water, poor air quality, and climate change as quality-of-life issues; now, many people and businesses see them as survival issues. The automobile industry has seen innovation in electric and hybrid cars in response to environmental concerns and economic benefits arising from using less expensive fuels. Industrial nations face a particular burden because their combined

populations consume proportionally much larger resources. Just seven nations, including China, the United States, and India, produce almost half of all greenhouse gases. China and India have added to that total carbon footprint because of their vast economic and manufacturing expansion over the past decade.

Apart from government initiatives, large multinational companies have a responsibility as well for creating environmentally conscious practices, and can do so profitably. For instance, Timberland, which is a division of the VF Corporation, has over 110 stores in China because of strong demand for its boots, shoes, clothes, and outdoor gear in that country. It highlights its environmental credentials and corporate social responsibility through investments such as the reforestation efforts in northern China's Horqin Desert. About 1700 acres of trees had been planted by 2015, along with efforts to improve production of vegetables in the Horqin region by about 4% between 2001 and 2010.[7] Timberland hopes to increase its footprint globally by environmentally differentiating itself from the competition. We discuss environmental issues in greater detail in Chapter 15, "Supply Chain Sustainability."



Entrance to Timberland store at a shopping mall in Shenzhen, China.

Sorbis/Shutterstock

The challenge is clear: Issues of ethics, workforce diversity, and the environment are becoming part of every manager's job. When designing and operating processes, managers should consider integrity, respect for the individual, and customer satisfaction along with more conventional performance measures such as productivity, quality, cost, and profit.

As we learn next, the fourth industrial revolution is providing several technology-driven solutions to meeting the trending challenges in operations management, while also radically transforming the practice of operations and supply chain management.

Fourth Industrial Revolution (Industry 4.0)

Accelerating change in the form of information technology, e-commerce, robotics, and the Internet is dramatically affecting the design of new services and products as well as a firm's sales, order fulfillment, and purchasing processes. The first industrial revolution occurred between 1760 and 1840, and introduced the use of water and steam-powered machines and tools instead of hand-powered ones. The second industrial revolution, which lasted from 1870 to the start of World War I in 1914, was marked by great productivity increases that were spurred by technological advances in railroads and electricity-driven production lines replacing human labor, which caused an increase in unemployment. The third industrial revolution started after World War II and ushered in the digital age with an extensive use of computers in production processes. The **fourth industrial revolution (Industry 4.0)** is the ongoing automation of traditional manufacturing and industrial practices, using modern smart technology. Communications on a large scale between virtually connected smart machines that can monitor themselves to diagnose and solve problems without human intervention can lead to a tremendous increase in productivity at lowered costs.[8]

fourth industrial revolution (Industry 4.0)
The ongoing automation of traditional manufacturing and industrial practices using modern smart technology.

The term *Industry 4.0* was first used at a Hannover fair in Germany in 2011, and it represents the fourth industrial revolution. Many believe that the technologies developed recently will allow companies to enter a new computerized era of manufacturing and managing large systems that were too complex to integrate, monitor, and control before the advent of Industry 4.0. Many new technologies can be associated with Industry 4.0, and they can be categorized in different ways. We use an adapted framework of Frank et al. (2019)[9] to categorize the Industry 4.0 technologies into four groups: Smart Manufacturing, Smart Products, Smart Supply, and Base Technologies.

- *Smart Manufacturing Technologies* help a company's internal operations to become more efficient and can serve to increase virtual integration, augment virtualization, enhance

[7]https://footwearnews.com/2015/focus/athletic-outdoor/timberland-tree-planting-china-horqin-desert-145781/#!#:~:text=Timberland%27s%20efforts%20have%20resulted%20in%20more%20than%201%2C700,1%2C700%20acres%20being%20planted%20in%20China%27s%20Horqin%20Desert (August 7, 2020).

[8]https://en.wikipedia.org/wiki/Fourth_Industrial_Revolution (August 7, 2020).

[9]A. G. Frank, L. S. Dalenogare, and N. F. Ayala. (2019). Industry 4.0 Technologies: Implementation Patterns in Manufacturing Companies. *International Journal of Production Economics, 210*, 15–26.

automation, improve product traceability, and facilitate efficient energy management. **Manufacturing execution systems (MES)** are computerized systems used in manufacturing to track and document the transformation of raw materials into finished goods and optimize their production output.[10] Sensors and programmable logic controllers can collect real-time data about equipment, and then MES can be used to monitor if production is being executed according to the plan in real time.

manufacturing execution systems (MES)

Computerized systems used in manufacturing to track and document the transformation of raw materials to finished goods and optimize their production output.

Smart Manufacturing Technologies rely heavily on **artificial intelligence (AI)**, which is a constellation of technologies, from machine learning to natural language processing, that allows machines to sense, comprehend, act, and learn.[11] AI is the machine counterpart of the natural intelligence displayed by human beings. Robots with AI can work in repeatable and ergonomically unfriendly tasks, and learn more quickly to adapt to producing new products. In addition, Collaborative Robots can be integrated with operators to increase overall quality and productivity. Other technologies can enhance an operator's productivity and reduce workplace injuries, such as exoskeletons that can help workers in lifting products and/or tools by reducing the stress and pressure on their arms and/or knees. Additive manufacturing, such as 3D printing of digital models, allows companies to achieve a very high level of customization, although the production volume is not high. Other technologies such as virtual reality and/or augmented reality have a variety of different applications, such as helping in product development to visualize products before they are physically produced, and as a training tool to simulate a variety of working conditions and situations.

artificial intelligence (AI)

A constellation of technologies, from machine learning to natural language processing, that allows machines to sense, comprehend, act, and learn.

- *Smart Products Technologies* are front-end technologies that embed digital capabilities in products themselves. For example, sensors can be used to monitor how products are performing in the field, and digital remote interfaces can be used to connect those products to their manufacturer. In addition, artificial intelligence with analytical algorithms based on predictive diagnostics can have optimization functions to enhance product performance. In practice, some cars, electrical equipment, and appliances already have those capabilities, which allow the user and/or service technicians to monitor product performance in real time.
- *Smart Supply Technologies* relate to supporting the digital integration of a company with its suppliers, customers, and internal operations in real time. Digital platforms with suppliers increase the visibility of inventory, distribution centers, demand, and scheduled deliveries. Systems integration with customers is key to sustaining on-time delivery of products with minimum inventory. Blockchains are an example of a Smart Supply Technology that is covered in greater detail in Chapter 14, "Supply Chain Integration."
- *Base Technologies* are needed to support the application of the other Smart technologies. These technologies create the interconnectivity and make it possible for other technologies to work. For example, the Internet of Things (IoT) represents the integration of sensors and computers in an Internet environment through wireless communication; cloud computing services enable an on-demand network of a shared pool of computing resources; big data gathers a large amount of results and information from the interaction of these systems; and data analytics, based on sophisticated statistical and machine learning methods, can be used to improve the performance of the product, decision-making processes, production processes, and/or product performance.

Due to their relevance, widespread use, and impact across a wide spectrum of industries and settings, from this vast set we highlight and discuss two specific technologies next.

The Internet of Things

Internet of Things (IoT)

The interconnectivity of objects, embedded with software, sensors, and actuators that enable these objects to collect and exchange data over a network without requiring human intervention.

It is common to see pedestrians on a busy street or shoppers in a mall accessing the Internet on their handheld devices. For these people, it is important to be "connected." What if "things" were as connected as humans? If you think that idea is from a science fiction novel, you are wrong. The **Internet of Things (IoT)** is the interconnectivity of objects, embedded with software, sensors, and actuators that enable these objects to collect and exchange data over a network without requiring human intervention. For example, in the IoT, a "thing" can be a person with a heart transplant monitor, a sensor in an automobile that sends real-time operating information to the manufacturer, or Wi-Fi–enabled remote monitoring devices to control such items as home lighting, heating, kitchen, and security systems.[12] It is estimated that there will be more than 64 billion IoT devices

[10] https://en.wikipedia.org/wiki/Manufacturing_execution_system (August 12, 2020).

[11] www.accenture.com/ai-insights (August 12, 2020).

[12] For a complete discussion of the IoT, see James Manyika, Michael Chui, Peter Bisson, Jonathan Woetzel, Richard Dobbs, Jacques Bughin, and Dan Aharon, "The Internet of Things: Mapping the Value Beyond the Hype," McKinsey Global Institute (June 2015).

worldwide by 2025, generating an economic impact of $4 to $7 trillion every year.[13] Imagine the enormity of the data collected and the potential effect on our lives and the operations of companies and civic infrastructure. Although this tremendous growth of IoT has raised security and privacy concerns, its impact on our everyday lives is unmistakable and includes applications in diverse industries and contexts, such as manufacturing, agriculture, military, health care, smart homes, smart cities, communications, transportation, and energy management, to mention a few.

Operations Management Applications While the IoT is growing exponentially, here are some examples of how it affects the field of operations management today.

- *Product design and development.* Sensors imbedded in a product can transmit real-time data on its use that can be helpful in the design of new products. New designs can ward off problems customers are having with the current model. In some cases when the product has a user interface capability, actual fixes to problems can be downloaded to the product via the Internet.
- *Health care.* Devices implanted in patients can monitor blood pressure and heart rates and trigger emergency services if necessary. The response time for emergencies, a competitive priority for hospitals, can be greatly reduced with these devices.
- *Preventive maintenance.* Sensor data can be used to determine when a machine part is wearing out and should be replaced before it actually fails. Machine failure, which is always unscheduled, is more expensive than performing maintenance when the machine is not being used.
- *Inventory management.* Sensors or cameras can be installed in inventory storage bins to measure the amount of inventory. These devices can actually trigger an order for more inventory when needed.
- *Logistics.* The movement of personnel and materials is an important aspect of a firm's operations. Real-time rerouting, autonomous (self-driving) vehicles, and using the Internet to track containers and packages are but a few of the applications of IoT in logistics.
- *City management.* Transportation is one of the largest areas of application of IoT in cities. For example, with the use of tracking data of public transit systems from IoT devices, the commute time of passengers can be reduced by improved schedules that reduce the buffer time in their itinerary. Traffic-light management can improve drive times through the city in real time. IoT smart meters can signal electrical distribution problems, water leaks, and dangerous levels of air pollution. Songdo, South Korea, is the first fully equipped and wired smart city. Computers are built into the buildings and the streets. Nearly everything in the city will stream data to a bank of computers that will be monitored and analyzed with little or no human intervention.[14]



Chris Ratcliffe/Bloomberg/Getty Images

An employee demonstrates connecting to the Internet on a Samsung Electronics Co. Family Hub fridge freezer, inside the Smart Home section at a John Lewis Plc department store in London, United Kingdom, on Friday, April 8, 2016. The increasing integration of connected devices—what is commonly referred to as the Internet of things, or IoT—promises enormous benefits for consumers and businesses.

Given these examples, and those you can imagine coming in the not-too-distant future, you might be thinking that the IoT will make operations management obsolete. Not so fast! The IoT generates huge amounts of data, often referred to as "big data." (See Chapter 8, "Forecasting," for more details on big data.) That data must be organized and analyzed to be of any use. Firms use high-powered analytical models to sift through the data and make sense of it, resulting in a format that managers can use for decision making. In some cases, the data are fed in real time back to the IoT sensor for a programmed decision, as in the inventory management example.

[13]https://techjury.net/blog/internet-of-things-statistics/ (August 7, 2020).

[14]"Internet of Things," https://en.wikipedia.org/wiki/Internet_of_things (November 17, 2016); Songdo IBD, songdoibd.com (Dec. 10, 2016); https://en.wikipedia.org/wiki/Songdo_International_Business_District (August 10, 2020).

In other cases, monitoring and accumulating data from a process may take months and ultimately result in a change to the process itself. Regardless, operations managers are very much involved.

Concerns and Barriers Does the Internet of Things pose challenges for operations managers? Absolutely. If the IoT is to have extensive use, several concerns must be addressed.

- *Technology.* The cost of the basic hardware such as sensors, tracking identifiers, batteries, and storage must continue to drop. In addition, the bandwidth needed to support the interconnectivity of billions of devices must increase.
- *Privacy.* The amount of private data accessed and transmitted by IoT devices causes concerns of privacy. Does the manufacturer of an implant device have rights to the data collected by the device so as to improve future versions of it? Some sort of legal understanding of ownership rights needs to be in place for each application.
- *Security.* With billions of devices creating and transmitting data there is a real concern for the security of those data. The problem is only exacerbated as new IoT devices are introduced to the market.
- *Organizational roles.* Operations management and information technology, traditionally two separate functional areas, will have to become more aligned with the advent of IoT. Actuators and sensors provide operating data that not only aid decision making but also affect the business metrics used to evaluate operating performance. It behooves operations managers to learn the capabilities of the IoT.

The Internet of Things is certainly a trend that affects operations and supply chain management in a major way. Whether it is an opportunity or a challenge depends upon how it is embraced. Keep in mind, however, that the IoT, as complicated and pervasive as it is, is only a Base Technology and an enabler for the decision-making tools available to operations managers. The key is knowing what to do when addressing various operating problems as they arise. That is the purpose of this text.



frederic REGLAIN/Alamy Stock Photo

3D Printers making protective visors in a town hall in Paris.

Additive Manufacturing

Recognizing Smart Manufacturing Technologies and incorporating them into the fabric of a firm's operations and supply chains are keys to the future success of a firm. One such disruptive technology, a major part of Industry 4.0, is **additive manufacturing (AM)**, which is a term used to describe the technologies that build three-dimensional (3D) objects by adding layers of material such as plastic, metal, or concrete. Also known as *3D printing*, AM involves computers, 3D modeling software, 3D printing machine equipment, and layering material. Once a 3D design is provided using computer-aided design (CAD), the printing equipment lays down successive layers of liquid, powder, sheet material, and so on, to fabricate a 3D object. While AM was mostly used to build prototypes during the product development phase, it is now moving beyond its previous boundaries by playing an integral game-changing role in manufacturing firms' supply chains.

additive manufacturing (AM)
The technologies that build 3D objects by adding layers of material such as plastic, metal, or concrete.

Operations and Supply Chain Implications of AM Additive manufacturing adoption cases show the potential benefits of AM in terms of improving various supply chain performance outcomes. Moreover, AM can even motivate new business models by decentralizing the production process.[15] The benefits of AM include:

- *Reduced material inputs.* Traditionally, the cost of material input required for production was related to the product's design complexity. AM may help firms overcome the trade-off between cost and complexity. For example, Lockheed Martin was able to reduce the required material inputs for producing a highly complex aerospace component by using AM. The component, which previously required 33 pounds of metal to create a 1-pound component, was reduced to nearly 1 pound of metal. Scrap that occurs in the form of removed material

[15]M. Kelly, J. Crane, and C. Haley. (2015). *3D Opportunity for the Supply Chain: Additive Manufacturing Delivers*. Westlake, TX: Deloitte University Press.

is also reduced, contributing to a reduction in waste and environmental sustainability. Lockheed Martin was also able to reduce the weight of a satellite, which reduced the size of the rocket and the amount of fuel needed to launch it. A larger payload could now be carried using the same size rocket and fuel, which is significant because the rocket is one of the most expensive parts of a mission.[16]

- *Simplified production.* AM helps firms eliminate intermediary processes of parts production and subassemblies because separate pieces can be manufactured as single objects. This allows manufacturers to achieve reductions in labor, tooling, and work-in-process inventory holding costs. A research study from Italy showed that AM helped LED manufacturers drastically reduce the time to market for a new product.[17] The common practice of launching a new LED product involves showcasing them at design fairs, selecting internal components, running technical tests, and designing the appropriate packaging that, in total, may take from 6 months to several years. Because AM does not require molds, and setting up production for small production volumes is very quick once the 3D printer has been programmed, manufacturers can quickly test various design alternatives via rapid prototyping and send finalized designs to their mass production facilities.
- Although reducing or eliminating assembly resources may simplify production, it does carry significant implications for supply chain networks: The skill of labor required to produce a part often influences where that part can be produced and still remain economically competitive. With higher-skilled AM labor needed, countries with lower wage and skill levels could become less attractive locations for production facilities.
- *Production and supply chain flexibility.* AM can contribute to production flexibility by being able to reduce the time and resources necessary to design and develop new products, or even change input materials with ease during production. As a result, firms can react more rapidly to changing market preferences, shorten lead times in the supply chain, and reduce the required levels of finished goods inventory. For example, a luxury car manufacturer has used AM in developing air manifolds for a V8 engine. By being able to produce multiple design iterations quickly through rapid prototyping, the new product development cycle was shrunk by 50 percent, from 12 months to 6 months.

  AM can also be used to offer highly customized products. Product customization potentially yields an increase in customers' perceived product value, and thus, a higher willingness to pay. Firms can enhance the perceived product value by increasing the customers' involvement in the production process by allowing them to co-design a product. As an example, Twikit.com offers customized medals and trophies built via AM.[18] Using AM, Blizzard entertainment was able to provide customized character figurines based on customer preferences.
- *Decentralized, distributed production networks.* Distributed production on demand, or on-demand production in distributed locations, represents a scenario in which customers can fabricate objects at or near the point of use. In this regard, AM supports the strategies of *postponement* (see Chapter 12, "Supply Chain Design") and *forward inventory placement* (see Chapter 13, "Supply Chain Logistic Networks"). This significantly reduces the inventories required to support customer availability expectations, reduces lead time, and reduces dependency on forecast accuracy for low-volume products. When this scenario is taken to the extreme, distributed AM production networks may even partially eliminate the need for seller-controlled means of production. Consumers could purchase access to designs and produce goods at home or at other production-capable locations. For example, UPS is expanding its third-party logistics service to offer on-demand AM services in 60 UPS stores and a dedicated facility, called Fast Radius, that provides 3D printing, computerized numerical control machinery (CNC), and rapid injection molding services for industrial companies. In conjunction with the software company SAP, customers' orders will be seamlessly routed to the nearest UPS AM facility for production and delivery. The on-demand network will benefit customers of all sizes who need the capabilities of 3D printing and do not have the necessary resources to do the job. Mass adoption of a distributed production model such as this could have far-reaching effects on global trading, as AM technology could enable countries that have traditionally been dependent on imported goods to reduce their reliance on foreign production. The potential for on-demand AM is boundless. NASA is experimenting with using AM to produce required parts on the International Space Station, while the U.S. Navy is investigating the use of AM to produce spare parts while at sea.

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[16]See http://www.lockheedmartin.com/us/news/features/2014/additive-manufacturing.html for more details.

[17]P. S. Perez, M. Levi, and V. Folli. (2014). *A Study of Additive Manufacturing Applied to the Design and Production of LED Luminaires*. Milan, Italy: Politecnico Di Milano.

[18]C. Weller, R. Kleer, and F. T. Piller. (2015). Economic Implications of 3D Printing: Market Structure Models in Light of Additive Manufacturing Revisited. *International Journal of Production Economics, 164,* 43–56.

Enablers of Adopting AM Regardless of the varying AM usages, the people and technology that help capture the value in AM typically require a mix of enabling elements and processes:[19]

- *Talent/Workforce.* The more sophisticated the application of AM becomes, the greater is the need for new competencies, skills, talent infrastructure, and workforce planning. Many manufacturers rely on CAD programs in designing AM parts. The original CAD programs were not built to consider the unique features of AM to build parts with complex internal structures. The industry is still undergoing the pains of transition to a disruptive technology and, until a fully integrated CAD for AM emerges, firms will experience a shortage of AM specialized designers.

  The absence of clear guidelines for procedures and design know-how is also making it difficult to obtain the required workforce skills and optimize product designs. The International Standardization Organization (ISO) and the American Society for Testing and Materials (ASTM) are the two main institutions that have established technical committees and published AM standards. The published guidelines are still limited, and additional guidelines on reporting and testing procedures will be added in the future.
- *Intellectual property rights.* AM also poses severe risks to the intellectual property rights with respect to safeguarding product designs. Stringent checks and balances need to be in place to protect intellectual property. As copying product designs via digitalized 3D blueprints is even easier than before, managing digital security and protecting intellectual property will become critically important.
- *Quality assurance.* Validating the quality and consistency of AM production is currently the greatest challenge in using AM to produce more sophisticated, high-valued parts. While this is less of a challenge for parts requiring lower conformance and functionality, it is still an essential component of any AM production solution. Parts may lack resistance to environmental influences and fail with exposure to high-stress conditions. Moreover, process variability may still be high, making reproducibility a challenge. There is a need for establishing global quality and testing standards for AM.
- *Process.* Deploying AM can affect the entire workflow of an organization. Modifying existing processes and activities helps ensure that AM is deployed to its full potential. Currently, available materials and the choice of colors and surface finishes are quite limited. Moreover, the build space of AM machines sets a physical limit to product dimensions. As the production process is constrained by AM specifications, there is a need for further development of improved open-space designs for AM machines.

Additive manufacturing is not the first, nor will it be the last, technology that will require changes to the four core processes of a supply chain. Regardless of the disruption, successful operations and supply chain managers focus on optimizing the performance of these core processes, which is the focus of this textbook.

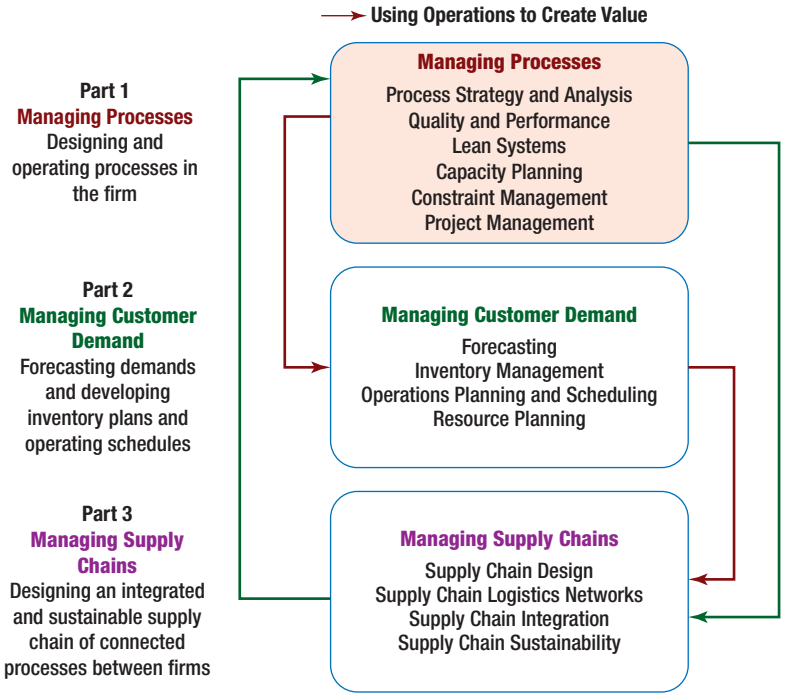
Developing Skills for Your Career

You can develop skills for your career by understanding how firms can meet their current and future challenges through a better design of operating processes and supply chains. This textbook will help you achieve that goal and become an effective manager even if your major lies in a functional area of business other than operations and supply chain management. Each chapter has a Managerial Challenge, which is a realistic problem scenario affecting various functional areas, in which the principles of operations management expressed in the chapter can be useful. Further, the trends and challenges we identified earlier represent opportunities to improve existing processes and supply chains or to create new, innovative ones, regardless of the functional area. The management of processes and supply chains goes beyond designing them; it requires the ability to ensure they achieve their goals and maximize their competitiveness in the markets they serve. We share this philosophy of operations management, as illustrated in Figure 1.7. To assist you in your learning, we use this figure at the start of each chapter to show how the topic of the chapter fits into our philosophy of operations management. In addition, this text also contains several chapter supplements that can be accessed through online resources.

Figure 1.7 shows that all effective operations decisions follow from a sound operations strategy. Consequently, our text has three major parts: "Part 1: Managing Processes," "Part 2: Managing Customer Demand," and "Part 3: Managing Supply Chains." The flow of topics reflects our approach of first understanding how a firm's operations can help provide a solid foundation for competitiveness, before tackling the essential process design decisions that will support its strategies. Each part begins with a strategy discussion to support the decisions in that part. Once it

[19]K. Marchese, R. Gorham, J. Joyce, B. Sniderman, and M. Passaretti. (2017). *3D Opportunity for Business Capabilities*. Westlake, TX: Deloitte University Press.

is clear how firms design and improve processes, we explain how they implement those designs to satisfactorily meet customer demand. Finally, we examine the design and operation of supply chains that link processes, whether they are internal or external to the firm. The performance of the supply chains determines the firm's outcomes, which include the services or products the firm produces, the financial results, and feedback from the firm's customers. These outcomes, which are considered in the firm's strategic plan, are discussed throughout this text.



▲ **FIGURE 1.7**
Managing Processes, Customer Demand, and Supply Chains

Part 1: Managing Processes In Part 1, we focus on analyzing processes and how they can be improved to meet the goals of the operations strategy. We begin by addressing the strategic aspects of process design and then present a six-step systematic approach to process analysis. Each chapter in this part deals with some aspect of that approach. We discuss the tools that help managers analyze processes, and we reveal the methods firms use to measure process performance and quality. These methods provide the foundation for programs such as Six Sigma and total quality management. Making processes "lean" by eliminating activities that do not add value while improving those that do add value are also key decisions in the redesign of processes. We also look at long-term capacity planning of firms, as well as shorter-term tactical decisions aimed at better identification and management of system constraints and bottlenecks. The activities involved in managing processes are essential for providing significant benefits to the firm. Effective management of its processes can allow a firm to reduce its costs and also increase customer satisfaction.

The concluding chapter of Part 1 is a discussion of the methods and tools of project management. Project management is an effective approach to implementing operations strategy through the introduction of new services or products as well as any changes to a firm's processes or supply chains.

Part 2: Managing Customer Demand The focus of this part of the book is on effectively forecasting and managing customer demand. Therefore, we begin by taking a look at forecasting methods and their accuracy, followed by managing inventory such that enough is kept on hand for satisfying customer demand but without tying up excessive resources in it. We follow that with chapters focused on two key planning activities for effective operations: (1) operations planning and scheduling, and (2) resource planning. Together, these planning activities allow for the creation of goods and services that would meet customer demand in a cost-effective fashion.

Part 3: Managing Supply Chains The focus of Part 3 is on supply chains involving processes both internal and external to the firm and the tools that enhance their execution. We follow that with understanding how the design of supply chains and major strategic decisions, such as outsourcing and locating facilities, affect performance. We also look at new technologies and contemporary issues surrounding supply chain integration and the impact of supply chains on the environment.

Later chapters deal with a variety of subjects: process analysis, including methods used in programs such as Six Sigma and total quality management and those used in making lean processes; managing processes, essential for providing significant benefits to the firm by reducing costs and increasing customer satisfaction; effectively forecasting and managing customer demand, including the use of inventory management and planning activities; and managing supply chains, which involves using processes both internal and external to the firm and incorporating new technologies.

Adding Value with Process Innovation

Of great importance is that the effective operation of a firm and its supply chain is as vital as the design and implementation of its processes. Skilled managers in this field inherently understand that process innovation can make a big difference even in a low-growth industry. Examining processes from the perspective of the value they add is an important part of a successful manager's agenda, as is gaining an understanding of how core processes and related supply chains are linked to their competitive priorities, markets, and the operations strategy of a firm. Who says operations management does not make a difference?



Mark Duncan/AP/Shutterstock

Through operational innovations that add value to its products and catchy promotional advertisements, Progressive Insurance has been able to achieve amazing growth in a low-growth industry. Here, Stephanie Courtney, who plays the character Flo in commercials for Progressive Insurance, waves to a friend after throwing out a pitch before a baseball game between the Kansas City Royals and Cleveland Indians, in Cleveland, Ohio.

In the long run, all management decisions should reflect corporate strategy. To that end, regardless of the functional area, all managers either directly use the principles of operations management or are directly influenced by them. Processes can be found throughout the organization, from the boardroom to the billing department, and this text is all about managing those processes. At the strategic level, new capabilities must be developed and existing capabilities must be maintained to best serve the firm's external customers. Managers of all disciplines must design new processes that have strategic implications. They are also deeply involved in the development, organization, and operation of supply chains that link external suppliers and external customers to the firm's internal processes, as the Managerial Challenges in each chapter show.

Plans, policies, and actions should be linked to all functional areas to support the firm's overall goals and objectives. Taking a process view of a firm facilitates these links. Regardless of whether you aspire to be an operations manager, or you just want to use the principles of operations management to become a more effective manager, remember that effective management of people, capital, information, and materials is critical to the success of any process and any supply chain.

As you study operations management, keep two principles in mind:

1. Each part of an organization, not just the operations function, must design and operate processes that are part of a supply chain and deal with quality, technology, and staffing issues.
2. Each function of an organization has its own identity and yet is connected with operations through shared processes.

Great strategic decisions lead nowhere if the tactical decisions that support them are wrong. Remember: All managers are involved in tactical decisions, including process improvement and performance measurement, managing and planning projects, generating production and staffing plans, managing inventories, and scheduling resources. You will find numerous examples of these decisions, and the implications of making them, throughout this text. You will also learn about the decision-making tools practicing managers use to recognize and define the problem and then choose the best solution. The topics in this text will help you meet operations challenges and achieve operational innovation regardless of your chosen career path.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
1.1 Describe the role of operations in an organization and its historical evolution over time.	The section "Role of Operations in an Organization" shows how different functional areas of business come together to create value for a firm.	
1.2 Describe the process view of operations in terms of inputs, processes, outputs, information flows, suppliers, and customers.	See the section "A Process View," which focuses on how nested and other processes work. Understand the key differences between manufacturing and service processes. Review Figure 1.2 for the important inputs, outputs, and information flows associated with any process.	
1.3 Describe the supply chain view of operations in terms of linkages between core and support processes.	Review Figure 1.4 for the important supply chain linkage and information flows.	
1.4 Define an operations strategy and its linkage to corporate strategy and market analysis.	See the section "Operations Strategy" and subsection "Corporate Strategy" and review Figure 1.5.	
1.5 Identify nine competitive priorities used in operations strategy, and explain how a consistent pattern of decisions can develop organizational capabilities.	The section "Competitive Priorities and Capabilities" discusses the important concept of order winners and qualifiers. Review Table 1.3 for important illustrations and examples of how leading edge firms implemented different competitive priorities to create a unique positioning in the marketplace. Review Table 1.5, which provides a nice illustrative example of how firms must identify gaps in their competitive priorities and build capabilities through related process and operational changes.	

Learning Objective	Guidelines for Review	Online Resources
1.6 Identify the latest trends in operations management and understand how firms can address the challenges facing operations and supply chain managers in a firm.	The section "Trends and Challenges in Operations Management" describes the pressures and challenges that managers face in achieving productivity improvements, enhancing sustainability, and maintaining workforce diversity in the face of global competition.	**OM Explorer Tutor:** Productivity Measures **Active Model Exercise:** Productivity
1.7 Define the fourth industrial revolution (Industry 4.0) and understand how its embedded technologies and automation are transforming the practice of operations and supply chain management.	The section "Fourth Industrial Revolution (Industry 4.0)" lays out a framework of new technologies that constitute the fourth industrial revolution, and how they can be managed to improve processes and supply chains. Also review the subsections "The Internet of Things" and "Additive Manufacturing."	
1.8 Understand how to develop skills for your career using this textbook.	The section "Developing Skills for Your Career" lays out the foundations of this textbook, and how the content of each chapter can help you develop core understanding about managing processes and supply chains. Also review the subsection "Adding Value with Process Innovation."	

Key Equations

Trends and Challenges in Operations Management

1. Productivity is the ratio of output to input:

$$\text{Productivity} = \frac{\text{Output}}{\text{Input}}$$

Key Terms

additive manufacturing (AM) 44
artificial intelligence (AI) 42
competitive capabilities 32
competitive priorities 32
core competencies 30
core process 27
customer relationship process 27
external customers 25
external suppliers 25
fourth industrial revolution (Industry 4.0) 41
internal customers 25
internal suppliers 25
Internet of Things (IoT) 42
lead time 30
manufacturing execution systems (MES) 42
nested process 25
new service/product development process 27
operation 23
operations management 23
operations strategy 28
order fulfillment process 27
order qualifier 34
order winner 34
process 23
productivity 37
supplier relationship process 27
supply chain 23
supply chain management 23
supply chain processes 28
support process 27
time-based competition 33

Solved Problem 1

Student tuition at Boehring University is $150 per semester credit hour. The state supplements school revenue by $100 per semester credit hour. Average class size for a typical 3-credit course is 50 students. Labor costs are $4,000 per class, materials costs are $20 per student per class, and overhead costs are $25,000 per class.

a. What is the *multifactor* productivity ratio for this course process?
b. If instructors work an average of 14 hours per week for 16 weeks for each 3-credit class of 50 students, what is the *labor* productivity ratio?

SOLUTION

a. Multifactor productivity is the ratio of the value of output to the value of input resources.

$$\text{Value of output} = \left(\frac{50 \text{ students}}{\text{class}}\right)\left(\frac{3 \text{ credit hours}}{\text{students}}\right)\left(\frac{\$150 \text{ tuition} + \$100 \text{ state support}}{\text{credit hour}}\right)$$
$$= \$37{,}500/\text{class}$$

$$\begin{aligned}\text{Value of inputs} &= \text{Labor} + \text{Materials} + \text{Overhead}\\ &= \$4{,}000 + (\$20/\text{student} \times 50 \text{ students/class}) + \$25{,}000\\ &= \$30{,}000/\text{class}\end{aligned}$$

$$\text{Multi factor proctivity} = \frac{\text{Output}}{\text{Input}} = \frac{\$37{,}500/\text{class}}{\$30{,}000/\text{class}} = \mathbf{1.25}$$

b. Labor productivity is the ratio of the value of output to labor hours. The value of output is the same as in part (a), or $37,500/class, so

$$\text{Labor hours of input} = \left(\frac{14 \text{ hours}}{\text{week}}\right)\left(\frac{16 \text{ weeks}}{\text{class}}\right) = 224 \text{ hours/class}$$

$$\begin{aligned}\text{Labor productivity} &= \frac{\text{Output}}{\text{Input}} = \frac{\$37{,}500/\text{class}}{224 \text{ hours/class}}\\ &= \$\mathbf{167.41}/\text{hour}\end{aligned}$$

Solved Problem 2

Natalie Attire makes fashionable garments. During a particular week, employees worked 360 hours to produce a batch of 132 garments, of which 52 were "seconds" (meaning that they were flawed). Seconds are sold for $90 each at Attire's Factory Outlet Store. The remaining 80 garments are sold to retail distribution at $200 each. What is the *labor* productivity ratio of this manufacturing process?

SOLUTION

$$\begin{aligned}\text{Value of output} &= (52 \text{ defective} \times \$90/\text{defective}) + (80 \text{ garments} \times \$200/\text{garment})\\ &= \$20{,}680\\ \text{Labor hours of input} &= 360 \text{ hours}\\ \text{Labor productivity} &= \frac{\text{Output}}{\text{Input}} = \frac{\$20{,}680}{360 \text{ hours}}\\ &= \$\mathbf{57.44} \text{ in sales per hour}\end{aligned}$$

Discussion Questions

1. Consider your last (or current) job, internship, or volunteer experience.
   - **a.** What activities did you perform?
   - **b.** Who were your customers (internal and external), and how did you interact with them?
   - **c.** How could you measure the customer value you were adding by performing your activities?
   - **d.** Was your position in accounting, finance, human resources, management information systems, marketing, operations, or other? Explain.
2. Anglo American plc is a multinational mining company with its headquarters in South Africa. It is the world's largest producer of platinum as well as a major producer of diamond, copper, nickel, and coal. What should be the focus of Anglo American's operations strategy, and what are its competitive priorities?
3. A local hospital declares that it is committed to provide *care* to patients arriving at the emergency unit in less than 15 minutes and that it will never turn away patients who need to be hospitalized for further medical care. What implications does this commitment have for strategic operations management decisions (i.e., decisions relating to capacity and workforce)?
4. FedEx built its business on quick, dependable delivery of items being shipped by air from one business to another. Its early advantages included global tracking of shipments using Web technology. The advancement of Internet technology enabled competitors to become much more sophisticated in order tracking. In addition, the advent of Web-based businesses put pressure on increased ground transportation deliveries. Explain how this change in the environment has affected FedEx's operations strategy, especially relative to UPS, which has a strong hold on the business-to-consumer ground delivery business.
5. Suppose that you were conducting a market analysis for a new textbook about technology management. What would you need to know to identify a market segment? How would you make a needs assessment? What should be the collection of services and products?
6. Although all nine of the competitive priorities discussed in this chapter are relevant to a company's success in the marketplace, explain why a company should not necessarily try to excel in all of them. What determines the choice of the competitive priorities that a company should emphasize for its key processes?
7. Choosing which processes are core to a firm's competitive position is a key strategic decision. For example, Nike, a popular sports shoe company, focuses on the customer relationship, new product development, and supplier relationship processes and leaves the order fulfillment process to others. Allen Edmonds, a top-quality shoe company, considers all four processes to be

core processes. What considerations would you make in determining which processes should be core to your manufacturing company?

8. A local fast-food restaurant processes several customer orders at once. Service clerks cross paths, sometimes nearly colliding, while they trace different paths to fill customer orders. If customers order a special combination of toppings on their hamburgers, they must wait quite some time while the special order is cooked. How would you modify the restaurant's operations to achieve competitive advantage? Because demand surges at lunchtime, volume flexibility is a competitive priority in the fast-food business. How would you achieve volume flexibility?

9. Kathryn Shoemaker established Grandmother's Chicken Restaurant in Middlesburg 5 years ago. It features a unique recipe for chicken, "just like grandmother used to make." The facility is homey, with relaxed and friendly service. Business has been good during the past 2 years, for both lunch and dinner. Customers normally wait about 15 minutes to be served, although complaints about service delays have increased recently. Shoemaker is currently considering whether to expand the current facility or open a similar restaurant in neighboring Uniontown, which has been growing rapidly.
   a. What types of strategic plans must Shoemaker make?
   b. What environmental forces could be at work in Middlesburg and Uniontown that Shoemaker should consider?
   c. What are the possible distinctive competencies of Grandmother's?

10. Wild West, Inc., is a regional telephone company that inherited nearly 100,000 employees and 50,000 retirees from AT&T. Wild West has a new mission: to diversify. It calls for a 10-year effort to enter the financial services, real estate, cable TV, home shopping, entertainment, and cellular communication services markets—and to compete with other telephone companies. Wild West plans to provide cellular and fiber-optic communications services in markets with established competitors, such as the United Kingdom, and in markets with essentially no competition, such as Russia and former Eastern Bloc countries.
   a. What types of strategic plans must Wild West make? Is the "do-nothing" option viable? If Wild West's mission appears too broad, which businesses would you trim first?
   b. What environmental forces could be at work that Wild West should consider?
   c. What are the possible core competencies of Wild West? What weaknesses should it avoid or mitigate?

11. You are designing a grocery delivery business. Via the Internet, your company will offer staples and frozen foods in a large metropolitan area and then deliver them within a customer-defined window of time. You plan to partner with two major food stores in the area. What should be your competitive priorities and what capabilities do you want to develop in your core and support processes?

12. Under what conditions would you recommend a small manufacturer of consumer electrical goods to acquire additive manufacturing (AM) capabilities for producing some of the components needed for the manufacturing process, instead of sourcing them from external suppliers? How would these considerations change if the firm grows over time and production volumes increase dramatically?

Problems

The OM Explorer, POM for Windows, and Active Model software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations.

Trends and Challenges in Operations Management

1. (Refer to Solved Problem 1.) Coach Bjourn Toulouse led the Big Red Herrings to several disappointing football seasons. Only better recruiting will return the Big Red Herrings to winning form. Because of the current state of the program, Boehring University fans are unlikely to support increases in the $192 season ticket price. Improved recruitment will increase overhead costs to $30,000 per class section from the current $25,000 per class section. The university's budget plan is to cover recruitment costs by increasing the average class size to 75 students. Labor costs will increase to $6,500 per 3-credit course. Material costs will be about $25 per student for each 3-credit course. Tuition will be $200 per semester credit, which is supplemented by state support of $100 per semester credit.
   a. What is the multifactor productivity ratio? Compared to the result obtained in Solved Problem 1, did productivity increase or decrease for the course process?
   b. If instructors work an average of 20 hours per week for 16 weeks for each 3-credit class of 75 students, what is the *labor* productivity ratio?

2. Suds and Duds Laundry washed and pressed the following numbers of dress shirts per week.

Week	Work Crew	Total Hours	Shirts
1	Sud and Dud	24	68
2	Sud and Jud	46	130
3	Sud, Dud, and Jud	62	152
4	Sud, Dud, and Jud	51	125
5	Dud and Jud	45	131

   a. Calculate the *labor* productivity ratio for each week.
   b. Explain the labor productivity pattern exhibited by the data.

3. White Tiger Electronics produces CD players using an automated assembly line process. The standard cost of CD players is $150 per unit (labor, $30; materials, $70; and overhead, $50). The sales price is $300 per unit.

a. To achieve a 10 percent multifactor productivity improvement by reducing materials costs only, by what percentage must these costs be reduced?

b. To achieve a 10 percent multifactor productivity improvement by reducing labor costs only, by what percentage must these costs be reduced?

c. To achieve a 10 percent multifactor productivity improvement by reducing overhead costs only, by what percentage must these costs be reduced?

4. At Symtecks, the output of a specific process is valued at $100 per unit. The cost of labor is $50 per hour including benefits. The accounting department provided the following information about the process for the past four weeks:

	Week 1	Week 2	Week 3	Week 4
Units Produced	1,124	1,310	1,092	981
Labor ($)	12,735	14,842	10,603	9,526
Materials ($)	21,041	24,523	20,442	18,364
Overhead ($)	8,992	10,480	8,736	7,848

a. Use the multifactor productivity ratio to see whether recent process improvements had any effect and, if so, when the effect was noticeable.

b. Has labor productivity changed? Use the labor productivity ratio to support your answer.

5. Alyssa's Custom Cakes currently sells 5 birthday, 2 wedding, and 3 specialty cakes each month for $50, $150, and $100 each, respectively. The cost of labor is $50 per hour including benefits. It takes 90 minutes to produce a birthday cake, 240 minutes to produce a wedding cake, and 60 minutes to produce a specialty cake. Alyssa's current multifactor productivity ratio is 1.25.

a. Use the multifactor productivity ratio provided to calculate the average cost of the cakes produced.

b. Calculate Alyssa's labor productivity ratio in dollars per hour for each type of cake.

c. Based solely on the labor productivity ratio, which cake should Alyssa try to sell the most?

d. Based on your answer in part (a), is there a type of cake Alyssa should stop selling?

6. The Big Black Bird Company (BBBC) has a large order for special plastic-lined military uniforms to be used in an urgent military operation. Working the normal two shifts of 40 hours each per week, the BBBC production process usually produces 2,500 uniforms per week at a standard cost of $120 each. Seventy employees work the first shift and 30 employees work the second. The contract price is $200 per uniform. Because of the urgent need, BBBC is authorized to use around-the-clock production, 6 days per week. When each of the two shifts works 72 hours per week, production increases to 4,000 uniforms per week but at a cost of $144 each.

a. Did the multifactor productivity ratio increase, decrease, or remain the same? If it changed, by what percentage did it change?

b. Did the labor productivity ratio increase, decrease, or remain the same? If it changed, by what percentage did it change?

c. Did weekly profits increase, decrease, or remain the same?

7. Thomas Cope, located in Bolton, England, is a manufacturer of stainless steel exhaust hoods used in industrial kitchens. The firm works 20 days a month, and each employee works an average of 8 hours per day. To keep costs down, Thomas Cope employs labor with limited experience. This causes quality issues, and every day 10 percent of the production is scrapped. Each exhaust hood sells for £125. Labor is paid at £15/hour, materials cost per exhaust hood is £40, and overhead cost is £3,500. The firm currently has 250 employees.

a. Calculate the labor and multifactor productivity ratios.

b. To improve the firm's multifactor productivity, Thomas Cope has three choices 1) increase 20 percent sales by reducing the sales price by 10 percent, 2) improve quality by hiring skilled labor at £20 per hour resulting in no defects, or 3) reduce material costs by 10 percent. Which option has the greatest impact on the multifactor productivity measure?

8. Mariah Enterprises makes a variety of consumer electronic products. Its camera manufacturing plant is considering choosing between two different processes, named Alpha and Beta, which can be used to make two component parts A and B. To make the correct decision, the managers would like to compare the labor and multifactor productivity of process Alpha with that of process Beta. The value of process output for component A and B are $175 and $140 per unit, respectively. The corresponding overhead costs are $6,000 and $5,000, respectively.

	PROCESS ALPHA		PROCESS BETA	
Product	**A**	**B**	**A**	**B**
Output (units)	50	60	30	80
Labor ($)	$1,200	$1,400	$1,000	$2,000
Materials ($)	$2,500	$3,000	$1,400	$3,500

a. Which process, Alpha or Beta, is more productive?

b. What conclusions can you draw from your analysis?

9. Akiko, a mobile Vegan café, in London sells wraps, bowls, and burgers. It employs two sandwich artists to assemble the wraps as per customer requests. The café's current daily labor cost is £160, the equipment cost is £175, and the overhead cost is £125. Daily demands, along with selling price and material costs per beverage, are given here:

	Wraps	Bowls	Burgers
Number of units sold	250	300	100
Price per item	£4	£5.50	£6.00
Materials (£)	£0.90	£1.40	£1.75

Jimmy Riverside, the manager at Akiko, would like to understand how adding waffles and ice-cream will alter the café's productivity. His market research shows that waffles and ice-cream will attract both American and European tourists. Assuming that the new equipment is purchased before these are added to the menu, Jimmy has developed new average daily demand and cost projections. The new equipment cost is £350, and the overhead cost is £100. Modified daily

demands, as well as selling price and material costs per units for the new product lines, are given here:

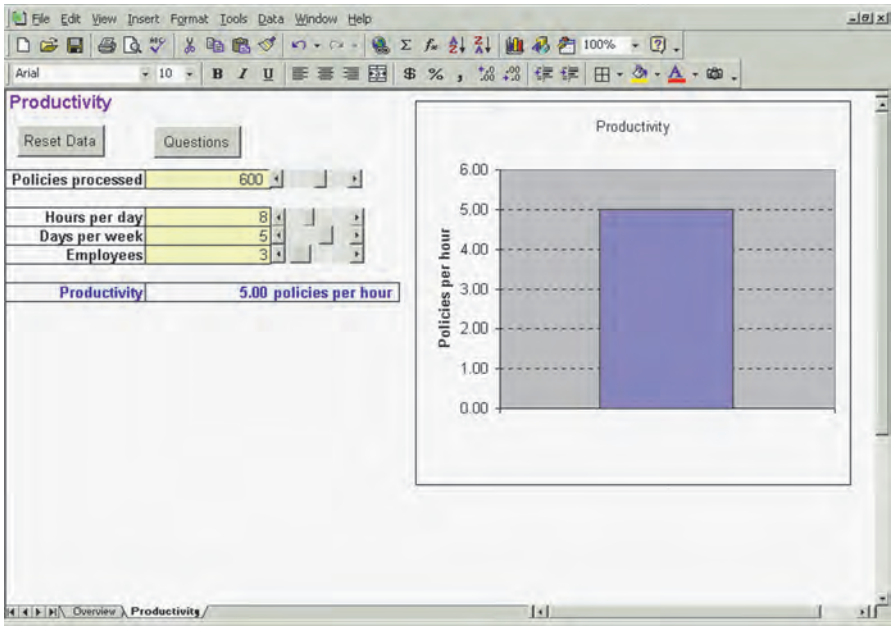
	Wraps	Bowls	Burgers	Waffles and Ice-cream
Number of units sold	250	300	100	90
Price per item	£4	£5.50	£6.00	£4.50
Material (£)	£0.90	£1.40	£1.75	£1.50

a. Calculate the change in labor and multifactor productivity if waffles and ice-cream are added to the menu.

b. If everything else remains unchanged, how many units of waffles and ice-cream would have to be sold to ensure that the multifactor productivity remains at its current level?

Active Model Exercise

This Active Model is available online. It allows you to evaluate the important elements of labor productivity.



◀ **ACTIVE MODEL 1.1**
Labor Productivity Using Data from Example 1.1

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QUESTIONS

1. If the insurance company can process 60 (10 percent) more policies per week, by what percentage will the productivity measure rise?
2. Suppose the 8-hour day includes a 45-minute lunch. What is the revised productivity measure, excluding lunch?
3. If an employee is hired, what will be the weekly number of policies processed if the productivity of five policies per hour is maintained?
4. Suppose that, during the summer, the company works for only 4 days per week. What will be the weekly number of policies processed if the productivity of five policies per hour is maintained?

CASE Chad's Creative Concepts

Chad's Creative Concepts designs and manufactures wood furniture. Founded by Chad Thomas on the banks of Lake Erie in Sandusky, Ohio, the company began by producing custom-made wooden furniture for vacation cabins located along the coast of Lake Erie and on nearby Kelly's Island and Bass Island. Being an "outdoors" type himself, Thomas originally wanted to bring "a bit of the outdoors" inside. Chad's Creative Concepts developed a solid reputation for creative designs and high-quality workmanship. Sales eventually encompassed the entire Great Lakes region. Along with growth came additional opportunities.

Traditionally, the company focused entirely on custom-made furniture, with the customer specifying the kind of wood from which the piece would be made. As the company's reputation grew and sales increased, the sales force began selling some of the more popular pieces to retail furniture outlets. This move into retail outlets led Chad's Creative Concepts into the production of a more standard line of furniture. Buyers of this line were much more price sensitive and imposed more stringent delivery requirements than did clients for the custom line. Custom-designed furniture, however, continued to dominate sales, accounting for 60 percent of volume and 75 percent of dollar sales.

Currently, the company operates a single manufacturing process in Sandusky, where both custom furniture and standard furniture are manufactured. The equipment is mainly general purpose in nature to provide the flexibility needed for producing custom pieces of furniture. The layout puts together saws in one section of the facility, lathes in another, and so on. The quality of the finished product reflects the quality of the wood chosen and the craftsmanship of individual workers. Both custom and standard furniture compete for processing time on the same equipment by the same craftspeople.

During the past few months, sales of the standard line steadily increased, leading to more regular scheduling of this product line. However, when scheduling trade-offs had to be made, custom furniture was always given priority because of its higher sales and profit margins. Thus, scheduled lots of standard furniture pieces were left sitting around the plant in various stages of completion.

As he reviews the progress of Chad's Creative Concepts, Thomas is pleased to note that the company has grown. Sales of custom furniture remain strong, and sales of standard pieces are steadily increasing. However, finance and accounting indicate that profits are not what they should be. Costs associated with the standard line are rising. Dollars are being tied up in inventory, both in raw materials and work-in-process. Expensive public warehouse space has to be rented to accommodate the inventory volume. Thomas also is concerned with increased lead times for both custom and standard orders, which are causing longer promised delivery times. Capacity is being pushed, and no space is left in the plant for expansion. Thomas begins a careful assessment of the overall impact that the new standard line is having on his manufacturing process.

QUESTIONS

1. What types of decisions must Chad Thomas make daily for his company's operations to run effectively? Over the long run?
2. How did sales and marketing affect operations when the company began to sell standard pieces to retail outlets?
3. How has the move to producing standard furniture affected the company's financial structure?
4. What might Chad Thomas have done differently to avoid some of the problems he now faces?[20]

VIDEO CASE Using Operations to Create Value at Crayola

Operations processes are at the heart of Crayola, the Easton, Pennsylvania, maker of crayons, markers, and paints loved by children of all ages around the world. Since 1903, the company has been taking wax, dyes, and other raw materials and turning them into a colorful array of products sold through an extensive network of distributors and retailers such as Walmart and Target stores. Each day, the company produces 13 million crayons, 2 million markers, 500,000 jars of paint, 170,000 pounds of modeling compounds, and 22,000 Silly Putty© eggs from its three manufacturing plants.

Crayola derives much of its own inspiration and creativity by asking, "What would a kid do?"—especially when focusing on innovation. Not that kids have the knowledge to create complex systems and operational processes. Rather, the question leads to creative solutions by freeing employees to think about the company's competitive priorities in new ways. In the supply chain, the company maintains five "pillars" of operational leadership. These pillars focus attention on differentiating the company on (1) innovation, (2) sustainability, (3) agility and resilience, (4) cost, and (5) quality and ethical responsibility.



Pearson Education

Crayola, headquartered in Pennsylvania, has become a leader in its industry by focusing on operational excellence and innovation.

The company has a history of innovation. They were the first to introduce an art education program called Dream-Makers into the nation's elementary schools. Washable markers and crayons also were firsts for the industry and continue to be best-sellers for the company. Recently, the language on crayon paper packaging changed to include three languages—French, English, and Spanish—instead of one. This change alone saved $400,000 in paper and printing costs, since the packaging could now be used across multiple markets.

In the area of sustainability, Crayola built a solar farm on a 20-acre site adjacent to its manufacturing plant in Easton. The farm produces enough energy to completely run the plant as well as the headquarters building nearby. The 850 million colored pencils produced each year only use reforested wood, with one tree planted for every tree harvested. Sourcing for paraffin wax used in crayons recently moved from Louisiana to western Pennsylvania, saving 5,000 barrels of oil annually related to wax transportation. All plastic components are made with recycled plastics. And any excess wax from the production of crayons is reintroduced into the manufacturing process so no waste is produced.

The company is aggressively pursuing new markets outside the United States. China's market of children ages 0 to 14 is larger than all the other global markets combined, with more than half the world's child population. Yet only 14 percent of the company's total sales come from international markets. So, particular attention is being devoted to growing the company's manufacturing and distribution presences there. As you can imagine, this means operations managers must think about how to grow the current supply chain beyond the boundaries of existing domestic and international borders if additional expansion is to occur.

QUESTIONS

1. Map Crayola's five pillars of operational leadership to the competitive priorities in Table 1.3.
2. Create an assessment of Crayola's competitive priorities as it relates to their plans to expand to Asia.
3. Which of the competitive priorities might present the biggest challenge to Crayola as it expands internationally?

[20] *Source:* This case was prepared by Dr. Brooke Saladin, Wake Forest University, as a basis for classroom discussion. Copyright © Brooke Saladin. Reprinted by permission.

SUPPLEMENT

A

DECISION MAKING

LEARNING OBJECTIVES *After reading this supplement, you should be able to:*

A.1 Explain break-even analysis, using both the graphic and algebraic approaches.

A.2 Define and construct a preference matrix.

A.3 Explain how decision theory can be used to make decisions under conditions of certainty, uncertainty, and risk.

A.4 Describe how to draw and analyze a decision tree.

Operations managers make many decisions as they manage processes and supply chains. Although the specifics of each situation vary, decision making generally involves the same basic steps: (1) recognize and clearly define the problem, (2) collect the information needed to analyze possible alternatives, and (3) choose and implement the most feasible alternative.

Sometimes, hard thinking in a quiet room is sufficient. At other times, interacting with others or using more formal procedures are needed. Here, we present four such formal procedures: break-even analysis, the preference matrix, decision theory, and the decision tree.

- Break-even analysis helps the manager identify how much change in volume or demand is necessary before a second alternative becomes better than the first alternative.
- The preference matrix helps a manager deal with multiple criteria that cannot be evaluated with a single measure of merit, such as total profit or cost.
- Decision theory helps the manager choose the best alternative when outcomes are uncertain.
- A decision tree helps the manager when decisions are made sequentially—when today's best decision depends on tomorrow's decisions and events.

Break-Even Analysis

To evaluate an idea for a new service or product, or to assess the performance of an existing one, determining the volume of sales at which the service or product breaks even is useful. The **break-even quantity** is the volume at which total revenues equal total costs. Use of this technique is known as **break-even analysis**. Break-even analysis can also be used to compare processes by finding the volume at which two different processes have equal total costs.

break-even quantity
The volume at which total revenues equal total costs.

break-even analysis
The use of the break-even quantity; it can be used to compare processes by finding the volume at which two different processes have equal total costs.



Syda Productions/Shutterstock

A manager is doing some hard thinking and analysis on his computer before reaching a final decision.

Evaluating Services or Products

We begin with the first purpose: to evaluate the profit potential of a new or existing service or product. This technique helps the manager answer questions, such as the following:

- Is the predicted sales volume of the service or product sufficient to break even (neither earning a profit nor sustaining a loss)?
- How low must the variable cost per unit be to break even, based on current prices and sales forecasts?
- How low must the fixed cost be to break even?
- How do price levels affect the break-even volume?

Break-even analysis is based on the assumption that all costs related to the production of a specific service or product can be divided into two categories: (1) variable costs and (2) fixed costs.

variable cost
The portion of the total cost that varies directly with volume of output.

fixed cost
The portion of the total cost that remains constant regardless of changes in levels of output.

The **variable cost**, c, is the portion of the total cost that varies directly with volume of output: costs per unit for materials, labor, and usually some fraction of overhead. If we let Q equal the number of customers served or units produced per year, total variable cost $= cQ$. The **fixed cost**, F, is the portion of the total cost that remains constant regardless of changes in levels of output: the annual cost of renting or buying new equipment and facilities (including depreciation, interest, taxes, and insurance); salaries; utilities; and portions of the sales or advertising budget. Thus, the total cost of producing a service or good equals fixed costs plus variable costs multiplied by volume, or

$$\text{Total cost} = F + cQ$$

The variable cost per unit is assumed to be the same no matter how small or large Q is, and thus, total cost is linear. If we assume that all units produced are sold, total annual revenues equal revenue per unit sold, p, multiplied by the quantity sold, or

$$\text{Total revenue} = pQ$$

If we set total revenue equal to total cost, we get the break-even quantity point as

$$pQ = F + cQ$$
$$(p - c)Q = F$$
$$Q = \frac{F}{p - c}$$

We can also find this break-even quantity graphically. Because both costs and revenues are linear relationships, the break-even quantity is where the total revenue line crosses the total cost line.

sensitivity analysis
A technique for systematically changing parameters in a model to determine the effects of such changes.

Break-even analysis cannot tell a manager whether to pursue a new service or product idea or drop an existing line. The technique can only show what is likely to happen for various forecasts of costs and sales volumes. To evaluate a variety of "what-if" questions, we use an approach called **sensitivity analysis**, a technique for systematically changing parameters in a model to determine the effects of such changes. The concept can be applied later to other techniques, such as linear programming. Here we assess the sensitivity of total profit to different pricing strategies, sales volume forecasts, or cost estimates.

EXAMPLE A.1 Finding the Break-Even Quantity

Online Resources
Active Model A.1 provides additional insight on this break-even example and its extensions with four "what-if" questions.

Tutor A.1 in OM Explorer provides a new example to practice break-even analysis.

A hospital is considering a new procedure to be offered at $200 per patient. The fixed cost per year would be $100,000, with total variable costs of $100 per patient. What is the break-even quantity for this service? Use both algebraic and graphic approaches to get the answer.

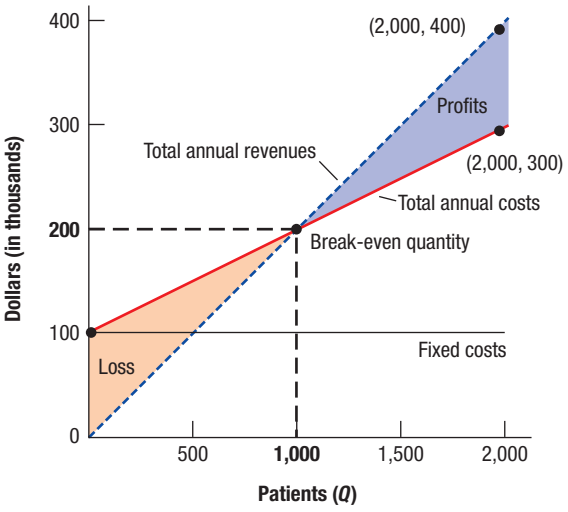
SOLUTION

The formula for the break-even quantity yields

$$Q = \frac{F}{p - c} = \frac{100{,}000}{200 - 100} = 1{,}000 \text{ patients}$$

To solve graphically, we plot two lines: one for costs and one for revenues. Two points determine a line, so we begin by calculating costs and revenues for two different output levels. The following table shows the results for $Q = 0$ and $Q = 2{,}000$. We selected zero as the first point because of the ease of plotting total revenue (0) and total cost (F). However, we could have used any two reasonably spaced output levels.

Quantity (patients) (Q)	Total Annual Cost ($) (100,000 + 100$Q$)	Total Annual Revenue ($) (200$Q$)
0	100,000	0
2,000	300,000	400,000



▲ **FIGURE A.1**
Graphic Approach to Break-Even Analysis



Spiroview Inc/Shutterstock

We can now draw the cost line through points (0, 100,000) and (2,000, 300,000). The revenue line goes between (0, 0) and (2,000, 400,000). As Figure A.1 indicates, these two lines intersect at 1,000 patients, the break-even quantity.

DECISION POINT

Management expects the number of patients needing the new procedure will exceed the 1,000-patient break-even quantity but first wants to learn how sensitive the decision is to demand levels before making a final choice.

EXAMPLE A.2 Sensitivity Analysis of Sales Forecasts

If the most pessimistic sales forecast for the proposed service in Figure A.1 were 1,500 patients, what would be the procedure's total contribution to profit and overhead per year?

SOLUTION

The graph shows that even the pessimistic forecast lies above the break-even volume, which is encouraging. The procedure's total contribution, found by subtracting total costs from total revenues, is

$$pQ - (F + cQ) = 200(1{,}500) - [100{,}000 + 100(1{,}500)]$$
$$= \$50{,}000$$

DECISION POINT

Even with the pessimistic forecast, the new procedure contributes $50,000 per year. After evaluating the proposal with the present value method (see online Supplement F), management added the new procedure to the hospital's services.

Evaluating Processes

Often, choices must be made between two processes or between an internal process and buying services or materials on the outside. In such cases, we assume that the decision does not affect revenues. The manager must study all the costs and advantages of each approach. Rather than find the quantity at which total costs equal total revenues, the analyst finds the quantity for which the total costs for two alternatives are equal. For the make-or-buy decision, it is the quantity for which the total "buy" cost equals the total "make" cost. Let F_b equal the fixed cost (per year) of the buy option, F_m equal the fixed cost of the make option, c_b equal the variable cost (per unit) of the buy option, and c_m equal the variable cost of the make option. Thus, the total cost to buy is $F_b + c_bQ$ and the total cost to make is $F_m + c_mQ$. To find the break-even quantity, we set the two cost functions equal and solve for Q:

$$F_b + c_bQ = F_m + c_mQ$$

$$Q = \frac{F_m - F_b}{c_b - c_m}$$

The make option should be considered, ignoring qualitative factors, only if its variable costs are lower than those of the buy option. The reason is that the fixed costs for making the service or product are typically higher than the fixed costs for buying. Under these circumstances, the buy option is better if production volumes are less than the break-even quantity. Beyond that quantity, the make option becomes better. Chapter 12, "Supply Chain Design," brings out other considerations when making make-or-buy decisions.

EXAMPLE A.3 Break-Even Analysis for Make-or-Buy Decisions

Online Resources

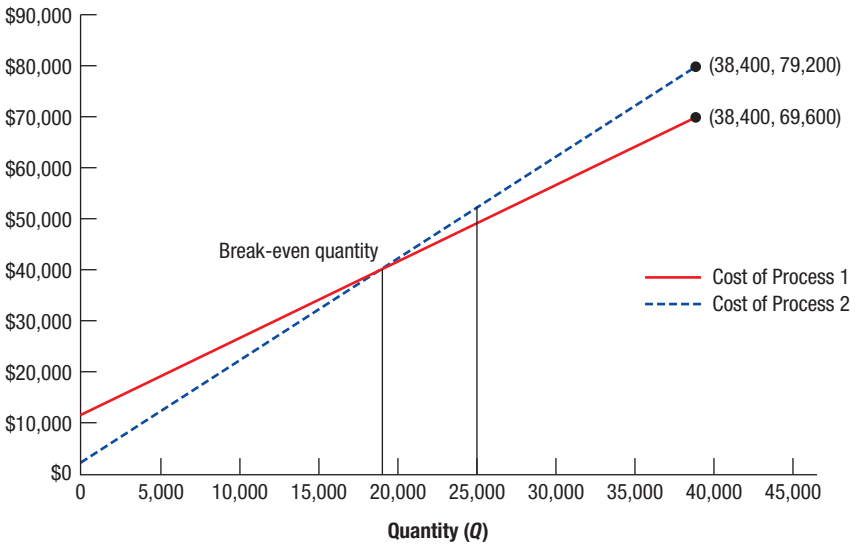
Active Model A.2 provides additional insight on this make-or-buy example and its extensions.

Tutor A.2 in OM Explorer provides a new example to practice break-even analysis on make-or-buy decisions.

The manager of a fast-food restaurant featuring hamburgers is adding salads to the menu. For each of the two new options, the price to the customer will be the same. The make option is to install a salad bar stocked with vegetables, fruits, and toppings and let the customer assemble the salad. The salad bar would have to be leased and a part-time employee hired. The manager estimates the fixed costs at $12,000 and variable costs totaling $1.50 per salad. The buy option is to have preassembled salads available for sale. They would be purchased from a local supplier at $2.00 per salad. Offering preassembled

FIGURE A.2 ▶
Break-Even Analysis Solver of OM Explorer for Example A.3

	Process 1	Process 2
Fixed costs (F)	$12,000	$2,400
Variable costs (c)	$1.50	$2.00
Expected demand	25,000	
Break-even quantity	19,200.0	
Decision: Process 1		



salads would require installation and operation of additional refrigeration, with an annual fixed cost of $2,400. The manager expects to sell 25,000 salads per year.

What is the make-or-buy quantity?

SOLUTION

The formula for the break-even quantity yields the following:

$$Q = \frac{F_m - F_b}{c_b - c_m}$$

$$= \frac{12{,}000 - 2{,}400}{2.0 - 1.5} = 19{,}200 \text{ salads}$$

Figure A.2 shows the solution from OM Explorer's *Break-Even Analysis* Solver. The break-even quantity is 19,200 salads. As the 25,000-salad sales forecast exceeds this amount, the make option is preferred. Only if the restaurant expected to sell fewer than 19,200 salads would the buy option be better.



Ministr-84/Shutterstock

A drive-through only restaurant that does not have seating capacity will have lower fixed costs than a full-service restaurant, and therefore will need a lower number of customers to reach the break-even point.

DECISION POINT

Management chose the make option after considering other qualitative factors, such as customer preferences and demand uncertainty. A deciding factor was that the 25,000-salad sales forecast is well above the 19,200-salad break-even quantity.

Preference Matrix

Decisions often must be made in situations where multiple criteria cannot be naturally merged into a single measure (such as dollars). For example, a manager deciding in which of two cities to locate a new plant would have to consider such unquantifiable factors as quality of life, worker attitudes toward work, and community reception in the two cities. These important factors cannot be ignored. A **preference matrix** is a table that allows the manager to rate an alternative according to several performance criteria. The criteria can be scored on any scale, such as from 1 (worst possible) to 10 (best possible) or from 0 to 1, as long as the same scale is applied to all the alternatives being compared. Each score is weighted according to its perceived importance, with the total of these weights typically equaling 100. The total score is the sum of the weighted scores (weight × score) for all the criteria. The manager can compare the scores for alternatives against one another or against a predetermined threshold. We use the preference matrix technique extensively in this text to address decisions where there are qualitative, as well as quantitative, factors to consider.

preference matrix

A table that allows the manager to rate an alternative according to several performance criteria.

EXAMPLE A.4 Evaluating an Alternative with a Preference Matrix

The following table shows the performance criteria, weights, and scores (1 = worst, 10 = best) for a new product: a thermal storage air conditioner. If management wants to introduce just one new product and the highest total score of any of the other product ideas is 800, should the firm pursue making the air conditioner?

Online Resource

Tutor A.3 in OM Explorer provides a new example to practice with preference matrixes.

Performance Criterion	Weight (*A*)	Score (*B*)	Weighted Score (*A* × *B*)
Market potential	30	8	240
Unit profit margin	20	10	200
Operations compatibility	20	6	120
Competitive advantage	15	10	150
Investment requirement	10	2	20
Project risk	5	4	20
			Weighted score = 750

SOLUTION

Because the sum of the weighted scores is 750, it falls short of the score of 800 for another product. This result is confirmed by the output from OM Explorer's *Preference Matrix* Solver in Figure A.3.

FIGURE A.3 ▶
Preference Matrix Solver for Example A.4

Insert a Criterion | Add a Criterion | Remove a Criterion

	Weight (A)	Score (B)	Weighted Score (A x B)
Market potential	30	8	240
Unit profit margin	20	10	200
Operations compatability	20	6	120
Competitive advantage	15	10	150
Investment requirement	10	2	20
Project risk	5	4	20
		Final Weighted Score	750

DECISION POINT

Management should drop the thermal storage air-conditioner idea. Another new product idea is better, considering the multiple criteria, and that management only wanted to introduce one new product at the time.

Not all managers are comfortable with the preference matrix technique. It requires the manager to state criteria weights before examining the alternatives, although the proper weights may not be readily apparent. Perhaps only after seeing the scores for several alternatives can the manager decide what is important and what is not. Because a low score on one criterion can be compensated for or overridden by high scores on others, the preference matrix method also may cause managers to ignore important signals. In Example A.4, the investment required for the thermal storage air conditioner might exceed the firm's financial capability. In that case, the manager should not even be considering the alternative no matter how high its score.

Decision Theory

decision theory
A general approach to decision making when the outcomes associated with alternatives are often in doubt.

Decision theory is a general approach to decision making when the outcomes associated with alternatives are often in doubt. It helps operations managers with decisions on process, capacity, location, and inventory because such decisions are about an uncertain future. Decision theory can also be used by managers in other functional areas. With decision theory, a manager makes choices using the following process:

1. List the feasible *alternatives*. One alternative that should always be considered as a basis for reference is to do nothing. A basic assumption is that the number of alternatives is finite. For example, in deciding where to locate a new retail store in a certain part of the city, a manager could theoretically consider every grid coordinate on the city's map. Realistically, however, the manager must narrow the number of choices to a reasonable number.
2. List the *events* (sometimes called *chance events* or *states of nature*) that have an impact on the outcome of the choice but are not under the manager's control. For example, the demand experienced by the new facility could be low or high, depending not only on whether the location is convenient to many customers but also on what the competition does and general retail trends. Then, group events into reasonable categories. For example, suppose that the average number of sales per day could be anywhere from 1 to 500. Rather than have 500 events, the manager could represent demand with just three events: 100 sales/day, 300 sales/day, or 500 sales/day. The events must be mutually exclusive and collectively exhaustive, meaning that they do not overlap and that they cover all eventualities.

payoff table
A table that shows the amount for each alternative if each possible event occurs.

3. Calculate the *payoff* for each alternative in each event. Typically, the payoff is total profit or total cost. These payoffs can be entered into a **payoff table**, which shows the amount for each alternative if each possible event occurs. For three alternatives and four events, the table would have 12 payoffs (3×4). If significant distortions will occur if the time value of money is not recognized, the payoffs should be expressed as present values or internal rates of return (see online Supplement F). For multiple criteria with important qualitative factors, use the weighted scores of a preference matrix approach as the payoffs.

4. Estimate the likelihood of each event, using past data, executive opinion, or other forecasting methods. Express it as a *probability*, making sure that the probabilities sum to 1.0. Develop probability estimates from past data if the past is considered a good indicator of the future.
5. Select a *decision rule* to evaluate the alternatives, such as choosing the alternative with the lowest expected cost. The rule chosen depends on the amount of information the manager has on the event probabilities and the manager's attitudes toward risk.

Using this process, we examine decisions under three different situations: certainty, uncertainty, and risk.

Decision Making Under Certainty

The simplest situation is when the manager knows which event will occur. Here the decision rule is to pick the alternative with the best payoff for the known event. The best alternative is the highest payoff if the payoffs are expressed as profits. If the payoffs are expressed as costs, the best alternative is the lowest payoff.

EXAMPLE A.5 Decisions Under Certainty

A manager is deciding whether to build a small or a large facility. Much depends on the future demand that the facility must serve, and demand may be small or large. The manager knows with certainty the payoffs that will result under each alternative, shown in the following payoff table. The payoffs (in $000) are the present values of future revenues minus costs for each alternative in each event.

	POSSIBLE FUTURE DEMAND	
Alternative	**Low**	**High**
Small facility	200	270
Large facility	160	800
Do nothing	0	0

What is the best choice if future demand will be low?



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SOLUTION

In this example, the best choice is the one with the highest payoff. If the manager knows that future demand will be low, the company should build a small facility and enjoy a payoff of $200,000. The larger facility has a payoff of only $160,000. The "do nothing" alternative is dominated by the other alternatives; that is, the outcome of one alternative is no better than the outcome of another alternative for each event. Because the "do nothing" alternative is dominated, the manager does not consider it further.

DECISION POINT

If management really knows future demand, it would build the small facility if demand will be low and the large facility if demand will be high. If demand is uncertain, it should consider other decision rules.

Decision Making Under Uncertainty

Here, we assume that the manager can list the possible events but cannot estimate their probabilities. Perhaps, a lack of prior experience makes it difficult for the firm to estimate probabilities. In such a situation, the manager can use one of four decision rules:

1. ***Maximin.*** Choose the alternative that is the "best of the worst." This rule is for the *pessimist*, who anticipates the "worst case" for each alternative.
2. ***Maximax.*** Choose the alternative that is the "best of the best." This rule is for the *optimist*, who has high expectations and prefers to "go for broke."

3. ***Laplace.*** Choose the alternative with the best *weighted payoff.* To find the weighted payoff, give equal importance (or, alternatively, equal probability) to each event. If there are n events, the importance (or probability) of each is $1/n$, so they add up to 1.0. This rule is for the *realist.*
4. ***Minimax Regret.*** Choose the alternative with the best "worst regret." Calculate a table of regrets (or opportunity losses), in which the rows represent the alternatives and the columns represent the events. A regret is the difference between a given payoff and the best payoff in the same column. For an event, it shows how much is lost by picking an alternative to the one that is best for this event. The regret can be lost profit or increased cost, depending on the situation.

EXAMPLE A.6 Decisions Under Uncertainty

Online Resource

Tutor A.4 in OM Explorer provides a new example to make decisions under uncertainty.

Reconsider the payoff matrix in Example A.5. What is the best alternative for each decision rule?

SOLUTION

a. *Maximin.* An alternative's worst payoff is the *lowest* number in its row of the payoff matrix because the payoffs are profits. The worst payoffs ($000) are

Alternative	Worst Payoff
Small facility	200
Large facility	160

The best of these worst numbers is $200,000, so the pessimist would build a small facility.

b. *Maximax.* An alternative's best payoff ($000) is the *highest* number in its row of the payoff matrix, or

Alternative	Best Payoff
Small facility	270
Large facility	800

The best of these best numbers is $800,000, so the optimist would build a large facility.

c. *Laplace.* With two events, we assign each a probability of 0.5. Thus, the weighted payoffs ($000) are

Alternative	Weighted Payoff
Small facility	0.5(200) + 0.5(270) = **235**
Large facility	0.5(160) + 0.5(800) = **480**

The best of these weighted payoffs is $480,000, so the realist would build a large facility.

d. *Minimax Regret.* If demand turns out to be low, the best alternative is a small facility and its regret is 0 (or 200 − 200). If a large facility is built when demand turns out to be low, the regret is 40 (or 200 − 160).

		REGRET	
Alternative	**Low Demand**	**High Demand**	**Maximum Regret**
Small facility	200 − 200 = **0**	800 − 270 = **530**	**530**
Large facility	200 − 160 = **40**	800 − 800 = **0**	**40**

The column on the right shows the worst regret for each alternative. To minimize the maximum regret, pick a large facility. The biggest regret is associated with having only a small facility and high demand.

DECISION POINT

The pessimist would choose the small facility. The realist, optimist, and manager choosing to minimize the maximum regret would build the large facility.

Decision Making Under Risk

Here we assume that the manager can list the events and estimate their probabilities. The manager has less information than with decision making under certainty, but more information than with decision making under uncertainty. For this intermediate situation, the *expected value* decision rule is widely used (both in practice and in this book). The expected value for an alternative is found by weighting each payoff with its associated probability and then adding the weighted payoff scores. The alternative with the best expected value (highest for profits and lowest for costs) is chosen.

This rule is much like the Laplace decision rule, except that the events are no longer assumed to be equally likely (or equally important). The expected value is what the *average* payoff would be if the decision could be repeated time after time. Of course, the expected value decision rule can result in a bad outcome if the wrong event occurs. However, it gives the best results if applied consistently over a long period of time. The rule should not be used if the manager is inclined to avoid risk.

EXAMPLE A.7 Decisions Under Risk

Reconsider the payoff matrix in Example A.5. For the expected value decision rule, which is the best alternative if the probability of small demand is estimated to be 0.4 and the probability of large demand is estimated to be 0.6?

Online Resource

Tutor A.5 in OM Explorer provides a new example to make decisions under risk.

SOLUTION

The expected value for each alternative is as follows:

Alternative	Expected Value
Small facility	0.4(200) + 0.6(270) = **242**
Large facility	0.4(160) + 0.6(800) = **544**

DECISION POINT

Management would choose a large facility if it used this expected value decision rule because it provides the best long-term results if consistently applied over time.

Decision Trees

The decision tree method is a general approach to a wide range of processes and supply chain decisions, such as product planning, process analysis, process capacity, and location. It is particularly valuable for evaluating different capacity expansion alternatives when demand is uncertain and sequential decisions are involved. For example, a company may expand a facility in 2015 only to discover in 2018 that demand is much higher than forecasted. In that case, a second decision may be necessary to determine whether to expand again or build a second facility.

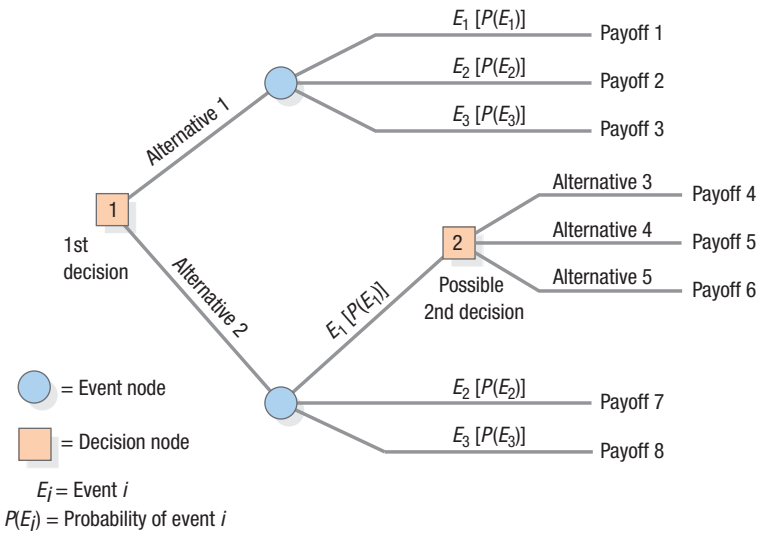
decision tree

A schematic model of alternatives available to the decision maker, along with their possible consequences.

A **decision tree** is a schematic model of alternatives available to the decision maker along with their possible consequences. The name derives from the treelike appearance of the model. It consists of a number of square *nodes*, representing decision points, which are left by *branches* (which should be read from left to right), representing the alternatives. Branches leaving circular, or chance, nodes represent the events. The probability of each chance event, *P(E)*, is shown above each branch. The probabilities for all branches leaving a chance node must sum to 1.0. The conditional payoff, which is the payoff for each possible alternative–event combination, is shown at the end of each combination. Payoffs are given only at the outset, before the analysis begins, for the end points of each alternative–event combination. In Figure A.4, for example, payoff 1 is the financial outcome the manager expects if alternative 1 is chosen and then chance event 1 occurs.

No payoff can be associated yet with any branches farther to the left, such as alternative 1 as a whole because it is followed by a chance event and is not an end point. Payoffs often are expressed as the present value of net profits. If revenues are not affected by the decision, the payoff is expressed as net costs.

▼ **FIGURE A.4**
A Decision Tree Model



After drawing a decision tree, we solve it by working from right to left, calculating the *expected payoff* for each node as follows:

1. For an event node, we multiply the payoff of each event branch by the event's probability. We add these products to get the event node's expected payoff.
2. For a decision node, we pick the alternative that has the best expected payoff. If an alternative leads to an event node, its payoff is equal to that node's expected payoff (already calculated). We "saw off," or "prune," the other branches not chosen by marking two short lines through them. The decision node's expected payoff is the one associated with the single remaining unpruned branch. We continue this process until the leftmost decision node is reached. The unpruned branch extending from it is the best alternative to pursue. If multistage decisions are involved, we must await subsequent events before deciding what to do next. If new probability or payoff estimates are obtained, we repeat the process.

Various software applications are available for drawing decision trees. PowerPoint can be used to draw decision trees, although it does not have the capability to analyze the decision tree. More extensive capabilities, in addition to POM for Windows, are found with SmartDraw (http://www.smartdraw.com), PrecisionTree decision analysis from Palisade Corporation (http://www.palisade.com), and TreePlan (http://www.treeplan.com/treeplan.htm).

EXAMPLE A.8 Analyzing a Decision Tree

Online Resource

Active Model A.3 provides additional insight on this decision tree example and its extensions.

A retailer must decide whether to build a small or a large facility at a new location. Demand at the location can be either low or high, with probabilities estimated to be 0.4 and 0.6, respectively. If a small facility is built and demand proves to be high, the manager may choose not to expand (payoff = $223,000) or to expand (payoff = $270,000). If a small facility is built and demand is low, there is no reason to expand and the payoff is $200,000. If a large facility is built and demand proves to be low, the choice is to do nothing ($40,000) or to stimulate demand through local advertising. The response to advertising may be either modest or sizeable, with their probabilities estimated to be 0.3 and 0.7, respectively. If it is modest, the payoff is estimated to be only $20,000; the payoff grows to $220,000 if the response is sizeable. Finally, if a large facility is built and demand turns out to be high, the payoff is $800,000.



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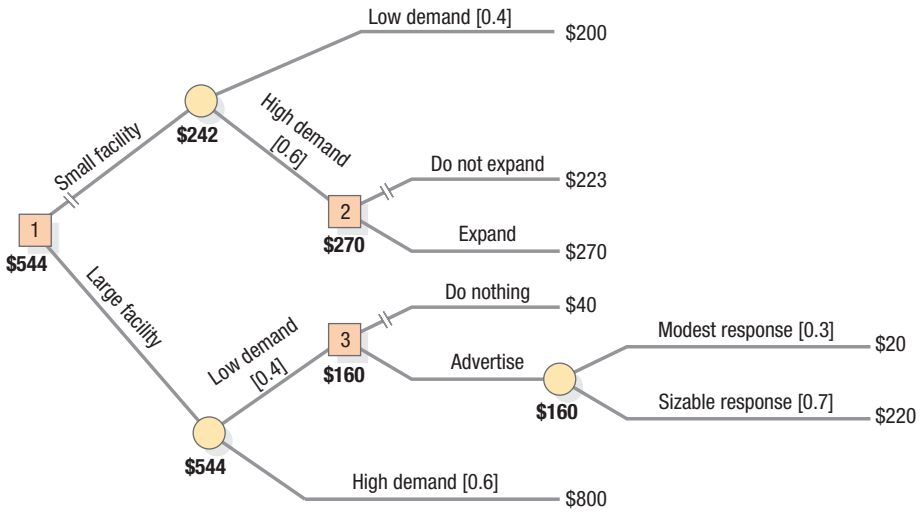
Draw a decision tree. Then analyze it to determine the expected payoff for each decision and event node. Which alternative—building a small facility or building a large facility—has the higher expected payoff?

SOLUTION

The decision tree in Figure A.5 shows the event probability and the payoff for each of the seven alternative-event combinations. The first decision is whether to build a small or a large facility. Its node is shown first, to the left, because it is the decision the retailer must make now. The second decision node—whether to expand at a later date—is reached only if a small facility is built and demand turns out to be high. Finally, the third decision point—whether to advertise—is reached only if the retailer builds a large facility and demand turns out to be low.

Analysis of the decision tree begins with calculation of the expected payoffs from right to left, shown on Figure A.5 beneath the appropriate event and decision nodes.

1. For the event node dealing with advertising, the expected payoff is 160, or the sum of each event's payoff weighted by its probability [0.3(20) + 0.7(220)].
2. The expected payoff for decision node 3 is 160 because *Advertise* (160) is better than *Do nothing* (40). Prune the *Do nothing* alternative.
3. The payoff for decision node 2 is 270 because *Expand* (270) is better than *Do not expand* (223). Prune *Do not expand*.
4. The expected payoff for the event node dealing with demand, assuming that a small facility is built, is 242 [or 0.4(200) + 0.6(270)].



◀ **FIGURE A.5**
Decision Tree for Retailer (in $000)

5. The expected payoff for the event node dealing with demand, assuming that a large facility is built, is 544 [or 0.4(160) + 0.6(800)].
6. The expected payoff for decision node 1 is 544 because the large facility's expected payoff is largest. Prune *Small facility*.

DECISION POINT

The retailer should build the large facility. This initial decision is the only one made now. Subsequent decisions are made after learning whether demand actually is low or high.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
A.1 Explain break-even analysis, using both the graphic and algebraic approaches.	The section "Break-Even Analysis" covers this analysis. Example A.1 and Solved Problem 1 demonstrate both approaches. Example A.3 shows its use in evaluating different processes.	**Active Model Exercises:** A.1: Break-Even Analysis; A.2: Make-or-Buy Decision **OM Explorer Solver:** Break-Even Analysis **OM Explorer Tutors:** A.1: Break-Even Analysis; Evaluating Services and Products; A.2: Break-Even Analysis; Evaluating Processes **POM for Windows:** Break-Even Analysis; Cost-Volume Analysis
A.2 Define and construct a preference matrix.	See the section "Preference Matrix" for making decisions involving unquantifiable factors, where some factors are rated more important than others. Example A.4 and Solved Problem 2 demonstrate the calculations.	**OM Explorer Solver:** Preference Matrix **OM Explorer Tutor:** A3: Preference Matrix **POM for Windows:** Preference Matrix
A.3 Explain how decision theory can be used to make decisions under conditions of certainty, uncertainty, and risk.	The section "Decision Theory" begins with the construction of a payoff table that shows the payoff for each feasible alternative and each event. See the table in Example A.5. In addition, the sections "Decision Making Under Uncertainty" and "Decision Making Under Risk" cover these decision rules for when the outcomes associated with alternatives are in doubt. Examples A.6 and A.7 demonstrate how these rules work and so does Solved Problem 3.	**OM Explorer Solver:** Decision Theory **OM Explorer Tutors:** A.4: Decisions Under Uncertainty; A.5: Decisions Under Risk; A.6: Location Decisions Under Uncertainty **POM for Windows:** Decision Tables
A.4 Describe how to draw and analyze a decision tree.	The section "Decision Trees" shows how to draw and analyze decision trees where several alternatives are available over time. Example A.8 and Solved Problem 4 show how to work back from right to left, pruning as you go, until the best alternative is found for decision node 1.	**Active Model Exercise:** A.3: Decision Tree **POM for Windows:** Decision Trees (graphical)

Key Equations

Break-Even Analysis

1. Break-even quantity: $Q = \dfrac{F}{p - c}$
2. Evaluating processes, make-or-buy indifference quantity: $Q = \dfrac{F_m - F_b}{c_b - c_m}$

Key Terms

break-even analysis 55
break-even quantity 55
decision theory 60
decision tree 63
fixed cost 56
payoff table 60
preference matrix 59
sensitivity analysis 56
variable cost 56

Solved Problem 1

The owner of a small manufacturing business has patented a new device for washing dishes and cleaning dirty kitchen sinks. Before trying to commercialize the device and add it to his or her existing product line, the owner wants reasonable assurance of success. Variable costs are estimated at $7 per unit produced and sold. Fixed costs are about $56,000 per year.

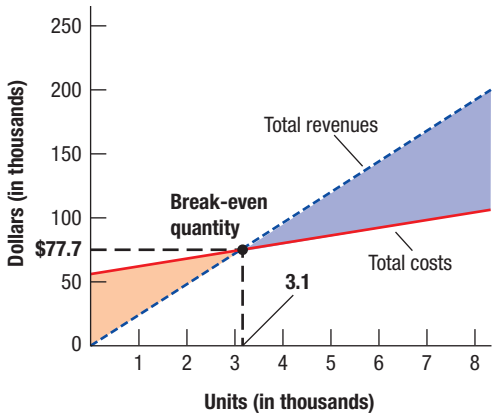
a. If the selling price is set at $25, how many units must be produced and sold to break even? Use both algebraic and graphic approaches.
b. Forecasted sales for the first year are 10,000 units if the price is reduced to $15. With this pricing strategy, what would be the product's total contribution to profits in the first year?

SOLUTION

a. Beginning with the algebraic approach, we get

$$Q = \frac{F}{p - c} = \frac{56{,}000}{25 - 7}$$
$$= \mathbf{3{,}111} \text{ units}$$

FIGURE A.6 ▶



Using the graphic approach, shown in Figure A.6, we first draw two lines:

$$\text{Total revenue} = 25Q$$
$$\text{Total cost} = 56{,}000 + 7Q$$

The two lines intersect at $Q = 3{,}111$ units, the break-even quantity.

b. Total profit contribution = Total revenue − Total cost
$$= pQ - (F + cQ)$$
$$= 15(10{,}000) - [56{,}000 + 7(10{,}000)]$$
$$= \mathbf{\$24{,}000}$$

Solved Problem 2

Herron Company is screening three new product ideas: A, B, and C. Resource constraints allow only one of them to be commercialized. The performance criteria and ratings, on a scale of 1 (worst) to 10 (best), are shown in the following table. The Herron managers give equal weights to the performance criteria. Which is the best alternative, as indicated by the preference matrix method?

	RATING		
Performance Criterion	**Product A**	**Product B**	**Product C**
1. Demand uncertainty and project risk	3	9	2
2. Similarity to present products	7	8	6
3. Expected return on investment (ROI)	10	4	8
4. Compatibility with current manufacturing process	4	7	6
5. Competitive advantage	4	6	5

SOLUTION

Each of the five criteria receives a weight of 1/5 or 0.20.

Product	Calculation	Total Score
A	$(0.20 \times 3) + (0.20 \times 7) + (0.20 \times 10) + (0.20 \times 4) + (0.20 \times 4)$	$= 5.6$
B	$(0 \times 9) + (0.20 \times 8) + (0.20 \times 4) + (0.20 \times 7) + (0.20 \times 6)$	$= \mathbf{6.8}$
C	$(0.20 \times 2) + (0.20 \times 6) + (0.20 \times 8) + (0.20 \times 6) + (0.20 \times 5)$	$= 5.4$

The best choice is Product B. Products A and C are well behind in terms of total weighted score.

Solved Problem 3

Adele Weiss manages the campus flower shop. Flowers must be ordered three days in advance from her supplier in Mexico. Although Valentine's Day is fast approaching, sales are almost entirely last-minute, impulse purchases. Advance sales are so small that Weiss has no way to estimate the probability of low (25 dozen), medium (60 dozen), or high (130 dozen) demand for red roses on the big day. She buys roses for $15 per dozen and sells them for $40 per dozen. Construct a payoff table. Which decision is indicated by each of the following decision criteria?

a. Maximin

b. Maximax

c. Laplace

d. Minimax regret

Online Resource

Tutor A.6 in OM Explorer examines decisions under uncertainty for a location example.

SOLUTION

The payoff table for this problem is

	DEMAND FOR RED ROSES		
Alternative	**Low (25 dozen)**	**Medium (60 dozen)**	**High (130 dozen)**
Order 25 dozen	$625	$625	$625
Order 60 dozen	$100	$1,500	$1,500
Order 130 dozen	($950)	$450	$3,250
Do nothing	$0	$0	$0

a. Under the maximin criteria, Weiss should order **25** dozen, because if demand is low, Weiss's profits are $625, the best of the worst payoffs.

b. Under the maximax criteria, Weiss should order **130** dozen. The greatest possible payoff, $3,250, is associated with the largest order.

c. Under the Laplace criteria, Weiss should order **60** dozen. Equally weighted payoffs for ordering 25, 60, and 130 dozen are about \$625, \$1,033, and \$917, respectively.

d. Under the minimax regret criteria, Weiss should order **130** dozen. The maximum regret of ordering 25 dozen occurs if demand is high: \$3,250 − \$625 = 2,625. The maximum regret of ordering 60 dozen occurs if demand is high: \$3,250 − 1,500 = 1,750. The maximum regret of ordering 130 dozen occurs if demand is low: \$625 − (−\$950) = \$**1,575**.

Solved Problem 4

White Valley Ski Resort is planning the ski lift operation for its new ski resort. Management is trying to determine whether one or two lifts will be necessary; each lift can accommodate 250 people per day. Skiing normally occurs in the 14-week period from December to April, during which the lift will operate 7 days per week. The first lift will operate at 90 percent capacity if economic conditions are bad, the probability of which is believed to be about a 0.3. During normal times the first lift will be utilized at 100 percent capacity, and the excess crowd will provide 50 percent utilization of the second lift. The probability of normal times is 0.5. Finally, if times are really good, the probability of which is 0.2, the utilization of the second lift will increase to 90 percent. The equivalent annual cost of installing a new lift, recognizing the time value of money and the lift's economic life, is \$50,000. The annual cost of installing two lifts is only \$90,000 if both are purchased at the same time. If used at all, each lift costs \$200,000 to operate, no matter how low or high its utilization rate. Lift tickets cost \$20 per customer per day.

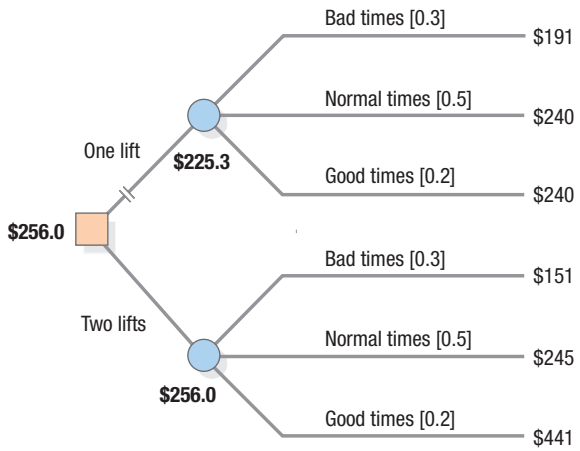
Should the resort purchase one lift or two?

SOLUTION

The decision tree is shown in Figure A.7. The payoff (\$000) for each alternative-event branch is shown in the following table. The total revenues from one lift operating at 100 percent capacity are \$**490,000** (or 250 customers × 98 days × \$20/customer-day).

Alternative	Economic Condition	Payoff Calculation (Revenue – Cost)
One lift	Bad times	0.9(490) − (50 + 200) = 191
	Normal times	1.0(490) − (50 + 200) = 240
	Good times	1.0(490) − (50 + 200) = 240
Two lifts	Bad times	0.9(490) − (90 + 200) = 151
	Normal times	1.5(490) − (90 + 400) = 245
	Good times	1.9(490) − (90 + 400) = 441

FIGURE A.7 ▶



Problems

The OM Explorer, POM for Windows, and Active Model software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations.

Break-Even Analysis

1. Mary Williams, owner of Williams Products, is evaluating whether to introduce a new product line. After thinking through the production process and the costs of raw materials and new equipment, Williams estimates the variable costs of each unit produced and sold at $6 and the fixed costs per year at $60,000.
   a. If the selling price is set at $18 each, how many units must be produced and sold for Williams to break even? Use both graphic and algebraic approaches to get your answer.
   b. Williams forecasts sales of 10,000 units for the first year if the selling price is set at $14 each. What would be the total contribution to profits from this new product during the first year?
   c. If the selling price is set at $12.50, Williams forecasts that first-year sales would increase to 15,000 units. Which pricing strategy ($14.00 or $12.50) would result in the greater total contribution to profits?
   d. What other considerations would be crucial to the final decision about making and marketing the new product?
2. A product at the Jennings Company enjoyed reasonable sales volumes, but its contributions to profits were disappointing. Last year, 17,500 units were produced and sold. The selling price is $22 per unit, the variable cost is $18 per unit, and the fixed cost is $80,000.
   a. What is the break-even quantity for this product? Use both graphic and algebraic approaches to get your answer.
   b. If sales were not expected to increase, by how much would Jennings have to reduce its variable cost to break even?
   c. Jennings believes that a $1 reduction in price will increase sales by 50 percent. Is this enough for Jennings to break even? If not, by how much would sales have to increase?
   d. Jennings is considering ways to either stimulate sales volume or decrease variable cost. Management believes that either sales can be increased by 30 percent or that variable cost can be reduced to 85 percent of its current level. Which alternative leads to higher contributions to profits, assuming that each is equally costly to implement? (*Hint:* Calculate profits for both alternatives and identify the one having the greatest profits.)
   e. What is the percent change in the per-unit profit contribution generated by each alternative in part (d)?
3. An interactive television service that costs $10 per *month* to provide can be sold on the information highway for $15 per client per *month*. If a service area includes a potential of 15,000 customers, what is the most a company could spend on *annual* fixed costs to acquire and maintain the equipment?
4. A restaurant is considering adding fresh brook trout to its menu. Customers would have the choice of catching their own trout from a simulated mountain stream or simply asking the waiter to net the trout for them. Operating the stream would require $10,600 in fixed costs per year. Variable costs are estimated to be $6.70 per trout. The firm wants to break even if 800 trout dinners are sold per year. What should be the price of the new item?
5. Spartan Castings must implement a manufacturing process that reduces the amount of particulates emitted into the atmosphere. Two processes have been identified that provide the same level of particulate reduction. The first process is expected to incur $350,000 of fixed cost and add $50 of variable cost to each casting Spartan produces. The second process has fixed costs of $150,000 and adds $90 of variable cost per casting.
   a. What is the break-even quantity beyond which the first process is more attractive?
   b. What is the difference in total cost if the quantity produced is 10,000?
6. A news clipping service is considering modernization. Rather than manually clipping and photocopying articles of interest and mailing them to its clients, employees electronically input stories from most widely circulated publications into a database. Each new issue is searched for key words, such as a client's company name, competitors' names, type of business, and the company's products, services, and officers. When matches occur, affected clients are instantly notified via an online network. If the story is of interest, it is electronically transmitted, so the client often has the story and can prepare comments for follow-up interviews before the publication hits the street. The manual process has fixed costs of $400,000 per year and variable costs of $6.20 per clipping mailed. The price charged the client is $8.00 per clipping. The computerized process has fixed costs of $1,300,000 per year and variable costs of $2.25 per story electronically transmitted to the client.
   a. If the same price is charged for either process, what is the annual volume beyond which the automated process is more attractive?
   b. The present volume of business is 225,000 clippings per year. Many of the clippings sent with the current process are not of interest to the client or are multiple copies of the same story appearing in several publications. The news clipping service believes that by improving service and by lowering the price to $4.00 per story, modernization will increase volume to 900,000 stories transmitted per year. Should the clipping service modernize?
   c. If the forecasted increase in business is too optimistic, at what volume will the new process (with the $4.00 price) break even?
7. Hahn Manufacturing purchases a key component of one of its products from a local supplier. The current purchase price is $1,500 per unit. Efforts to standardize parts succeeded to the point that this same component can now be used in five different products. Annual component usage should increase from 150 to 750 units. Management wonders whether it is time to make the component in-house rather than to continue buying it from the supplier. Fixed costs would increase by about $40,000 per year for the new equipment and tooling needed. The cost of raw materials and variable overhead would be about $1,100 per unit, and labor costs would be $300 per unit produced.
   a. Should Hahn make rather than buy?
   b. What is the break-even quantity?
   c. What other considerations might be important?
8. Techno Corporation is currently manufacturing an item at variable costs of $5 per unit. Annual fixed costs of manufacturing this item are $140,000. The current

selling price of the item is $10 per unit, and the annual sales volume is 30,000 units.

a. Techno can substantially improve the item's quality by installing new equipment at additional annual fixed costs of $60,000. Variable costs per unit would increase by $1, but, as more of the better-quality product could be sold, the annual volume would increase to 50,000 units. Should Techno buy the new equipment and maintain the current price of the item? Why or why not?

b. Alternatively, Techno could increase the selling price to $11 per unit. However, the annual sales volume would be limited to 45,000 units. Should Techno buy the new equipment and raise the price of the item? Why or why not?

9. The Tri-County Generation and Transmission Association is a nonprofit cooperative organization that provides electrical service to rural customers. Based on a faulty long-range demand forecast, Tri-County overbuilt its generation and distribution system. Tri-County now has much more capacity than it needs to serve its customers. Fixed costs, mostly debt service on investment in plant and equipment, are $82.5 million per year. Variable costs, mostly fossil fuel costs, are $25 per megawatt-hour (MWh, or million watts of power used for 1 hour). The new person in charge of demand forecasting prepared a short-range forecast for use in next year's budgeting process. That forecast calls for Tri-County customers to consume 1 million MWh of energy next year.

a. How much will Tri-County need to charge its customers per MWh to break even next year?

b. The Tri-County customers balk at that price and conserve electrical energy. Only 95 percent of forecasted demand materializes. What is the resulting surplus or loss for this nonprofit organization?

10. Earthquake, drought, fire, economic famine, flood, and a pestilence of TV court reporters have caused an exodus from the City of Angels to Boulder, Colorado. The sudden increase in demand is straining the capacity of Boulder's electrical system. Boulder's alternatives have been reduced to buying 150,000 MWh of electric power from Tri-County G&T at a price of $75 per MWh, or refurbishing and recommissioning the abandoned Pearl Street Power Station in downtown Boulder. Fixed costs of that project are $10 million per year, and variable costs would be $35 per MWh. Should Boulder build or buy?

11. Tri-County G&T sells 150,000 MWh per year of electrical power to Boulder at $75 per MWh, has fixed costs of $82.5 million per year, and has variable costs of $25 per MWh. If Tri-County has 1,000,000 MWh of demand from its customers (other than Boulder), what will Tri-County have to charge to break even?

Preference Matrix

12. The Forsite Company is screening three ideas for new services. Resource constraints allow only one idea to be commercialized at the present time. The following estimates have been made for the five performance criteria that management believes to be most important:

	RATING		
Performance Criterion	**Service A**	**Service B**	**Service C**
Capital equipment investment required	0.6	0.8	0.3
Expected return on investment (ROI)	0.7	0.3	0.9
Compatibility with current workforce skills	0.4	0.7	0.5
Competitive advantage	1.0	0.4	0.6
Compatibility with EPA requirements	0.2	1.0	0.5

a. Calculate a total weighted score for each alternative. Use a preference matrix and assume equal weights for each performance criterion. Which alternative is best? Worst?

b. Suppose that the expected ROI is given twice the weight assigned to each of the remaining criteria. (The sum of weights should remain the same as in part [a].) Does this modification affect the ranking of the three potential services?

13. You are in charge of analyzing five new suppliers of an important raw material and have been given the information shown in the table (1 = worst, 10 = best). Management has decided that criteria 2 and 3 are equally important and that criteria 1 and 4 are each four times as important as criterion 2. No more than two new suppliers are required, but each new vendor must exceed a total score of 70 percent of the maximum total points to be considered.

	RATING				
Performance Criterion	**Vendor A**	**Vendor B**	**Vendor C**	**Vendor D**	**Vendor E**
Quality of raw material	8	7	3	6	9
Environmental impact	3	8	4	7	7
Responsiveness to order changes	9	5	7	6	5
Cost of raw material	7	6	9	2	7

a. Which new vendors do you recommend?

b. Would your decision change if the criteria were considered equally important?

14. Accel Express, Inc., collected the following information on where to locate a warehouse (1 = poor, 10 = excellent):

		LOCATION SCORE	
Location Factor	**Factor Weight**	**A**	**B**
Construction costs	10	8	5
Utilities available	10	7	7
Business services	10	4	7
Real estate cost	20	7	4
Quality of life	20	4	8
Transportation	30	7	6

a. Which location, A or B, should be chosen on the basis of the total weighted score?

b. If the factors were weighted equally, would the choice change?

15. Janice Gould of Krebs Consulting is in the process of making a recommendation to a client regarding the corporate-wide purchase of an analytical software platform. She has made the following estimates on management's most important performance criteria and has rated three software packages across these criteria.

		RATING		
Performance Criterion	**Factor Weight**	**Software A**	**Software B**	**Software C**
Functionality	25	9	8	9
Vendor reliability	10	7	5	9
Compatibility with current systems	20	6	8	6
Maintenance and support	10	5	5	8
Total cost	25	4	8	5
Speed of implementation	10	8	4	7

a. Which software platform would you recommend?

b. Assume that the client has a change of mind and now argues that the maintenance and support criterion is already accounted for by the total cost criterion. Further, the client asks Ms. Gould to drop maintenance and support and add its factor weight to total cost. Will this client request alter the recommendation?

Decision Theory

16. Build-Rite Construction has received favorable publicity from guest appearances on a public TV home improvement program. Public TV programming decisions seem to be unpredictable, so Build-Rite cannot estimate the probability of continued benefits from its relationship with the show. Demand for home improvements next year may be either low or high. But Build-Rite must decide now whether to hire more employees, do nothing, or develop subcontracts with other home improvement contractors. Build-Rite has developed the following payoff table:

	DEMAND FOR HOME IMPROVEMENTS		
Alternative	**Low**	**Moderate**	**High**
Hire	($250,000)	$100,000	$625,000
Subcontract	$100,000	$150,000	$415,000
Do nothing	$50,000	$80,000	$300,000

Which alternative is best, according to each of the following decision criteria?

a. Maximin

b. Maximax

c. Laplace

d. Minimax regret

17. Robert Ragsdale is trying to decide if he should purchase repair and replacement insurance on a new laptop computer that he is planning to purchase. The policy costs $400.00 at the time of purchase, and over the next 3 years will replace the laptop if it is stolen or repair it if it is broken. The following table contains the total costs of this decision.

Alternative	**Computer Is Stolen**	**Computer Breaks**	**Computer Neither Breaks Nor Is Stolen**
Buy the Insurance	$2,900.00	$2,900.00	$2,900.00
Do Not Buy the Insurance	$5,000.00	$3,100.00	$2,500.00

Which alternative is best, according to each of the following decision criteria?

a. Maximin

b. Maximax

c. Laplace

d. Minimax regret

18. Benjamin Moses, chief engineer of Offshore Chemicals, Inc., must decide whether to build a new processing facility based on an experimental technology. If the new facility works, the company will realize a net profit of $20 million. If the new facility fails, the company will lose $10 million. Benjamin's best guess is that there is a 40 percent chance that the new facility will work.

What decision should Benjamin Moses make?

19. A manager is trying to decide whether to build a small, medium, or large facility. Demand can be low, average, or high, with the estimated probabilities being 0.25, 0.40, and 0.35, respectively.

A small facility is expected to earn an after-tax net present value of just $18,000 if demand is low. If demand is average, the small facility is expected to earn $75,000; it can be increased to medium size to earn a net present value of $60,000. If demand is high, the small facility is expected to earn $75,000 and can be expanded to medium size to earn $60,000 or to large size to earn $125,000.

A medium-sized facility is expected to lose an estimated $25,000 if demand is low and earn $140,000 if demand is average. If demand is high, the medium-sized facility is expected to earn a net present value of $150,000; it can be expanded to a large size for a net payoff of $145,000.

If a large facility is built and demand is high, earnings are expected to be $220,000. If demand is average for the large facility, the present value is expected to be $125,000; if demand is low, the facility is expected to lose $60,000.

Which alternative is best, according to each of the following decision criterion?

a. Maximin

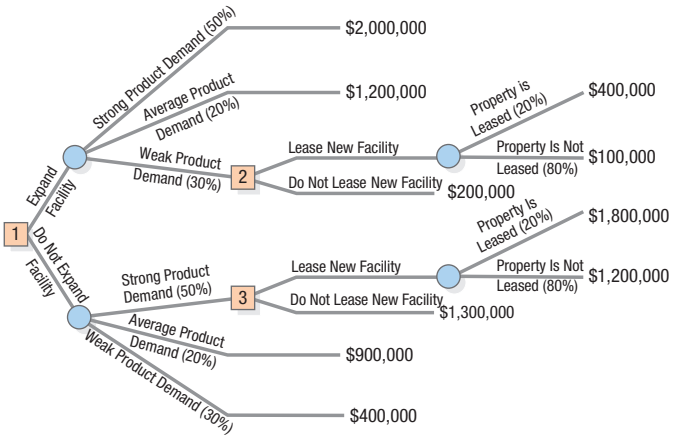
b. Maximax

c. Minimax regret

Decision Trees

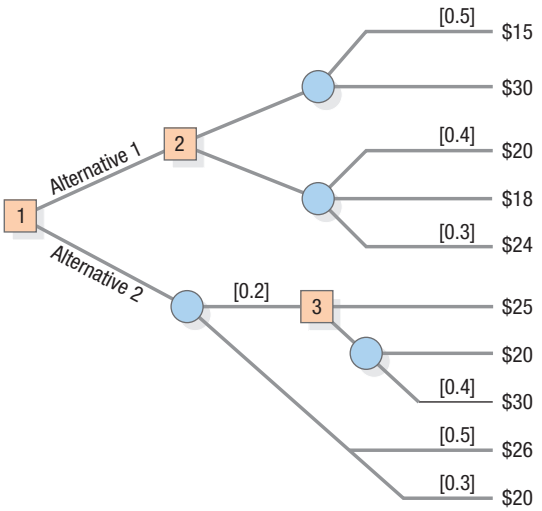
20. Draw a decision tree for the three options described in Problem 19. What should management do to achieve the highest expected payoff?

21. The owner of Pearl Automotive Dealers is trying to decide whether to expand his current facility. If he expands and customer demand turns weak, there is a chance he could lease part of his newly constructed facility to another dealer. If he doesn't expand and strong demand occurs, he could attempt to lease another facility across town. Analyze the decision tree in Figure A.8. What is the best set of decisions and the expected payoff?



▲ FIGURE A.8

22. Analyze the decision tree in Figure A.9. What is the expected payoff for the best alternative? First, be sure to infer the missing probabilities.



▲ FIGURE A.9

23. A manager is trying to decide whether to buy one machine or two. If only one is purchased and demand proves to be excessive, the second machine can be purchased later. Some sales will be lost, however, because the lead time for producing this type of machine is 6 months. In addition, the cost per machine will be lower if both are purchased at the same time. The probability of low demand is estimated to be 0.20. The after-tax net present value of the benefits from purchasing the two machines together is $90,000 if demand is low and $180,000 if demand is high.

If one machine is purchased and demand is low, the net present value is $120,000. If demand is high, the manager has three options. Doing nothing has a net present value of $120,000; subcontracting, $160,000; and buying the second machine, $140,000.

a. Draw a decision tree for this problem.

b. How many machines should the company buy initially? What is the expected payoff for this alternative?

24. A manufacturing plant has reached full capacity. The company must build a second plant—either small or large—at a nearby location. The demand is likely to be high or low. The probability of low demand is 0.3. If demand is low, the large plant has a present value of $5 million and the small plant, a present value of $8 million. If demand is high, the large plant pays off with a present value of $18 million, and the small plant with a present value of only $10 million. However, the small plant can be expanded later if demand proves to be high for a present value of $14 million.

a. Draw a decision tree for this problem.

b. What should management do to achieve the highest expected payoff?

2

PROCESS STRATEGY AND ANALYSIS

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

2.1 Understand the process structure in services and how to position a service process on the customer-contact matrix.

2.2 Understand the process structure in manufacturing and how to position a manufacturing process on the product-process matrix.

2.3 Explain the major process strategy decisions and their implications for operations.

2.4 Discuss how process decisions should strategically fit together.

2.5 Compare and contrast the two commonly used strategies for change, and understand a systematic way to analyze and improve processes.

2.6 Discuss how to define, measure, and analyze processes.

2.7 Identify the commonly used approaches for effectively improving and controlling processes.

CVS Pharmacy



Roman Tiraspolsky/Shutterstock

People walk by a CVS pharmacy on 3rd Avenue in Manhattan.

CVS Pharmacy is the largest pharmacy chain in the United States, with over 9,600 locations and 2015 revenues exceeding US$150 billion. Owned by CVS Health, it was originally opened as the Consumer Value Store (CVS) in Lowell, Massachusetts, in 1963. By 2002, CVS had become one of America's largest retail drugstores. While it sells a wide

assortment of merchandise including cosmetic products, greeting cards, and convenience foods among others, over two-thirds of its revenue is generated by the pharmacies. CVS also operates 1,100 MinuteClinic medical clinics and Diabetes Care Centers, which are staffed by nurse practitioners and physician assistants specializing in family health care. In response to the pandemic crisis in 2020, CVS Health partnered with the state of New York and also ramped up its testing capacity across the United States to nearly 1.5 million COVID-19 tests per month.

Despite a rapid growth and expansion in business, customer satisfaction in the pharmacies was declining because of increasing service failures in its order fulfillment process. This was an important issue because it increased the waiting time for customers and stressed employees working at the pickup stations. CVS deployed a task force team to identify the root causes behind the poor service and develop a set of process improvement strategies. The team found out that because they were not tracking the refill limits in the information system, customers would not find out whether they would get their refills until their next pickup visit. In addition, the drug utilization review system—which alerts potential threats arising from using the wrong drug or over-prescription and halts the order fulfillment based on the patient's medication records and possible drug interactions that might take place—did not function flawlessly. While pharmacists were capable of resolving 90 percent of these problem cases through a follow-up review, the remaining 10 percent of the alerts required contacting a doctor, which would delay the prescription fulfillment. The automated insurance checking system also caused problems. When customers changed their insurers or jobs, or if there were typos in the script, the employee would have to contact the customer, insurer, or sometimes even the doctor to verify the information. CVS would still fill the prescription even when the insurance issue had not been resolved; however, the customer had to pay full price at the time of pickup. In addition to process failures and congestions within the store, there were also other factors that led to frustration at the customers' end. For example, patients living with complex illnesses such as rheumatoid arthritis often faced difficulties in getting their medications via in-store visits. Walking into the store was not a pleasant experience for these patients, and to make matters worse, the pharmacy often did not have the required specialty drugs in storage.

After a thorough assessment, CVS implemented a number of changes to the existing process. Issues with the existing in-store order fulfillment process were addressed by reorganizing process flows. For example, CVS moved the data entry process to the beginning of order drop-off to make sure that all the information is acquired while the customer is still present. Next, CVS bundled all quality-related processes together into a quality assurance step to ensure that the pharmacists focused on the customers' safety and getting the correct drug at the right dosage into the packaging. This step also included the drug utilization review. CVS also implemented visualization technology to enhance visibility of the current orders and pending tasks. An online "virtual queue" allowed workers at the pharmacy station to prioritize their work and focus their efforts on tasks that were congesting the waiting line. Finally, CVS launched an initiative called "Specialty Connect" to provide simpler ordering and delivery options to specialty

drug customers. Through this program, customers can place orders online to skip the line, or have medications delivered by mail. Patients could also consult a centralized group of clinical and insurance experts for assistance.

Implementing these process changes was not an easy task. CVS had to present the results of the task force team study, including interviews, analyses, observations, and videos, to the pharmacy supervisors to persuade them to adopt the recommendations. Diffusion of best practices relied on a network of pharmacy supervisors who would travel around their districts and initiate improvement projects. As a result, the customer satisfaction on waiting times improved and the overall satisfaction was greatly enhanced. This improvement in customer satisfaction resulted in increased pharmacy contributions to revenue and decreased customer complaints. Also, since its launch, Specialty Connect has served approximately 75,000 patients, with 97 percent reporting satisfaction with the program. Understanding and improving their core customer-facing service processes paid big dividends for CVS.[1]

In Chapter 1, we learned how firms create value by properly aligning their operations strategy with the competitive priorities and capabilities that they emphasize in the marketplace. In Part 1 of the book, we focus on managing internal processes of the firm, including the design and analysis of these processes (Chapter 2, "Process Strategy and Analysis"), measurement of process quality (Chapter 3, "Quality and Performance"), understanding how elimination of waste can make processes more lean and efficient (Chapter 4, "Lean Systems"), management of process capacity and its constraints within different types of organizations (Chapter 5 "Capacity Planning," and Chapter 6, Constraint Management," respectively), and managing projects (Chapter 7, "Project Management").

Processes involve the use of an organization's resources to provide something of value and are perhaps the least understood and managed aspect of a business. No service can be provided and no product can be made without a process, and no process can exist without at least one service or product. Even with talented and motivated people, a firm cannot gain competitive advantage with faulty processes. Process decisions as such are strategic in nature. As we saw in Chapter 1, they should further a company's long-term competitive goals. In making process decisions, managers focus on controlling such competitive priorities as quality, flexibility, time, and cost. As exemplified by CVS Pharmacy, process management is an ongoing activity, with the same principles applying to both first-time and redesign choices. Many different choices are available in selecting human resources, equipment, outsourced services, materials, work flows, and methods that transform inputs into outputs. Another choice is which processes are to be done in-house and which processes are to be outsourced—that is, done outside the firm and purchased as materials and services. This decision helps to define the supply chain, and is covered more fully in subsequent chapters.

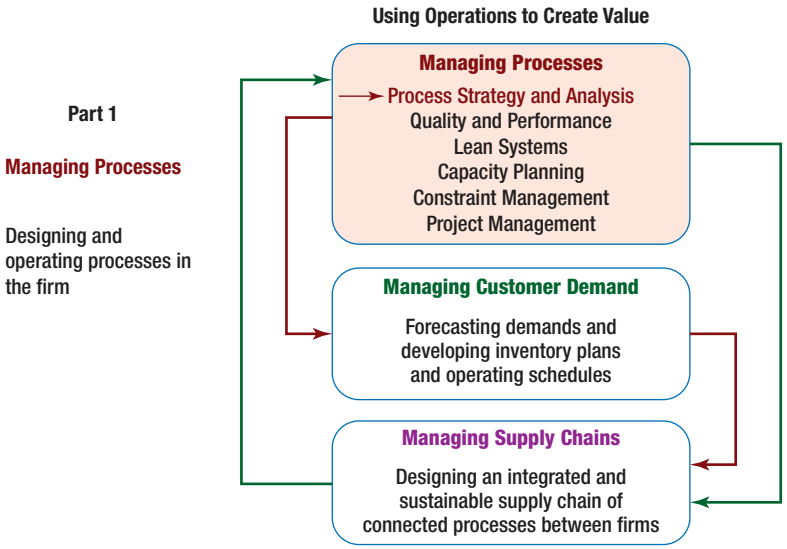
In this chapter, we focus on **process strategy**, which specifies the pattern of decisions made in managing processes so that the processes will achieve their competitive priorities, as well as **process analysis**, which is the documentation and detailed understanding of how work is performed

process strategy

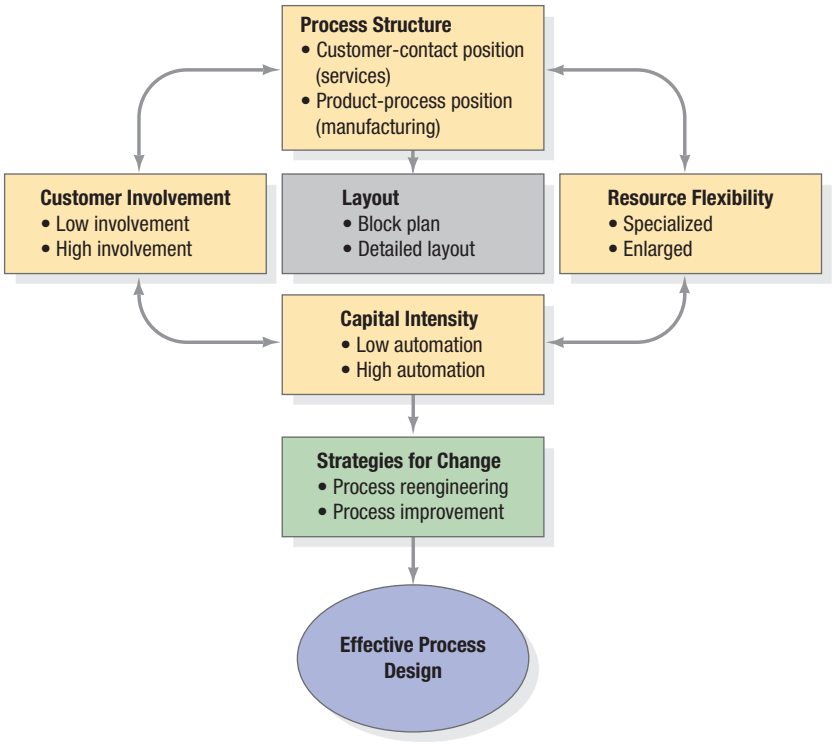
The pattern of decisions made in managing processes so that they will achieve their competitive priorities.

process analysis

The documentation and detailed understanding of how work is performed and how it can be redesigned.



[1] *Sources:* A. F. McAfee, "Pharmacy Service Improvement at CVS," *Harvard Business School* (2006); C. Cramer, "CVS Caremark Hosts Grand Opening of State-of-the-Art Mail Service Pharmacy and Customer Center," *Dow Jones Newswires* (2013); K. Sheridan, "CVS Revamps to Meet Specialty Medicine Needs," *InformationWeek* (2015); https://en.wikipedia.org/wiki/CVS_Pharmacy (August 3, 2020).



▲ **FIGURE 2.1**
Major Decisions for Effective Processes

and how it can be redesigned. Process decisions directly affect the process itself and indirectly the services and the products that it provides. All parts of an organization, as well as external suppliers and customers across the supply chain, need to be involved to ensure that processes are providing the most value to their internal and external customers.

Process strategy guides a variety of process decisions, and in turn is guided by operations strategy and the organization's ability to obtain the resources necessary to support them. We begin by defining four basic process decisions: (1) process structure, (2) customer involvement, (3) resource flexibility, and (4) capital intensity. We discuss these decisions for both service and manufacturing processes. We pay particular attention to ways in which these decisions fit together, depending on factors such as competitive priorities, customer contact, and volume, which in turn lead to two basic change strategies for analyzing and modifying processes: (1) process reengineering and (2) process improvement. Both these approaches need process analysis to identify and implement changes.

Three principles concerning process strategy are particularly important:

1. The key to successful process decisions is to make choices that fit the situation and that make sense together. They should not work at cross purposes, with one process optimized at the expense of other processes. A more effective process is one that matches key process characteristics and has a close *strategic fit*.
2. Although this section of the text focuses on individual processes, they are the building blocks that eventually create the firm's whole supply chain. The cumulative effect on customer satisfaction and competitive advantage is huge.
3. Whether processes in the supply chain are performed internally or by outside suppliers and customers, management must pay particular attention to the interfaces between processes. Dealing with these interfaces underscores the need for cross-functional coordination.

Whether dealing with processes for offices, service providers, or manufacturers, operations managers must consider four common process decisions. Figure 2.1 shows that they are all important steps toward an effective process design. These four decisions are best understood at the process or subprocess level rather than at the firm level.

process structure
The process type relative to the kinds of resources needed, how resources are partitioned between them, and their key characteristics.

layout
The physical arrangement of operations (or departments) relative to each other.

customer involvement
The ways in which customers become part of the process and the extent of their participation.

resource flexibility
The ease with which employees and equipment can handle a wide variety of products, output levels, duties, and functions.

capital intensity
The mix of equipment and human skills in a process.

- **Process structure** determines the process type relative to the kinds of resources needed, how resources are partitioned between them, and their key characteristics. A **layout** is the physical arrangement of operations (or departments) relative to each other.
- **Customer involvement** reflects the ways in which customers become part of the process and the extent of their participation.
- **Resource flexibility** is the ease with which employees and equipment can handle a wide variety of products, output levels, duties, and functions.
- **Capital intensity** is the mix of equipment and human skills in a process. The greater the cost of equipment relative to the cost of labor, the greater is the capital intensity.

The concepts that we develop around these four decisions establish a framework within which we can address the appropriate process design in every situation. We establish the patterns of choices that create a good fit between the four decisions. For example, if you walk through a manufacturing facility where materials flow smoothly from one workstation to the next (which we will define later to be a *line* process), you would be tempted to conclude that all processes should be line processes. They seem so efficient and organized. However, converting to a line process would be a big mistake if volumes are low and the products made are customized. Resources must be more flexible to handle a variety of products in such a situation. The result is a more disorganized appearance with jobs crisscrossing in many different directions depending on the product being made. Despite appearances, this process is the best choice.

Process Structure in Services

One of the first decisions a manager makes in designing a well-functioning process is to choose a process type that best achieves the competitive priorities for that process. Strategies for designing processes can be quite different, depending on whether a service is being provided or a product is being manufactured. We begin with service processes, given their huge implication for workforce resources in industrialized countries.

A process strategy that gets customers in and out of a fast-food restaurant quickly would not be the right process strategy for a five-star restaurant, where customers seek a leisurely dining experience. To gain insights, we must start at the process level and recognize key contextual variables associated with the process. A good process strategy for a service process depends first and foremost on the type and amount of customer contact. **Customer contact** is the extent to which the customer is present, is actively involved, and receives personal attention during the service process. Face-to-face interaction, sometimes called a *moment of truth* or *service encounter*, brings the customer and service providers together. At that time, customer attitudes about the quality of the service provided are shaped. Table 2.1 shows several dimensions of customer contact. Many levels are possible on each of the five dimensions. Also, some parts of a process can have low contact and other parts of a process can have high contact.

customer contact

The extent to which the customer is present, is actively involved, and receives personal attention during the service process.

TABLE 2.1 | DIMENSIONS OF CUSTOMER CONTACT IN SERVICE PROCESSES

Dimension	High Contact	Low Contact
Physical presence	Present	Absent
What is processed	People	Possessions or information
Contact intensity	Active, visible	Passive, out of sight
Personal attention	Personal	Impersonal
Method of delivery	Face to face	Regular mail or email

Customer-Contact Matrix

The customer-contact matrix, shown in Figure 2.2, brings together three elements: (1) the degree of customer contact, (2) customization, and (3) process characteristics. The matrix is the starting point for evaluating and improving a process.

Customer Contact and Customization The horizontal dimension of the matrix represents the service provided to the customer in terms of customer contact and competitive priorities. A key competitive priority is how much customization is needed. Positions on the left side of the matrix represent high customer contact and highly customized services. The customer is more likely to be present and active. The process is more likely to be visible to the customer, who receives more personal attention. The right side of the matrix represents low customer contact, passive involvement, less personalized attention, and a process out of the customer's sight.

Process Divergence and Flow The vertical dimension of the customer-contact matrix deals with two characteristics of the process itself: (1) process divergence and (2) flow. Each process can be analyzed on these two dimensions.

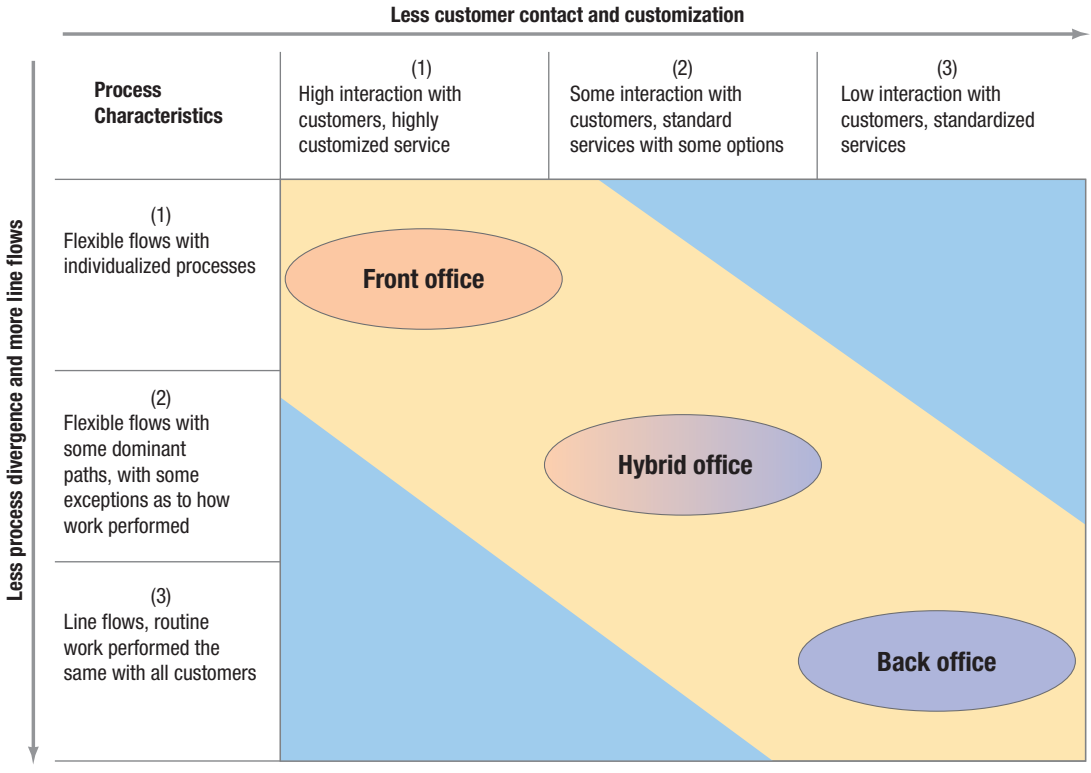


FIGURE 2.2
Customer-Contact Matrix for Service Processes

process divergence
The extent to which the process is highly customized with considerable latitude as to how its tasks are performed.

flexible flow
The customers, materials, or information moves in diverse ways, with the path of one customer or job often crisscrossing the path that the next one takes.

line flow
The customers, materials, or information moves linearly from one operation to the next, according to a fixed sequence.

front office
A process with high customer contact where the service provider interacts directly with the internal or external customer.

hybrid office
A process with moderate levels of customer contact and standard services with some options available.

back office
A process with low customer contact and little service customization.

Process divergence is the extent to which the process is highly customized with considerable latitude as to how its tasks are performed. If the process changes with each customer, virtually every performance of the service is unique. Examples of highly divergent service processes where many steps in them change with each customer are found in consulting, law, and architecture. A service with low divergence, in contrast, is repetitive and standardized. The work is performed exactly the same with all customers and tends to be less complex. Certain hotel services and telephone services are highly standardized to ensure uniformity.

When divergence is considerable, the work flow tends to be more flexible. A **flexible flow** means that the customers, materials, or information moves in diverse ways, with the path of one customer or job often crisscrossing the path that the next one takes. Each one can follow a carefully preplanned path, even though the first impression is one of disorganized, jumbled flows. Such an appearance goes naturally with high process divergence. A **line flow** means that the customers, materials, or information moves linearly from one operation to the next, according to a fixed sequence. When diversity is low and the process standardized, line flows are a natural consequence.

Service Process Structuring

Figure 2.2 shows several desirable positions in the matrix that effectively connect the service product with the process. The manager has three process structures, which form a continuum, to choose from: (1) front office, (2) hybrid office, and (3) back office. It is unlikely that a process can be a top performer if a process lies too far from one of these diagonal positions, occupying instead one of the extreme positions represented by the light blue triangles in the matrix (refer to Figure 2.2). Such positions represent too much of a disconnect between the service provided and process characteristics.

Front Office A **front-office** process has high customer contact where the service provider interacts directly with the internal or external customer. Because of the customization of the service and variety of service options, many of the steps in it have considerable divergence. Work flows are flexible, and they vary from one customer to the next. The high-contact service process tends to be adapted or tailored to each customer.

Hybrid Office A hybrid office tends to be in the middle of the five dimensions in Table 2.1, or perhaps high on some contact measures and low on others. A **hybrid-office** process has moderate levels of customer contact and standard services, with some options available from which the customer chooses. The work flow progresses from one workstation to the next, with some dominant paths apparent.

Back Office A **back-office** process has low customer contact and little service customization. The work is standardized and routine, with line flows from one service provider to the next until the service is completed. Preparing the monthly client fund balance reports in the financial services industry is a good example. It has low customer contact, low divergence, and a line flow.



Cathy Yeulet/123RF

A financial consultant discusses options with a couple at their home. This process scores high on customer contact, because the customers are present, take an active part in creating the service, receive personal attention, and have a face-to-face meeting.

Process Structure in Manufacturing

Many processes at a manufacturing firm are actually services to internal or external customers, and so the previous discussion on services applies to them. Similarly, manufacturing processes can be found in service firms. Clarity comes when viewing work at the process level, rather than the organizational level. Here we focus instead on the manufacturing processes. Because of the differences between service and manufacturing processes, we need a different view on process structure.

Product-Process Matrix

The product-process matrix (Figure 2.3) brings together three elements: (1) volume, (2) product customization, and (3) process characteristics. It synchronizes the product to be manufactured with the manufacturing process itself.

A good strategy for a manufacturing process depends first and foremost on

volume. Customer contact, a primary feature of the customer-contact matrix for services, normally is not a consideration for manufacturing processes (although it *is* a factor for the many service processes throughout manufacturing firms). For many manufacturing processes, high product customization means lower volumes for many of the steps in the process. The vertical dimension of the product-process matrix deals with the same two characteristics in the customer-contact matrix: process divergence and flow. Each manufacturing process should be analyzed on these two dimensions, just as was done for a service process.



Alamy Stock Photo

Line flows at a Five Guys Burgers and Fries location in Brooklyn, New York showing production of hamburgers and fries on an assembly line.

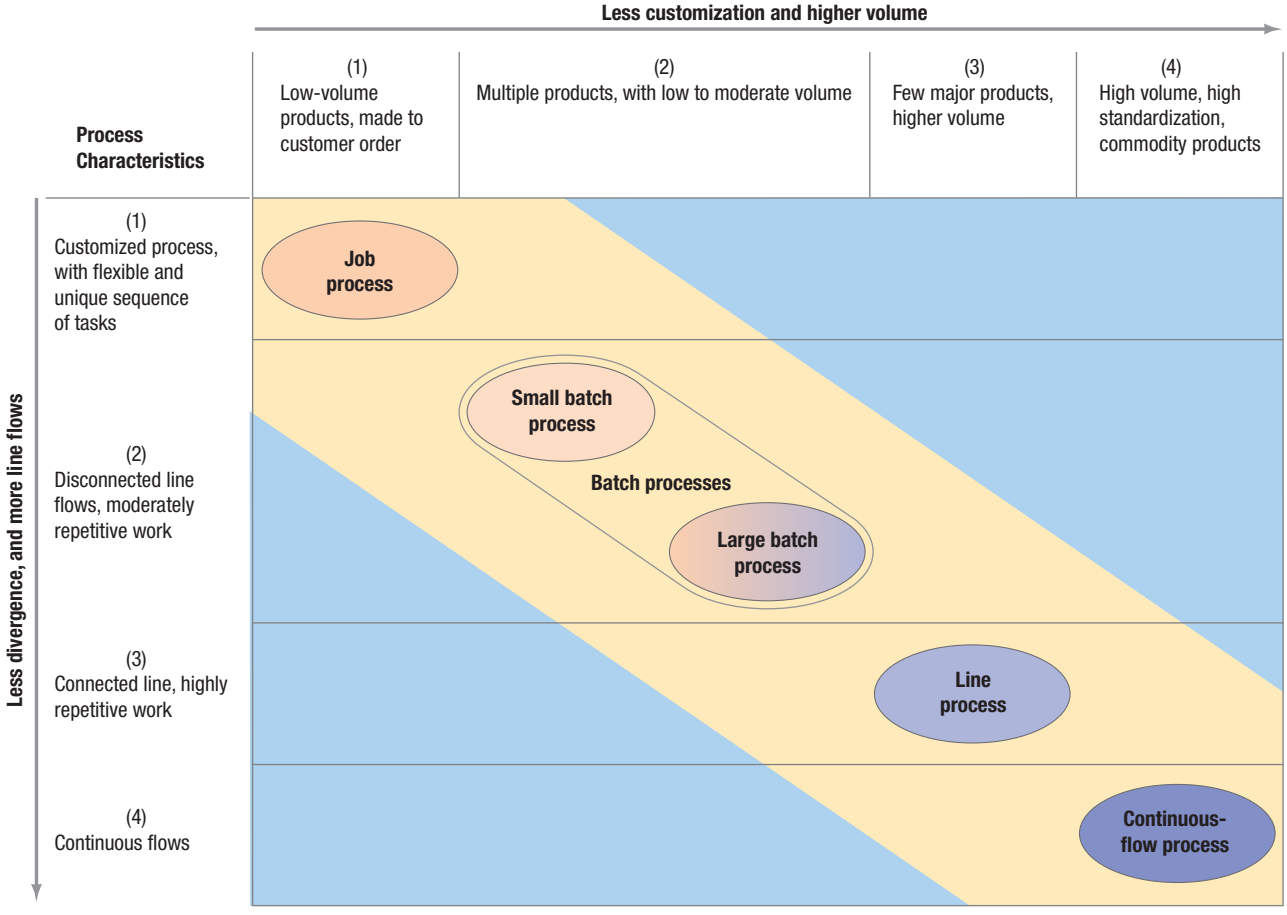
Manufacturing Process Structuring

Figure 2.3 shows several desirable positions (often called *process choices*) in the product-process matrix that effectively connect the manufactured product with the process. **Process choice** is the way of structuring the process by organizing resources around the process or organizing them around the products. Organizing around the process means, for example, that all milling machines are grouped together and process all products or parts needing that kind of transformation. Organizing around the product means bringing together all the different human resources and equipment needed for a specific product and dedicating them to producing just that product. The manager has four process choices, which form a continuum, to choose from: (1) job process, (2) batch process, (3) line process, and (4) continuous-flow process. As with the customer-contact matrix, it is unlikely that a manufacturing process can be a top performer if its position is too far from the diagonal. The fundamental message in Figure 2.3 is that the best choice for a manufacturing process depends on the volume and degree of customization required of the process. The process choice might apply to an entire manufacturing process or just one subprocess nested within it.

process choice

A way of structuring the process by organizing resources around the process or organizing them around the products.

▼ **FIGURE 2.3**
Product-Process Matrix for Manufacturing Processes





Cathy Yeulet/123RF

A job shop manufacturing floor, with workers in different areas of the shop processing different operations for creating a product.

job process

A process with the flexibility needed to produce a wide variety of products in significant quantities, with considerable divergence in the steps performed.

batch process

A process that differs from the job process with respect to volume, variety, and quantity.

line process

A process that lies between the batch and continuous processes on the continuum; volumes are high and products are standardized, which allows resources to be organized around particular products.

continuous-flow process

The extreme end of high-volume standardized production and rigid line flows, with production not starting and stopping for long time intervals.

Job Process A **job process** creates the flexibility needed to produce a wide variety of products in significant quantities, with considerable divergence in the steps performed. Customization is high and volume for any one product is low. The workforce and equipment are flexible to handle considerable task divergence. Companies choosing job processes often bid for work. Typically, they make products to order and do not produce them ahead of time. Each new order is handled as a single unit—that is, as a job. Examples are machining a metal casting for a customized order or producing customized cabinets.

With a job process, all equipment and workers capable of certain types of work are positioned together. Because customization is high and most jobs have a different sequence of steps, this process choice creates flexible flows through the operations rather than a line flow.

Batch Process The batch process is by far the most common process choice found in practice, leading to terms such as *small batch* or *large batch* to further distinguish one process choice from another. A **batch process** differs from the job process with respect to volume, variety, and quantity. The primary difference is that volumes are higher because the same or similar products or parts going into them are produced repeatedly. Some of the components going into the final product may be processed in advance. Production lots are handled in larger quantities (or *batches*) than they are with job processes. A batch of one product (or component part going into it or perhaps other products) is processed, and then production is switched to the next one. Eventually, the first product is produced again. A batch process has average or moderate volumes, but process divergence is still too great to warrant dedicating a separate process for each product. The process flow is flexible, but more dominant paths emerge than at a job process, and some segments of the process have a line flow. Examples of a batch process are making standard components that feed an assembly line or some processes that manufacture capital equipment.

Line Process A **line process** lies between the batch and continuous processes on the continuum; volumes are high and products are standardized, which allows resources to be organized around particular products. Divergence is minimal in the process or line flows, and little inventory is held between the processing steps. Each step performs the same process over and over, with little variability in the products manufactured. Production and material handling equipment is specialized. Products created by a line process include the assembly of computers, automobiles, appliances, and toys.

Standard products are produced in advance of their need and held in inventory so that they are ready when a customer places an order. Product variety is possible by careful control of the addition of standard options to the main product.

Continuous-Flow Process A **continuous-flow process** is the extreme end of high-volume standardized production, with rigid line flows. Process divergence is negligible. Its name derives from the way materials move through the process. Usually, one primary material (such as a liquid, a gas, or a powder) moves without stopping through the process. A continuous-flow process differs from a line process in one important respect: Materials (be they undifferentiated or discrete) flow through the process without stopping until the whole batch is finished. The time span can be several shifts or even several months. Examples of a continuous-flow process are petroleum refining; chemical processes; paper manufacturing; and processes making steel, soft drinks, and food.

Production and Inventory Strategies

Strategies for manufacturing processes differ from those in services not only because of low customer contact and involvement but also because of the ability to use inventories not only as purchased materials but also in the form of subassemblies or finished products. As we learned in Chapter 1, there are clearly exceptions to this rule, as Avis has an inventory of autos to rent, and FedEx has an inventory of in-process parcels. Design-to-order, make-to-order, assemble-to-order, and make-to-stock strategies are four approaches to inventory that should be coordinated with process choice.

design-to-order strategy

A strategy that involves designing new products that do not currently exist, and then manufacturing them to meet unique customer specifications.

Design-to-Order Strategy A firm uses a **design-to-order strategy** when it can design new products that do not currently exist, and then manufacture them to meet unique customer specifications. Typically a job process is employed to create a highly customized product, such as a designer pair of shoes for a particular client.

Make-to-Order Strategy Manufacturers that make products to customer specifications in low volumes tend to use the **make-to-order strategy**, coupling it with job or small batch processes. Even though the product is based on a standard design, it is a more complex process than assembling a final product from standard components. This strategy provides a high degree of customization and typically uses job or small batch processes. The processes have high divergence. Specialized medical equipment, castings, and expensive homes are suited to the make-to-order strategy.

make-to-order strategy

A strategy used by manufacturers that make products to customer specifications in low volumes.

Assemble-to-Order Strategy The **assemble-to-order strategy** is an approach to producing a wide variety of products from relatively few subassemblies and components after the customer orders are received. Typical competitive priorities are variety and fast delivery times. The assemble-to-order strategy often involves a line process for assembly and a batch process for fabrication. Because they are devoted to manufacturing standardized components and subassemblies in high volumes, the fabrication processes focus on creating appropriate amounts of component inventories for the assembly processes. Once the specific order from the customer is received, the assembly processes create the product from standardized components and subassemblies produced by the fabrication processes.

assemble-to-order strategy

A strategy for producing a wide variety of products from relatively few subassemblies and components after the customer orders are received.

Stocking finished products would be economically prohibitive because the numerous possible options make forecasting relatively inaccurate. Thus, the principle of **postponement** is applied, whereby the final activities in the provision of a product are delayed until the orders are received. The assemble-to-order strategy is also linked to **mass customization**, where highly divergent processes generate a wide variety of customized products at reasonably low costs. Both postponement and mass customization are covered more fully in Chapter 12, "Supply Chain Design."

postponement

The strategy of delaying final activities in the provision of a product until the orders are received.

mass customization

The strategy that uses highly divergent processes to generate a wide variety of customized products at reasonably low costs.

Make-to-Stock Strategy Manufacturing firms that hold items in stock for immediate delivery, thereby minimizing customer delivery times, use a **make-to-stock strategy**. This strategy is feasible for standardized products with high volumes and reasonably accurate forecasts. It is the inventory strategy of choice for line or continuous-flow processes. Examples of products produced with a make-to-stock strategy include garden tools, electronic components, soft drinks, and chemicals.

make-to-stock strategy

A strategy that involves holding items in stock for immediate delivery, thereby minimizing customer delivery times.

Combining a line process with the make-to-stock strategy is sometimes called **mass production**. It is what the popular press commonly envisions as the classical manufacturing process, because the environment is stable and predictable, with workers repeating narrowly defined tasks with low divergence.

mass production

A term sometimes used in the popular press for a line process that uses the make-to-stock strategy.

Layout

Selecting process structures for the various processes housed in a facility is a strategic decision, but must be followed by a more tactical decision—creating a layout. A *layout* is the physical arrangement of operations (or departments) created from the various processes and puts them in tangible form. For organizational purposes, processes tend to be clustered together into operations or departments. An *operation* is a group of human and capital resources performing all or part of one or more processes. For example, an operation could be several customer service representatives in a customer reception area; a group of machines and workers producing cell phones; or a marketing department. Regardless of how processes are grouped together organizationally, many of them cut across departmental boundaries. The flows across departmental lines could be informational, services, or products. Process structures that create more flows across departmental lines, as with job or batch processes, are the most challenging layout problems. Supplement K, "Layout," provides a more in-depth analysis of how to gather information and develop detailed layout plans.

Process Strategy Decisions

Having covered process structure decisions in both service and manufacturing organizations, we turn our attention now to the other three major process strategy decisions shown in Figure 2.1—customer involvement, resource flexibility, and capital intensity.

Customer Involvement

Customer involvement reflects the ways in which customers become part of the process and the extent of their participation. It is especially important for many service processes, particularly if customer contact is (or should be) high.

Possible Advantages The advantages of a more customer-focused process might increase the net value to the customer. Some customers seek active participation in and control over the service process, particularly if they will enjoy savings in both price and time. The manager must assess whether advantages outweigh disadvantages, judging them in terms of the competitive priorities and customer satisfaction. More customer involvement can mean better quality, faster



McClatchy-Tribune/Tribune Content Agency LLC/Alamy Stock Photo

Customers use the Create Your Taste self-ordering kiosk in the McDonald's on the 2500 block of Ogden Avenue in Downers Grove, Ill. It allows customers to directly place their order including the toppings, size, and sides.

delivery, greater flexibility, and even lower cost. Self-service is the choice of many retailers, such as gasoline stations, supermarkets, and bank services. Manufacturers of products (such as toys, bicycles, and furniture) may also prefer to let the customer perform the final assembly because product, shipping, and inventory costs frequently are lower. In fact, IKEA Furniture Company's business model is based on customers being actively involved in its processes.

Customer involvement can also help coordinate across the supply chain (see Chapter 14, "Supply Chain Integration"). Emerging technologies allow companies to engage in an active dialogue with customers and make them partners in creating value and forecasting future demand. Suppliers to automobile companies can be close collaborators in the process of developing new vehicles and are no longer passive providers of materials and services. The same is true for distributors. Walmart does more than just distribute Procter & Gamble's products: It shares daily sales information and works with Procter & Gamble in managing inventories and warehousing operations.

Possible Disadvantages Customer involvement is not always a good idea. In some cases, giving the customer more active contact in a service process will just be disruptive, making the process less efficient. Managing the timing and volume of customer demands becomes more challenging if the customer is physically present and expects prompt delivery. Exposing the facilities and employees to the customer can have important quality implications (favorable or unfavorable). Such changes make interpersonal skills a prerequisite to the service provider's job, but higher skill levels come at a cost. It also might mean having many smaller decentralized facilities closer to the various customer concentration areas if the customer comes to the service providers.

Resource Flexibility

flexible workforce

A workforce whose members are capable of doing many tasks, either at their own workstations or as they move from one workstation to another.

Online Resource

Tutor 2.1 in OM Explorer demonstrates how to do break-even analysis for equipment selection.

Just as managers must account for customer contact when making customer involvement decisions, so must they account for process divergence and diverse process flows when making resource flexibility decisions in Figure 2.1. For example, high task divergence and flexible process flows require more flexibility of the process's resources—its employees, facilities, and equipment. Employees need to perform a broad range of duties, and equipment must be general purpose. Otherwise, resource utilization will be too low for economical operations.

Workforce Operations managers must decide whether to have a **flexible workforce**. Members of a flexible workforce are capable of doing many tasks, either at their own workstations or as they move from one workstation to another. However, such flexibility often comes at a cost, requiring greater skills and thus more training and education. Nevertheless, benefits can be large: Worker flexibility can be one of the best ways to achieve reliable customer service and alleviate capacity bottlenecks. Resource flexibility helps to absorb the feast-or-famine workloads in individual operations that are caused by low-volume production, divergent tasks, flexible flows, and fluid scheduling.



Mint Images/Getty Images

A car mechanic must be flexibly cross-trained at many different tasks in order to repair a wide variety of cars from different manufacturers.

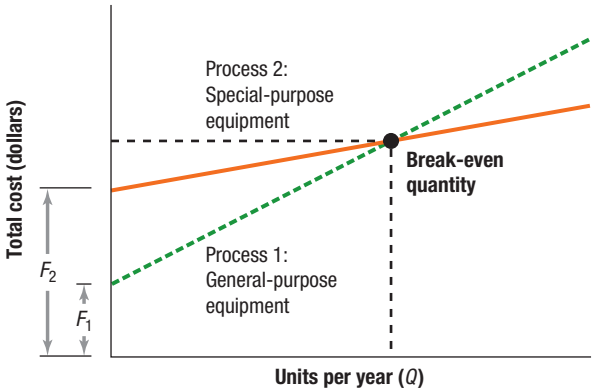
The type of workforce required also depends on the need for volume flexibility. When conditions allow for a smooth, steady rate of output, the likely choice is a permanent workforce that expects regular full-time employment. If the process is subject to hourly, daily, or seasonal peaks and valleys in demand, the use of part-time or temporary employees to supplement a smaller core of full-time employees may be the best solution. However, this approach may not be practical if knowledge and skill requirements are too high for a temporary worker to grasp quickly.

Equipment Low volumes mean that process designers should select flexible, general-purpose equipment. Figure 2.4 illustrates this relationship by showing the total cost lines for two different types of equipment that can be chosen for a process. Each line represents the total annual cost of the process at different volume levels. It is the sum of fixed costs and variable costs (see Supplement A, "Decision Making"). When volumes are low (because

customization is high), process 1 is the better choice. It calls for inexpensive general-purpose equipment, which keeps investment in equipment low and makes fixed costs (F_1) small. Its variable unit cost is high, which gives its total cost line a relatively steep slope. Process 1 does the job, but not at peak efficiency.

Conversely, process 2 is the better choice when volumes are high and customization is low. Its advantage is low variable unit cost, as reflected in the flatter total cost line. This efficiency is possible when customization is low because the equipment can be designed for a narrow range of products or tasks. Its disadvantage is high equipment investment and, thus, high fixed costs (F_2). When annual volume produced is high enough, spreading these fixed costs over more units produced, the advantage of low variable costs more than compensates for the high fixed costs.

The break-even quantity in Figure 2.4 is the quantity at which the total costs for the two alternatives are equal. At quantities beyond this point, the cost of process 1 exceeds that of process 2. Unless the firm expects to sell more than the break-even amount, which is unlikely with high customization and low volume, the capital investment of process 2 is not warranted.



▲ **FIGURE 2.4**
Relationship Between Process Costs and Product Volume

Capital Intensity

Capital intensity is the mix of equipment and human skills in the process; the greater the cost of equipment relative to the cost of labor, the greater is the capital intensity. As the capabilities of technology increase and its costs decrease, managers face an ever-widening range of choices, from operations utilizing very little automation to those requiring task-specific equipment and little human intervention. **Automation** is a system, process, or piece of equipment that is self-acting and self-regulating. Although automation is often thought to be necessary to gain competitive advantage, it has both advantages and disadvantages. Thus, the automation decision requires careful examination.

automation
A system, process, or piece of equipment that is self-acting and self-regulating.

Automating Manufacturing Processes Substituting labor-saving capital equipment and technology for labor has been a classic way of improving productivity and quality consistency in manufacturing processes. If investment costs are large, automation works best when volume is high, because more customization typically means reduced volume. Gillette, for example, spent $750 million on the production lines and robotics that gave it a capacity to make 1.2 billion razor cartridges a year. The equipment is complicated and expensive. Only with such high volumes could this line process produce the product at a price low enough that consumers could afford to buy it.

One big disadvantage of capital intensity can be the prohibitive investment cost for low-volume operations (see Figure 2.4). Generally, capital-intensive operations must have high utilization to be justifiable. Also, automation does not always align with a company's competitive priorities. If a firm offers a unique product or high-quality service, competitive priorities may indicate the need for hand labor and individual attention rather than new technology. A case in point is the downstream processes in Gillette's supply chain that package and store the razor cartridges. It customizes the packaging for different regions of the world, so that volumes for any one type of package are much lower. As a result of the low volumes, Gillette does not use expensive automation for these processes. In fact, it outsources them. It produces razor cartridges to stock using highly automated processes and then packages them in customized fashion at remote locations on demand.



James Hardy/PhotoAlto/Alamy Stock Photo

R.R. Donnelly has been able to achieve flexible automation by receiving books digitally and preparing them to go on press electronically. This allows the company to put books on press more quickly and print smaller, more manageable quantities in a single print run.

fixed automation
A manufacturing process that produces one type of part or product in a fixed sequence of simple operations.

flexible (or programmable) automation
A manufacturing process that can be changed easily to handle various products.

industrial robot
Versatile, computer-controlled machine programmed to perform various tasks.

Manufacturers use two types of automation: (1) fixed and (2) flexible (or programmable). Particularly appropriate for line and continuous-flow process choices, **fixed automation** produces one type of part or product in a fixed sequence of simple operations. Operations managers favor fixed automation when demand volumes are high, product designs are stable, and product life cycles are long. These conditions compensate for the process's two primary drawbacks: (1) large initial investment cost and (2) relative inflexibility. However, fixed automation maximizes efficiency and yields the lowest variable cost per unit if volumes are high.

Flexible (or programmable) automation can be changed easily to handle various products. The ability to reprogram machines is useful for both low- and high-customization processes. In the case of high customization, a machine that makes a variety of products in small batches can be programmed to alternate between products. When a machine has been dedicated to a particular product or family of products, as in the case of low customization and a line flow, and the product is at the end of its life cycle, the machine can simply be reprogrammed with a new sequence of tasks for a new product. An **industrial robot**, which is a versatile, computer-controlled machine programmed to perform various tasks, is a classic example of flexible automation. These "steel-collar" workers operate independently of human control. A robot's arm has up to six standard movements. The robot's "hand" can be changed to perform different tasks, such as materials handling, assembly, and testing. Machine learning and artificial intelligence technologies allow machines to learn from observed rules, as well as screening and sorting algorithms in detecting product defects and abusive customers, or even functioning as automated secretaries.

Automating Service Processes Using capital inputs as a labor-saving device is also possible for service processes. In educational services, for example, long-distance learning technology now can supplement or even replace the traditional classroom experience by using books, computers, websites, and videos as facilitating goods that go with the service. Justifying technology need not be limited to cost reduction. Sometimes, it can actually allow more task divergence by making available a wide menu of choices to the customer. It can also improve quality by being more consistent.

The need for volume to justify expensive automation is just as valid for service processes as for manufacturing processes. Increasing the volume lowers the cost per dollar of sales. Volume is essential for many capital-intensive processes in the transportation, communications, and utilities industries.

Economies of Scope If capital intensity is high, resource flexibility usually is low. In certain types of manufacturing operations, such as machining and assembly, programmable automation breaks this inverse relationship between resource flexibility and capital intensity. It makes possible both high capital intensity and high resource flexibility, creating economies of scope. **Economies of scope** reflect the ability to produce multiple products more cheaply in combination than separately. In such situations, two conflicting competitive priorities—customization and low price—become more compatible. However, taking advantage of economies of scope requires that a family of parts or products have enough collective volume to utilize equipment fully. Another enabler of economies of scope is additive manufacturing, which refers to three-dimensional (3D) printing technology. It allows firms to react to a wider variety of demands without incurring additional cost. Changes in designs or added complexity due to customized customer specifications can be incorporated by simply tweaking the 3D blueprint of the product. Simply by acquiring such additive manufacturing capabilities as described in Chapter 1, "Using Operations to Create Value," firms are able to achieve substantial economies of scope.

economies of scope
Economies that reflect the ability to produce multiple products more cheaply in combination than separately.



David R. Frazier Photolibrary, Inc./Alamy Stock Photo

Regional automated mail sorting facility in Boise, Idaho. Automating service processes in high volume environments such as these save labor and justify expensive capital investments.

Economies of scope also apply to service processes. Consider, for example, Disney, whose managers used the Internet to reap the benefits of economies of scope. They aggressively linked their Internet processes with one another and with other parts of Disney. A flexible technology that handles many services together can be less expensive than handling each one separately, particularly when the markets are not too volatile.

Strategic Fit

The manager should understand how the four major process decisions tie together, so as to spot ways of improving poorly designed processes. The choices should fit the situation and each other. When the fit is more *strategic*, the process will be more effective. We examine services and manufacturing processes, looking for ways to test for strategic fit.

Decision Patterns for Service Processes

After analyzing a process and determining its position on the customer-contact matrix in Figure 2.2, it may be apparent that it is improperly positioned, either too far to the left or right, or too far to the top or bottom. Opportunities for improvement become apparent. Perhaps, more customization and customer contact is needed than the process currently provides. Perhaps, instead, the process is too divergent, with unnecessarily flexible flows. Reducing divergence might reduce costs and improve productivity.

The process should reflect its desired competitive priorities. Front offices generally emphasize top quality and customization, whereas back offices are more likely to emphasize low-cost operation, consistent quality, and on-time delivery. The process structure selected then points the way to appropriate choices on customer involvement, resource flexibility, and capital intensity. High customer contact at a front-office service process means:

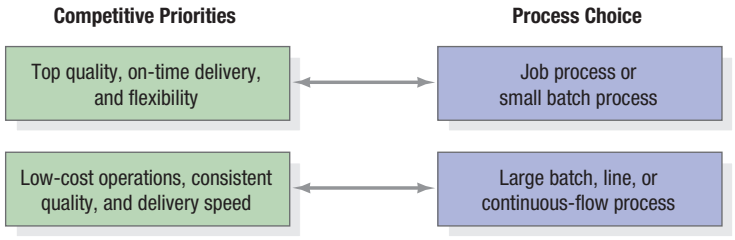
1. *Process Structure.* The customer (internal or external) is present, actively involved, and receives personal attention. These conditions create processes with high divergence and flexible process flows.
2. *Customer Involvement.* When customer contact is high, customers are more likely to become part of the process. The service created for each customer is unique.
3. *Resource Flexibility.* High process divergence and flexible process flows fit with more flexibility from the process's resources—its workforce, facilities, and equipment.
4. *Capital Intensity.* When volume is higher, automation and capital intensity are more likely. Even though higher volume is usually assumed in the back office, it is just as likely to be in the front office for financial services. Information technology is a major type of automation at many service processes, which brings together both resource flexibility and automation.

Of course, this list provides general tendencies rather than rigid prescriptions. Exceptions can be found, but these relationships provide a way of understanding how service process decisions can be linked coherently.

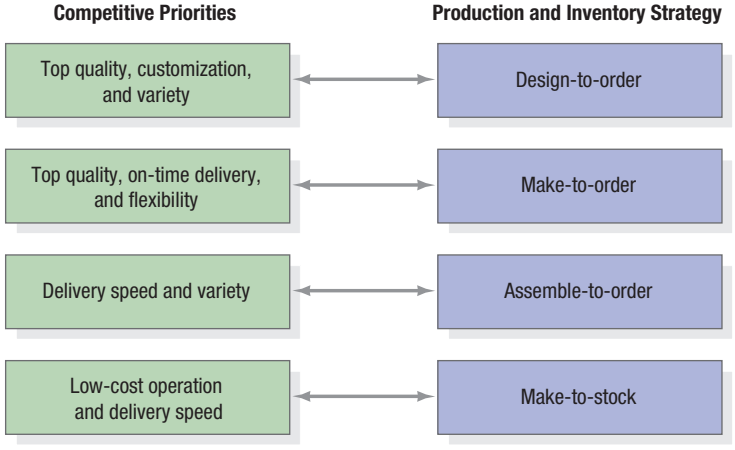
Decision Patterns for Manufacturing Processes

Just as a service process can be repositioned in the customer-contact matrix, a manufacturing process can also be moved in the product-process matrix. Changes can be made either in the horizontal direction of Figure 2.3 by changing the degree of customization and volume, or they can be moved in the vertical direction by changing process divergence. Competitive priorities must be considered when translating strategy into specific manufacturing processes. Figure 2.5 shows some usual tendencies found in practice. Job and small batch processes are usual choices if top quality, on-time delivery, and flexibility (customization, variety, and volume flexibility) are given primary emphasis. Large batch, line, and continuous-flow processes match up with an emphasis on low-cost operations, consistent quality, and delivery speed.

▼ **FIGURE 2.5**
Links of Competitive Priorities with Manufacturing Strategy



(a) Links with Process Choice



(b) Links with Production and Inventory Strategy

The production and inventory strategy should also be chosen to be consistent with the competitive priorities emphasized. As shown in Figure 2.5, the design-to-order strategy is consistent with top quality, customization, and variety. The focus is on meeting the unique needs of the customers by specifically designing a variety of products according to the customer specifications. The make-to-order strategy matches up with flexibility (particularly customization) and top quality. Because delivery speed is more difficult, meeting due dates and on-time delivery get the emphasis on the time dimension. The assemble-to-order strategy allows delivery speed and flexibility (particularly variety) to be achieved, whereas the make-to-stock strategy is the usual choice if delivery speed and low-cost operations are emphasized. Keeping an item in stock ensures quick delivery because it is generally available when needed, without delays in producing it. High volumes open up opportunities to reduce costs.

The process structure selected once again points the way to appropriate choices on customer involvement,



Mike Wintroath/AP Images

Focused factories are not just found in manufacturing. This single-specialty facility focuses just on heart surgery and has all the advanced resources needed that cannot be provided by a general hospital. Another example is the Toronto-based Shouldice Clinic, which focuses just on hernias.

resource flexibility, and capital intensity. High volumes per part type at a manufacturing process typically mean:

1. *Process Structure.* High volumes, combined with a standard product, make a line flow possible. It is just the opposite where a job process produces to specific customer orders.
2. *Customer Involvement.* Customer involvement is not a factor in most manufacturing processes, except for choices made on product variety and customization. Less discretion is allowed with line or continuous-flow processes to avoid the unpredictable demands required by customized orders.
3. *Resource Flexibility.* When volumes are high and process divergence is low, flexibility is not needed to utilize resources effectively, and specialization can lead to more efficient processes.
4. *Capital Intensity.* High volumes justify the large fixed costs of an efficient operation.

Gaining Focus

In the past, new services or products often were added to a facility in the name of better utilizing fixed costs and keeping everything under the same roof. The result was a jumble of competitive priorities, process structures, and technologies. In the effort to do everything, nothing was done well. A process that aims to achieve low cost and efficiency should not be mixed with a process that needs to be flexible and offer a large product variety. Focus means choosing one or the other, but not both simultaneously in the same facility.

Focus by Process Segments A facility's operations often can be neither characterized nor actually designed for one set of competitive priorities and one process choice. At a services facility, some parts of the process might seem like a front office and other parts like a back office. Such arrangements can be effective, provided that sufficient focus is given to each process by the management segmenting them into separate operations that are relatively autonomous.

plants within plants (PWPs)
Different operations within a facility with individualized competitive priorities, processes, and workforces under the same roof.

Plants within plants (PWPs) are different operations within a facility with individualized competitive priorities, processes, and workforces under the same roof. Boundaries for PWPs may be established by physically separating subunits or simply by revising organizational relationships. At each PWP, customization, capital intensity volume, and other relationships are crucial and must be complementary. The advantages of PWPs are fewer layers of management, greater ability to rely on team problem solving, and shorter lines of communication between departments. As illustrated in Managerial Practice 2.1, Ford Corporation has adopted a PWP-focused strategy at its highly successful Camacari plant in Brazil, where several suppliers produce parts under the same roof as the original manufacturer.

MANAGERIAL PRACTICE 2.1 Plants-Within-a-Plant at Ford Camacari

Ford Motor Company is a global automotive company with manufacturing operations located worldwide, including Brazil, Canada, China, Mexico, United Kingdom, and United States, among many others. Its Ford do Brasil subsidiary was established in 1919, and underwent several transformations in its ownership structure and range of manufacturing and assembly operations over the past hundred years. In Bahia, Camacari, a city in the rural northeast region of Brazil, Ford has invested over $4 billion to build one of the most advanced automobile factories in the world. Ford Ecosport Mini SUV and the Ford Fiesta models for the Brazilian market and other developing countries are manufactured here. The Camacari plant, which opened in 2001, is more automated than several of Ford's facilities in the United States, with more robots here than in many U.S. plants. Ford Camacari is also one of the most flexible factories in the world, capable of producing five different vehicle platforms at the same time on the same line. Ford owns the land and buildings, and all employees on the site are registered on a single human resource system.

However, the real revolution at Camacari lies in the close integration of Ford suppliers in the assembly process, while retaining individual processes and workforces for each supplier. The idea is to involve suppliers right from the vehicle's design stage to the final assembly. By locating the suppliers within the vehicle's manufacturing facility, the respective modules are manufactured and delivered to the main assembly line, with little logistics involved. While Ford controls the final assembly process, 21 component suppliers and 4 service providers are located on the site. Eight additional component suppliers are located offsite, but in close vicinity. Of the 21 component suppliers, 10 are in the final assembly area, which forms the "plants-within-a-plant" (PWP) configuration. They are Faurecia (door module), Visteon (cockpit), Pelzer (soft trim), Interim (headliner), Lear (seats), Mapri-Textron (fasteners), Valeo (front-end module), Benteler (suspension), ArvinMeritor (exhaust), and Pireli (tire assembly). Each supplier manages its own production processes and line settings on the site, and maintains its own



Joa Souza/Shutterstock

Ford Motor Company assembly workers work on the assembly line of the Ford Fiesta and Ecosport vehicles at a plant in Camacari, in the northeastern Brazilian state of Bahia. Ford invested US $1.2 billion at the Camacari's factory and created a unique environment that consolidates production line with their direct suppliers' own facilities where the models are made for the Brazilian market and exported to other development countries as well.

competitive priorities. Although these suppliers are not responsible for the final assembly, some of them carry out quality check measures beyond the boundaries of their embedded plants. This additional step ensures that the difference in competitive priorities and processes do not hinder the quality and seamless flow of production in the entire plant.

The workforce at Camacari is also different in a number of ways. The entire plant employs approximately 9,000 workers, including the suppliers. Because the majority do not have any prior industrial work experience, they undergo a 900-hour training program. This collective training program enhances the cohesiveness among employees and facilitates a culture of collaboration and joint problem solving. Unlike many U.S. auto plants, where workers' responsibilities are strictly limited to specific job classifications, workers are encouraged to learn as many skills as possible, which allows the plant to be flexible.

By having such a plant, Ford is able to have module suppliers commit to the success of the whole product because they get paid when the product is approved and functionally accepted. The suppliers would have to prioritize resolving delivery or quality issues with Ford, which eventually improves the final quality. When there is a problem with a part, it is simple to track down the source and work with the related supplier to correct it. Due to closer communication and knowledge transfer between companies and employees, Ford is experiencing faster learning curves and cross fertilization of practices in the workforce. Ford can shorten the development times and launch times for new products, and quickly ramp up production volumes because of the increased collaboration and involvement of suppliers. The reduced inventory and logistics costs more than compensate for the high interest rates charged for credit in Brazil.

However, this approach may have some disadvantages as well. Salary negotiations may align toward the entire plant's standards, reducing margin for the suppliers. Decision making can take longer for some issues, such as labor union negotiations, which require agreement of all the partners. Managing organizational culture is also not an easy task. This may complicate the startup of the factory, because of the mix of various management styles and company cultures the suppliers may bring into the plant. Finally, it increases the organizational inertia, because change is less likely to happen with suppliers embedded within the plant. When a module faces technical improvements, there is a risk that it might not be compatible with other modules, and it may require Ford to a change a supplier.

Overall, focused operations along with flexibility and close supplier involvement make the Camacari plant one of the most innovative ones among Ford's worldwide network of facilities. The Camacari plant is an example of how the PWP concept can be established beyond a single firm's boundary and create a closely integrated production facility that incorporates the benefits of collaborative problem solving at the interorganizational level.[2]

Focused Service Operations Service industries also implement the concepts of focus and PWPs. Specialty retailers opened stores with smaller, more accessible spaces. These focused facilities generally chipped away at the business of large department stores. Using the same philosophy, some department stores now focus on specific customers or products. Remodeled stores create the effect of many small boutiques under one roof.

Focused Factories Hewlett-Packard, Rolls-Royce, Japan's Ricoh and Mitsubishi, and Britain's Imperial Chemical Industries PLC are some of the firms that created **focused factories**, splitting large plants that produced all the company's products into several specialized smaller plants. The theory is that narrowing the range of demands on a facility will lead to better performance because management can concentrate on fewer tasks and lead a workforce toward a single goal.

focused factories
The result of a firm's splitting large plants that produced all the company's products into several specialized smaller plants.

Strategies for Change

The four major process decisions represent broad, strategic issues and define the nature of the processes a firm needs to compete effectively. However, decisions that are made must be translated into actual process designs or redesigns. There are two different but complementary philosophies for process design and change: (1) process reengineering and (2) process improvement. Process analysis, supported by the tools described later, is needed regardless of whether reengineering or process improvement is attempted. An individual or a whole team examines the process and looks for ways to streamline tasks, eliminate whole processes entirely, cut expensive materials or services, improve the environment, or make jobs safer. By comprehensively analyzing the process, one must find the ways to trim costs and delays and to improve customer satisfaction.

[2] *Sources:* B. G. Hoffman, "Ford's Test Bed: Brazil's Camacari Plant Is Model for the Future, *The Detroit News* (2007); M. Sako, "Outsourcing of Tasks and Outsourcing of Assets: Evidence from Automotive Supplier Parks in Brazil. *Platforms, Markets and Innovation* (2009), 251; https://en.wikipedia.org/wiki/Ford_Brasil (August 3, 2020).

Process Reengineering

reengineering
The fundamental rethinking and radical redesign of processes to improve performance dramatically in terms of cost, quality, service, and speed.

Reengineering is the fundamental rethinking and radical redesign of processes to improve performance dramatically in terms of cost, quality, service, and speed. Process reengineering is about reinvention rather than incremental improvement. It is strong medicine and not always needed or successful. Pain, in the form of layoffs and large cash outflows for investments in information technology, almost always accompanies massive change. However, reengineering processes can have big payoffs. Table 2.2 lists the key elements of the overall approach.

TABLE 2.2 | KEY ELEMENTS OF REENGINEERING

Element	Description
Critical processes	The emphasis of reengineering should be on core business processes. Normal process-improvement activities can be continued with the other processes.
Strong leadership	Senior executives must provide strong leadership for reengineering to be successful. Otherwise, cynicism, resistance ("we tried that before"), and boundaries between departments can block radical changes.
Cross-functional teams	A team, consisting of members from each functional area affected by the process change, is charged with carrying out a reengineering project. Self-managing teams and employee empowerment are the rule rather than the exception.
Information technology	Information technology is a primary enabler of process engineering. Most reengineering projects design processes around information flows, such as customer order fulfillment.
Clean-slate philosophy	Reengineering requires a "clean-slate" philosophy—that is, starting with the way the customer wants to deal with the company. To ensure a customer orientation, teams begin with internal and external customer objectives for the process.
Process analysis	Despite the clean-slate philosophy, a reengineering team must understand things about the current process: what it does, how well it performs, and what factors affect it. The team must look at every procedure involved in the process throughout the organization.

Reengineering has led to many successes and will continue to do so. However, it is not simple or easily done, nor is it appropriate for all processes or all organizations. The best understanding of a process, and how to improve it, often lies with the people who perform the work each day, not with cross-functional teams or top management.

Process Improvement

process improvement
The systematic study of the activities and flows of each process to improve it.

Process improvement is the systematic study of the activities and flows of each process to improve it. Its purpose is to "learn the numbers," understand the process, and dig out the details. Once a process is really understood, it can be improved. The relentless pressure to provide better quality at a lower price means that companies must continually review all aspects of their operations. Process improvement goes on, whether or not a process is reengineered. There is always a better way. Most processes can be improved if someone thinks of a way and implements it effectively. Indeed, companies will either adapt processes to the changing needs of customers or cease to exist. Long-term success comes from managers and employees who really understand their businesses. But all too often, highly publicized efforts that seem to offer quick-fix solutions fail to live up to expectations over the long haul, be they programs for conceptualizing a business vision, conducting culture transformation campaigns, or providing leadership training.

As the following Managerial Challenge illustrates, analyzing and improving processes are not limited to just the core operations of a firm, but can readily extend to other functional areas like marketing, finance, engineering, and accounting as well.

MANAGERIAL CHALLENGE Marketing

Templeton, Inc. is a packaging products manufacturing company with diversified operations in over two dozen countries scattered around the globe. Apart from supplying packaging raw materials, it also customizes the design and installation of machines that help the client firms uniquely package their products. The sales and marketing team at Templeton prides itself in its ability to develop deep client relationships by taking a life cycle approach to the sales and repair of its products. This approach assures customers that Templeton will service or repair any of its machines throughout their economic lives in a timely fashion. When packaging machines malfunction, repair orders are generated and sent to the sales and marketing team,

which then arranges for the inoperative module to be sent to Templeton's internal division responsible for processing these orders. The facility, after an initial diagnosis of the problem, will either repair the malfunctioning assembly or send the client a new one. The company has a standard turnaround time of 25 calendar days or less for fulfilling these customer requests.

Lucy Solano, the vice president of marketing and sales for Templeton's Packaging Products Division, noticed the steadily increasing customer complaints about repair orders being delayed and affecting production. A quick check revealed that more than 65% of the orders over the past quarter had been delayed beyond 25 days, with 35% of orders still not being filled after 2 months. Alarmed by these statistics, Lucy shared this customer data with Peter Jamison, the plant manager of the repair facility in Virginia, in the United States, which handled all such requests worldwide. They agreed to meet in person at the plant the following Monday.

Peter broadly described to Lucy the plant operations at their initial meeting. She was, however, overwhelmed when she toured the plant. She examined the computerized customer-order log and was dismayed to see the time lag between her department getting the order request, arranging for the delivery of the module for repair, and the actual time Peter's facility received the module. Much of the 25-day repair window was consumed by this process. This put the repair process in an expedite mode much of the time. The shop floor itself was cluttered with several different customer repair orders being worked upon simultaneously at many workstations. The staging area for the shipment of fixed machine assemblies was likewise busy. Lucy quickly realized that to truly analyze and improve the process in her department and at the plant, she would need to understand what happens to a typical customer order when it is received in the sales department, when and how the order and the malfunctioning module transition to the repair facility and the shop floor, how long it takes to complete, how long it waits in the shipping department, and what occurs in the processing of the paperwork to close out the order and get it delivered directly to the client site. A process analysis had not been done at the Virginia facility for well over a decade. Topics covered next in this chapter will be helpful to Lucy and Peter as they embark upon their quest of systematically improving the repair order-taking and completion process at Templeton, and once again meeting the customer service promises made by their sales and marketing team.

Process Analysis

Process analysis is the documentation and detailed understanding of how work is performed and how it can be redesigned. Looking at the strategic issues can help identify opportunities for improvement. Do gaps exist between a process's competitive priorities and its current competitive capabilities, as was found for the assessment of operations strategy at a credit card division in Chapter 1, "Using Operations to Create Value"? Do multiple measures of cost, top quality, quality consistency, delivery speed, and on-time delivery meet or exceed expectations? Is there a good *strategic fit* in the process? If the process provides a service, does its position on the customer-contact matrix (see Figure 2.2) seem appropriate? How does the degree of customer contact match up with process structure, customer involvement, resource flexibility, and capital intensity? Similar questions should be asked about manufacturing processes regarding the strategic fit between process choice, volume, and product customization.

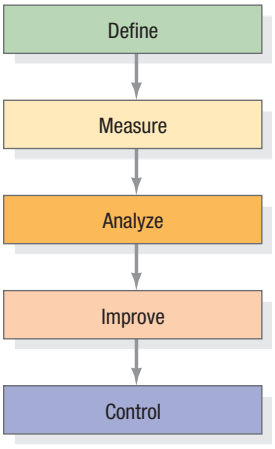
Process analysis begins with identifying and defining a new opportunity for improvement and ends with implementing and controlling a revised process, and which we capture through the Six Sigma Process Improvement Model. Other approaches to process improvement are statistical process control and process capability analysis, discussed in Chapter 3, "Quality and Performance," and value stream mapping, discussed in Chapter 4, "Lean Systems." We avoid overlap by covering each technique just once, while bringing out the essence of the approach covered in each chapter. The chapters do have a shared goal: better processes.

Six Sigma Process Improvement Model Figure 2.6 shows the Six Sigma Process Improvement Model, a five-step procedure that leads to improvements in process performance. This model can be applied to projects involving incremental improvements to processes or to projects requiring major changes, including a redesign of an existing process or the development of a new process.

The following steps constitute the model:

- *Define.* The scope and boundaries of the process to be analyzed are first established. Is it a broad process that stretches across the whole organization, involving many steps and many employees, or is it a more narrowly bracketed nested subprocess that is just part of one person's job? A process's scope can be too narrow or too broad. For example, a broadly defined process that outstrips the resources available, sometimes called "trying to boil the ocean," is doomed because it will increase employee frustration without producing any results.

▼ **FIGURE 2.6**
Six Sigma Process Improvement Model



The resources that management assigns to improving or reengineering a process should match the scope of the process. Once scope is established, determine the characteristics of the process's output that are critical to customer satisfaction and identify any gaps between these characteristics and the process's capabilities. Get a picture of the current process by documenting it using techniques outlined in this chapter.

metrics
Performance measures that are established for a process and the steps within it.

- *Measure.* It is important to have good performance measures to evaluate a process for clues on how to improve it. **Metrics** are performance measures for the process and the steps within it. A good place to start is with competitive priorities, but they need to be specific. The analyst creates multiple measures of quality, customer satisfaction, time to perform each step or the whole process, cost, errors, safety, environmental measures, on-time delivery, flexibility, and the like. Once the metrics are identified, it is time to collect information on how the process is currently performing on each one. Measurement can be rough-cut estimates or quite extensive. It is important to quantify the work the process does that affects the gap. Select what to measure, identify data sources, and prepare a data collection plan.
- *Analyze.* Use the data on measures to perform process analysis to determine where improvements are necessary. A careful analysis of the process and its performance on the selected metrics should uncover *disconnects*, or gaps, between actual and desired performance. Illogical, missing, or extraneous steps can cause performance gaps. They can also be caused by metrics that reinforce the silo mentality of individual departments when the process spans across several departments. The analyst or design team should dig deep to find the root causes of performance gaps. For instance, techniques for analyzing wait times and delays can provide important information (see Supplement B, "Waiting Lines" and online Supplement E, "Simulation"). Whether or not major redesign is necessary, establish procedures to make the desired outcome routine.
- *Improve.* Using analytical and creative thinking, the design team generates a long list of ideas for improvements. These ideas are then sifted and analyzed. Ideas that are justifiable, where benefits outweigh costs, are reflected in a new process design that can meet the new performance objectives. The new design should be documented "as proposed." Combining the new process design with the documentation of the current process gives the analysts clear before-and-after pictures. The new documentation should make clear how the revised process will work and the performance expected for the various metrics used. Implement the changes.
- *Control.* After the implementation, monitor the process to make sure that high performance levels are maintained. Once again, data analysis tools can be used to control the process. Implementation is more than developing a plan and carrying it out. Many processes have been redesigned effectively, but never get implemented. People resist change: "We have always done it that way" or "We tried that before." Widespread participation in process analysis is essential, not only because of the work involved but also because it builds commitment. It is much easier to implement something that is partly your own idea. In addition, special expertise may be needed, such as for developing software. New jobs and skills may be needed, involving training and investments in new technology. Implementation and control brings to life the steps needed to bring the redesigned process online. Management or the steering committee must make sure that the implementation project goes according to schedule.

Successful users have found that it is essential to rigorously follow the steps in the Six Sigma Improvement Model, which is sometimes referred to as the *DMAIC process* (whose name comes from using the first letter of each step in the model). To accomplish the goals of Six Sigma, employees must be trained in the "whys" and the "how-tos" of process performance and what it means to customers, both internal and external. Successful firms using Six Sigma develop a cadre of internal teachers who then are responsible for teaching and assisting teams involved in a process-improvement project. These teachers have different titles depending on their experience and level of achievement. **Green Belts** devote part of their time to teaching and helping teams with their projects and the rest of their time to their normally assigned duties. **Black Belts** are full-time teachers and leaders of teams involved in Six Sigma projects. Finally, **Master Black Belts** are full-time teachers who review and mentor "Black Belts."

Green Belt
Employees who have achieved the first level of training in a Six Sigma program and spend part of their time teaching and helping teams with their projects.

Black Belt
Employees who have reached the highest level of training in a Six Sigma program and spend all of their time teaching and leading teams involved in Six Sigma projects.

Master Black Belt
Full-time teachers and mentors to several Black Belts.

We dive a little deeper into the first three phases of the DMAIC process next, while elaborating on the Improve and Control phase in Chapter 3, "Quality and Performance."

Defining, Measuring, and Analyzing the Process

The Six Sigma Process Improvement Model starts with first defining and understanding the current state of the existing process. This step is needed before data can be collected to measure key attributes of the process, and then analyze that data to improve, design, and control a newly designed future state process.

Three major techniques for effectively defining and measuring processes are (1) flowcharts, (2) work measurement techniques, and (3) process charts. They allow you to "lift the lid and peer

inside" to see how an organization does its work. You can see how a process operates, at any level of detail, and how well it is performing. Trying to create one of these charts might even reveal a lack of any established process. It may not be a pretty picture, but it is how work actually gets done. Techniques for defining the process lend themselves to finding performance gaps, generating ideas for process improvements, and documenting the look of a redesigned process.



Wavebreakmedia Ltd PH20/Alamy Stock Photo

Designer presenting a flow chart during a meeting. The use of flowcharts can help in documenting and evaluating processes.

Flowcharts

A **flowchart** traces the flow of information, customers, equipment, or materials through the various steps of a process. Flowcharts are also known as flow diagrams, process maps, relationship maps, or blueprints. Flowcharts have no precise format and typically are drawn with boxes (with a brief description of the step inside), and with lines and arrows to show sequencing. The rectangle (□) shape is the usual choice for a box, although other shapes (○, ⬭, ⬭, ▽, or ▱) can differentiate between different types of steps (e.g., operation, delay, storage, and inspection). Colors and shading can also call attention to different types of steps, such as those particularly high on process divergence. Divergence is also communicated when an outgoing arrow from a step splits into two or more arrows that lead to different boxes. Although many representations are acceptable, there must be agreement on the conventions used. They can be given as a key somewhere in the flowchart, and/or described in accompanying text. It is also important to communicate *what* (e.g., information, customer order, customer, and materials) is being tracked.

flowchart

A diagram that traces the flow of information, customers, equipment, or materials through the various steps of a process.

You can create flowcharts with several programs. Microsoft PowerPoint offers many different formatting choices for flowcharts (see the Flowchart submenu under AutoShapes). Other powerful software packages for flowcharting and drawing diagrams (such as organization charts and decision trees) are SmartDraw (www.smartdraw.com), Microsoft Visio (www.microsoft.com/office/visio), and Micrografx (www.micrografx.com). Often, free downloads are available at such sites on a trial basis.

Flowcharts can be created for several levels in the organization. For example, at the strategic level, they could show the core processes and their linkages (as in Figure 1.4). At this level, the flowcharts do not have much detail; however, they give a bird's-eye view of the overall business. Just identifying a core process is often helpful. However, in this chapter, we focus at the process level, where we get into the details of the process being analyzed. Many steps may have subprocesses nested within them. Rather than representing everything in one flowchart, an overview of the whole process can first be created. Subsequently flowcharts can be developed to flesh out nested processes. This nesting approach often becomes a practical necessity because only so much detail can be shown in any single flowchart.

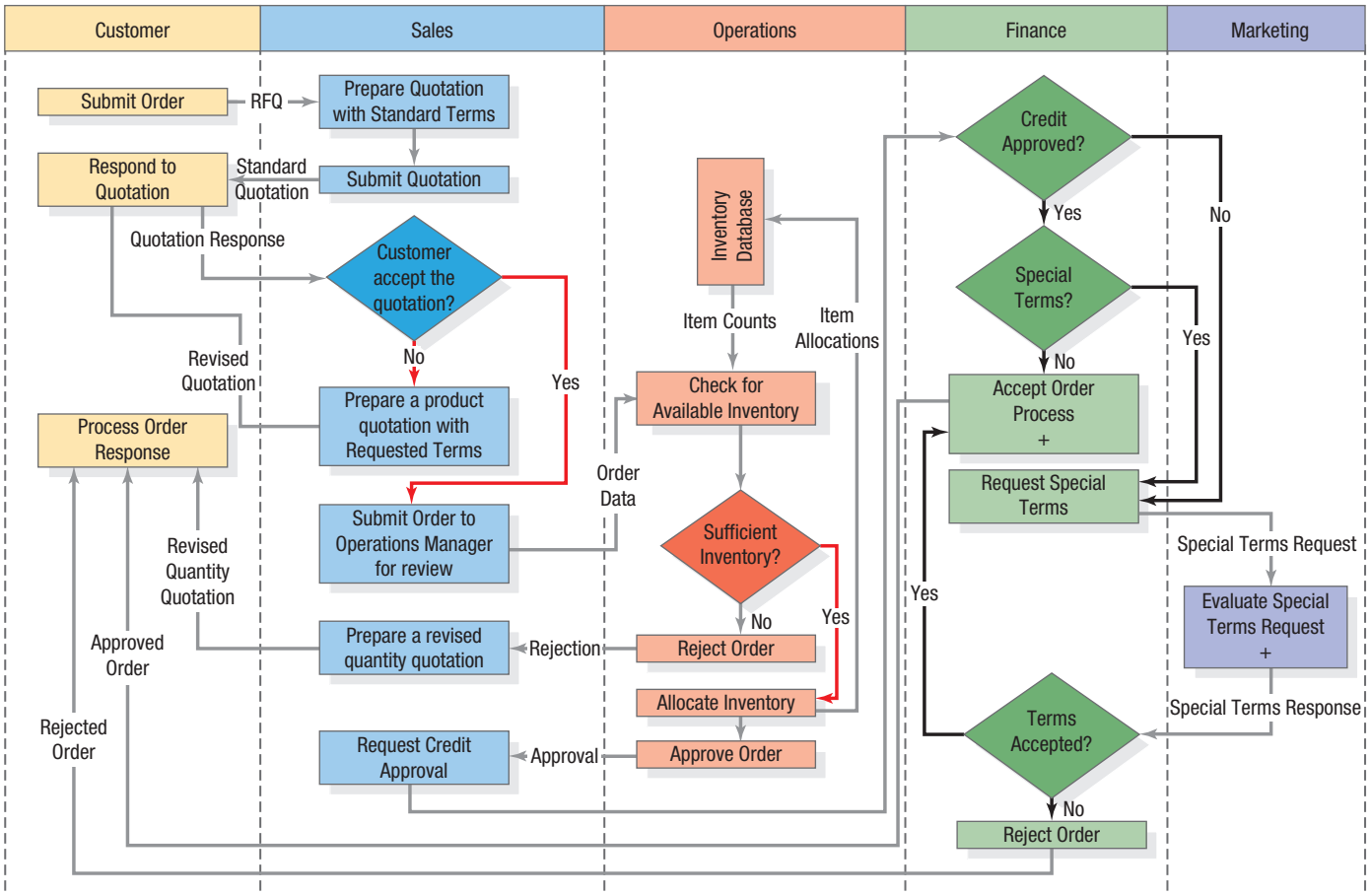
Swim Lane Flowchart One of the most commonly used forms of a flowchart is the **swim lane flowchart**. It is a visual representation that groups functional areas responsible for different subprocesses into lanes. It is most appropriate when the business process spans several department boundaries, and where parallel lines similar to lanes in a swimming pool separate each department or a functional area. Swim lanes are labeled according to the functional groups they represent and can be arranged either horizontally or vertically.

swim lane flowchart

A visual representation that groups functional areas responsible for different subprocesses into lanes. It is most appropriate when the business process spans several department boundaries.

The swim lane flowchart in Figure 2.7 illustrates the order placement and acceptance process at a manufacturing company. The process starts when an order is generated by a customer and ends when the order is actually rejected, modified, or approved by the company in consultation with the customer. All functions contributing to this process are included in the flowchart. The columns represent different departments or functional areas, and the steps appear in the department column where they are performed. The customer is also shown as one of the column headings. This approach shows the *handoffs* from one department to another when the outgoing arrow from a step goes to another column. Special dotted-line arrows are one way to show handoffs. Handoffs are points where cross-functional coordination is at particular risk due to the silo mentality. Misunderstandings, backlogs, and errors are more likely at these points.

Figure 2.7 illustrates one other feature. The diamond shape (◊) represents a yes/no decision or outcome, such as the results of an inspection or recognition of different kinds of customer requirements. In Figure 2.7, the diamond represents three yes/no decision points within finance, and one each within sales and operations. These yes/no decision points are more likely to appear when a process is high in divergence.



▲ **FIGURE 2.7**
Swim Lane Flowchart of the Order-Filling Process Showing Handoffs between Departments

Source: D. Kroenke, *Using MIS*, 4th ed., © 2012. Reprinted and electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.

service blueprint
A special flowchart of a service process that shows which steps have high customer contact.

Swim lane flowcharts allow the process analyst and managers to look at the horizontal organization rather than the vertical organization and departmental boundaries implied by a typical organizational chart. Swim lane flowcharts show how organizations produce their outputs through cross-functional work processes and allow the design team to see all the critical interfaces between functions and departments.

Service Blueprint A **service blueprint** is a special flowchart of a service process that shows which steps have high customer contact. It uses a dotted line of visibility to identify which steps are visible to the customer (and thus are more of a front-office process) and those that are not (back-office process). Of course, visibility is just one aspect of customer contact, and it may not adequately capture how actively the customer is involved or how much personal attention is required. A service blueprint can use colors, shading, or box shapes, instead of the lines of visibility, to show the extent and type of customer contact. Another approach to service blueprinting is to tag each step with a number, and then have an accompanying table that describes in detail the customer contact for each numbered step. There is no one "right way" to create a flow chart or service blueprint.

Work Measurement Techniques

Process definition would not be complete without estimates of the average time each step in the process would take. Time estimates are needed not just for process-improvement efforts but for capacity planning, constraint management, performance appraisal, and scheduling. Estimating task times can be as simple as making a reasoned guess, asking a knowledgeable person, or taking notes while observing the process. More extensive studies involve collecting data for several weeks, consulting cost accounting data, or checking data recorded in information systems.

Formal techniques that rely on the judgment of skilled observers are also available: (1) the time study method, (2) the elemental standard data method, (3) the predetermined data method, and (4) work sampling. A fifth method, (5) learning curve analysis, is particularly appropriate when a new product or process is introduced and the time per unit produced has not yet stabilized. The method chosen depends on the purpose of the data, process type (job, batch, or line), and degree of product customization. A more comprehensive treatment of these techniques is provided in online Supplement H, "Measuring Output Rates" and online Supplement I, "Learning Curve Analysis."

Time Study Method **Time study** uses a trained analyst to perform four basic steps in setting a time standard for a job or process: (1) selecting the work elements (steps in a flowchart or process chart) within the process to be studied, (2) timing the elements, (3) determining the sample size, and (4) setting the final standard. It is essentially the average time observed, adjusted for normal effort and making an allowance for breaks, unavoidable delays, and the like. The analyst records time spent on each element of the process being studied using a stopwatch, and records the time spent on each element for several repetitions. The analyst assigns a performance rating for each element to adjust for normal effort. Some elements may be performed faster or slower than normal, in the analyst's judgment. The allowance is expressed as a proportion or percent of the total *normal* time.

time study

A work measurement method using a trained analyst to perform four basic steps in setting a time standard for a job or process: selecting the work elements (or nested processes) within the process to be studied, timing the elements, determining the sample size, and setting the final standard.

Elemental Standard Data Method Another method is needed when products or services are highly customized, job processes prevail, and process divergence is great. **Elemental standard data** is a database of standards compiled by a firm's analysts for basic elements that they can draw on later to estimate the time required for a particular job. This approach works well when work elements within certain jobs are similar to those in other jobs. Sometimes, the time required for a work element depends on variable characteristics of the jobs, such as the amount of metal to be deposited for a welding process. In such cases, an equation that relates these characteristics to the time required is also stored in the database. Another method, such as time study or past records, still must be used to compile the normal times (before the allowance is added) stored in the database.

elemental standard data

A database of standards compiled by a firm's analysts for basic elements that they can draw on later to estimate the time required for a particular job, which is most appropriate when products or services are highly customized, job processes prevail, and process divergence is great.

EXAMPLE 2.1 Time Study of Watch Assembly Process

A process at a watch assembly plant has been changed. The process is divided into three work elements. A time study has been performed with the following results. The time standard for the process previously was 14.5 minutes. Based on the new time study, should the time standard be revised?



Bloomberg/Getty Images

Workers seen on a watch assembly line at the Jaeger-LeCoultre factory in Le Sentier, Switzerland.

SOLUTION

The new time study had an initial sample of four observations, with the results shown in the following table. The performance rating factor (RF) is shown for each element (to adjust for normal effort), and the allowance for the whole process is 18 percent of the total *normal* time.

	Obs 1	Obs 2	Obs 3	Obs 4	Average (min)	RF	Normal Time
Element 1	2.60	2.34	3.12	2.86	2.730	1.0	2.730
Element 2	4.94	4.78	5.10	4.68	4.875	1.1	5.363
Element 3	2.18	1.98	2.13	2.25	2.135	0.9	1.922
					Total Normal Time = **10.015 minutes**		

The normal time for an element in the table is its average time, multiplied by the RF. The total normal time for the whole process is the sum of the normal times for the three elements, or 10.015 minutes. To get the standard time (ST) for the process, just add in the allowance, or

$$ST = 10.015(1 + 0.18) = \mathbf{11.82} \text{ minutes/watch}$$

DECISION POINT

The time to assemble a watch appears to have decreased considerably. However, based on the precision that management wants, the analyst decided to increase the sample size before setting a new standard. Online Supplement H, "Measuring Output Rates," gives more information on determining the number of additional observations needed.

predetermined data method
A database approach that divides each work element into a series of micromotions that make up the element. The analyst then consults a published database that contains the normal times for the full array of possible micromotions.

work sampling
A process that estimates the proportion of time spent by people or machines on different activities, based on observations randomized over time.

Predetermined Data Method The **predetermined data method** divides each work element even more, into a series of micromotions that make up the element. The analyst then consults a published database that contains the normal times for the full array of possible micromotions. A process's normal time can then be calculated as the sum of the times given in the database for the elements performed in the process. This approach makes most sense for highly repetitive processes with little process divergence and line flows. The micromotions (such as reach, move, or apply pressure) are very detailed.

Work Sampling Method **Work sampling** estimates the proportion of time spent by people or machines on different activities, based on observations randomized over time. Examples of these activities include working on a service or product, doing paperwork, waiting for instructions, waiting for maintenance, or being idle. Such data can then be used to assess a process's productivity, estimate the allowances needed to set standards for other work measurement methods, and spot areas for process improvement. It is best used when the processes are highly divergent with flexible flows. Figure 2.8 shows the input data and numerical results for 1 week of observations. It shows an idle time of 23.81 percent for the week and also reports that 237 more observations are needed to achieve the confidence and precision levels required with the input data. How these conclusions are reached is explained in online Supplement H, "Measuring Output Rates."

(a) Input Data and Numerical Results

Increase Observations | Remove An Observation

Confidence *z*	1.96	Precision *p*	0.05

Observation Period	Times Busy	Times Idle	Observations
Monday	6	1	7
Tuesday	5	2	7
Wednesday	7	0	7
Thursday	9	2	11
Friday	5	5	10
Total	32	10	42

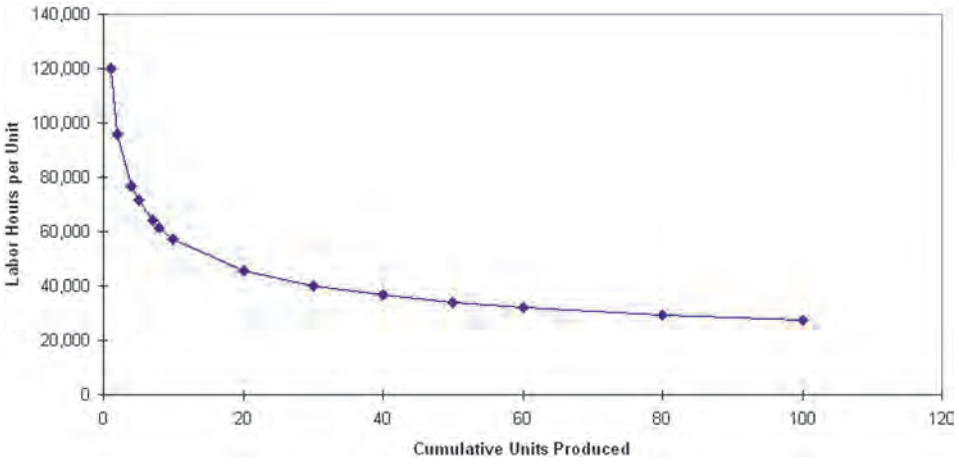
(b) Idle Time and Observations Required

Portion of idle times	0.2381
Total observations required	279
Additional observations required	237

▲ **FIGURE 2.8**
Work Sampling Study of Admission Clerk at Health Clinic Using OM Explorer's *Time Study* Solver

learning curve
A line that displays the relationship between processing time and the cumulative quantity of a product or service produced.

Learning Curve Analysis The time estimation techniques just covered assume that the process is stable. If the process is revised, then just repeat the method for the revised process after it stabilizes. Learning curve analysis, in contrast, takes into account that learning takes place on an ongoing basis, such as when new products or services are introduced frequently. With instruction and repetition, workers learn to perform jobs more efficiently, process improvements are identified, and better administration methods are created. These learning effects can be anticipated with a **learning curve**, a line that displays the relationship between processing time and the cumulative quantity of a product or service produced. The time required to produce a unit or create a service decreases as more units or customers are processed. The learning curve for a process depends on the rate of learning and the actual or estimated time for the first unit processed. Figure 2.9 demonstrates the learning curve assuming an 80 percent learning rate, with the first unit taking 120,000 hours and the cumulative average time for the first 10 units produced. The learning rate deals with each *doubling* of the output total. The time for the second unit is 80 percent of the first (or 120,000 × .80 = 96,000 hours), the time for the fourth unit is 80 percent of the second unit (or 96,000 × .80 = 76,800 hours), and so on. Finding the time estimate for a unit that is not an exact doubling (such as the fifth unit), and also the cumulative average time for the first 10 units, is explained in online Supplement I, "Learning Curve Analysis."



Time for first unit	120,000
Unit number	10
Time for unit 10	57,172
Cumulative average time per unit	75,784

◀ **FIGURE 2.9**
Learning Curve with 80% Learning Rate Using OM Explorer's *Learning Curves* Solver

Process Charts

process chart
An organized way of documenting all the activities performed by a person or group of people, at a workstation, with a customer, or on materials.

A **process chart** is an organized way of documenting all the activities performed by a person or group of people at a workstation, with a customer, or working with certain materials. It analyzes a process using a table, and provides information about each step in the process. In contrast to flowcharts, swim lane flowcharts, and service blueprints, it requires the time estimates (see work measurement techniques covered in the last section). Often it is used to drill down to the job level for an individual person, a team, or a focused nested process. It can have many formats. Here, we group the type of activities for a typical process into five categories:

- *Operation.* Changes, creates, or adds something. Drilling a hole and serving a customer are examples of operations.
- *Transportation.* Moves the study's subject from one place to another (sometimes called *materials handling*). The subject can be a person, a material, a tool, or a piece of equipment. A customer walking from one end of a counter to the other, a crane hoisting a steel beam to a location, and a conveyor carrying a partially completed product from one workstation to the next are examples of transportation. It could also be the shipment of a finished product to the customer or a warehouse.
- *Inspection.* Checks or verifies something but does not change it. Getting customer feedback, checking for blemishes on a surface, weighing a product, and taking a temperature reading are examples of inspections.
- *Delay.* Occurs when the subject is held up awaiting further action. Time spent waiting for a server; time spent waiting for materials or equipment; cleanup time; and time that workers, machines, or workstations are idle because they have no work to complete are examples of delays.
- *Storage.* Occurs when something is put away until a later time. Supplies unloaded and placed in a storeroom as inventory, equipment put away after use, and papers put in a file cabinet are examples of storage.

Depending on the situation, other categories can be used. For example, subcontracting for outside services might be a category, temporary storage and permanent storage, or environmental waste might be three separate categories. Choosing the right category for each activity requires taking the perspective of the subject charted. A delay for the equipment could be inspection or transportation for the operator.

Online Resource
Tutor 2.2 in OM Explorer provides a new example to practice creating process charts.

To complete a chart for a new process, the analyst must identify each step performed. If the process is an existing one, the analyst can actually observe the steps and categorize each step according to the subject being studied. The analyst then records the distance traveled and the time taken to perform each step. After recording all the activities and steps, the analyst summarizes the steps, times, and distances data. Figure 2.10 shows a process chart prepared using OM Explorer's *Process Chart* Solver. It is for a patient with a twisted ankle being treated at a hospital. The process begins at the entrance and ends with the patient exiting after picking up a prescription.

After a process is charted, the analyst sometimes estimates the annual cost of the entire process. It becomes a benchmark against which other methods for performing the process can be evaluated. Annual labor cost can be estimated by finding the product of (1) time in hours to perform the process each time, (2) variable costs per hour, and (3) number of times the process is performed each year, or

$$\begin{pmatrix}\text{Annual}\\ \text{labor cost}\end{pmatrix} = \begin{pmatrix}\text{Time to perform}\\ \text{the process in hours}\end{pmatrix}\begin{pmatrix}\text{Variable costs}\\ \text{per hour}\end{pmatrix}\begin{pmatrix}\text{Number of times process}\\ \text{is performed per year}\end{pmatrix}$$

For example, if the average time to serve a customer is 4 hours, the variable cost is \$25 per hour, and 40 customers are served per year, then the labor cost is \$4,000 per year (or 4 hr/customer × \$25/hr × 40 customers/yr).

In the case of the patient in Figure 2.10, this conversion would not be necessary, with total patient time being sufficient. What is being tracked is the patient's time, not the time and costs of the service providers.

You can design your own process chart spreadsheets to bring out issues that are particularly important for the process you are analyzing, such as categories for customer contact, process divergence, and the like. You can also track performance measures other than time and distance traveled, such as error rates. In addition, you can also create a different version of the process chart spreadsheet that examines processes much as done with flowcharts, except now in the form of a table. The columns that categorize the activity type could be replaced by one or more columns reporting different metrics of interest, rather than trying to fit them into a flowchart. Although it might not look as elegant, it could be just as informative—and easier to create.

FIGURE 2.10 ▶
Process Chart for Emergency Room Admission

Process:	Emergency room admission
Subject:	Ankle injury patient
Beginning:	Enter emergency room
Ending:	Leave hospital

Insert Step

Append Step

Remove Step

Summary

Activity	Number of Steps	Time (min)	Distance (ft)
Operation ●	5	23.00	
Transport ➡	9	11.00	815
Inspect ■	2	8.00	
Delay ◗	3	8.00	
Store ▼	—	—	

Step No.	Time (min)	Distance (ft)	●	➡	■	◗	▼	Step Description
1	0.50	15.0		X				Enter emergency room, approach patient window
2	10.00		X					Sit down and fill out patient history
3	0.75	40.0		X				Nurse escorts patient to ER triage room
4	3.00				X			Nurse inspects injury
5	0.75	40.0		X				Return to waiting room
6	1.00					X		Wait for available bed
7	1.00	60.0		X				Go to ER bed
8	4.00					X		Wait for doctor
9	5.00				X			Doctor inspects injury and questions patient
10	2.00	200.0		X				Nurse takes patient to radiology
11	3.00		X					Technician x-rays patient
12	2.00	200.0		X				Return to bed in ER
13	3.00					X		Wait for doctor to return
14	2.00		X					Doctor provides diagnosis and advice
15	1.00	60.0		X				Return to emergency entrance area
16	4.00		X					Check out
17	2.00	180.0		X				Walk to pharmacy
18	4.00		X					Pick up prescription
19	1.00	20.0		X				Leave the building



ESB Professional/Shutterstock

The leader of a design team presents several charts that document a process in their office that they are analyzing. He is identifying several areas of substandard performance across a range of different metrics. The next step will be to redesign the process. The flipchart on the right will be quite useful in generating rapid fire ideas from the team on how the process might be improved.

Data Analysis Tools

Metrics and performance information complete the documentation of a process. The specific metrics analysts choose depends on the process being analyzed and on the competitive priorities. Good starting points are the per-unit processing time and cost at each step, and the time elapsed from beginning to end of the process. Capacity utilization, environmental issues, and customer (or job) waiting times reveal where in the process delays are most likely to occur. Customer satisfaction measures, error rates, and scrap rates identify possible quality problems. We introduce many such metrics in subsequent chapters. Only when these subsequent chapters are understood do we really complete our discussion of process analysis.

Metrics can be displayed in various ways. Sometimes, they can be added directly on the flowchart or process chart. When the number of metrics gets unwieldy, another approach is to create a supporting table for the chart. Its rows are the steps in the flowchart, swim lane flowchart, service blueprint, or process chart. The columns are the current performance, goals, and performance gaps for various metrics. Various tools are available to help you understand the causes of these performance gaps and problems.[3] Here we present six tools: (1) checklists, (2) histograms and bar charts, (3) Pareto charts, (4) scatter diagrams, (5) cause-and-effect diagrams, and (6) graphs. Many of them were developed initially to analyze quality issues, but they apply equally well to process analysis in general.

checklist
A form used to record the frequency of occurrence of certain process failures.

process failure
Any performance shortfall, such as error, delay, environmental waste, rework, and the like.

Checklists Data collection through the use of a checklist is often the first step in the analysis of a metric. A **checklist** is a form used to record the frequency of occurrence of certain process failures. A **process failure** is any performance shortfall, such as error, delay, environmental waste, rework, and the like. The characteristics may be measurable on a continuous scale (e.g., weight,

[3]Several of these tools, particularly Pareto charts and cause-and-effect diagrams, are closely affiliated with Chapter 3, "Quality and Performance." We introduce them here because they apply to process failures in general and not just to quality rejects.

customer satisfaction on a 1 to 7 scale, unit cost, scrap loss percentage, time, or length) or on a yes/no basis (e.g., customer complaint, posting error, paint discoloration, or inattentive servers).

Histograms and Bar Charts Data from a checklist often can be presented succinctly and clearly with histograms or bar charts. A **histogram** summarizes data measured on a continuous scale, showing the frequency distribution of some process failure (in statistical terms, the central tendency and dispersion of the data). Often the mean of the data is indicated on the histogram. A **bar chart** (Figure 2.11) is a series of bars representing the frequency of occurrence of data characteristics measured on a yes/no basis. The bar height indicates the number of times a particular process failure was observed.

histogram
A summarization of data measured on a continuous scale, showing the frequency distribution of some process failure (in statistical terms, the central tendency and dispersion of the data).

bar chart
A series of bars representing the frequency of occurrence of data characteristics measured on a yes/no basis.

Pareto Charts When managers discover several process problems that need to be addressed, they have to decide which should be attacked first. Vilfredo Pareto, a 19th-century Italian scientist whose statistical work focused on inequalities in data, proposed that most of an "activity" is caused by relatively few of its factors. In a restaurant-quality problem, the activity could be customer complaints and the factor could be "discourteous server." For a manufacturer, the activity could be product defects and the factor could be "missing part." Pareto's concept, called the 80–20 rule, is that 80 percent of the activity is caused by 20 percent of the factors. By concentrating on the 20 percent of the factors (the "vital few"), managers can attack 80 percent of the process failure problems. Of course, the exact percentages vary with each situation, but inevitably relatively few factors cause most of the performance shortfalls.

The few vital factors can be identified with a **Pareto chart**, a bar chart on which the factors are plotted along the horizontal axis in decreasing order of frequency (Figure 2.12). The chart has two vertical axes, the one on the left showing frequency (as in a histogram) and the one on the right showing the cumulative percentage of frequency. The cumulative frequency curve identifies the few vital factors that warrant immediate managerial attention.

Pareto chart
A bar chart on which factors are plotted along the horizontal axis in decreasing order of frequency.

EXAMPLE 2.2 Pareto Chart for a Restaurant

The manager of a neighborhood restaurant is concerned about the lower numbers of customers patronizing his eatery. Complaints have been rising, and he would like to find out what issues to address and present the findings in a way his employees can understand.

SOLUTION

The manager surveyed his customers over several weeks and collected the following data:

Complaint	Frequency
Discourteous server	12
Slow service	42
Cold dinner	5
Cramped tables	20
Atmosphere	10

Figure 2.11 is a bar chart and Figure 2.12 is a Pareto chart, both created with OM Explorer's *Bar, Pareto, and Line Charts* Solver. They present the data in a way that shows which complaints are more prevalent (the vital few). You can reformat these charts for any yes/no metrics by unprotecting the spreadsheet and then making your revisions. Another approach is to create your own spreadsheets from scratch. More advanced software with point-and-click interfaces include Minitab (https://www.minitab.com/en-us/), SAS (https://www.sas.com/en_us/home.html), and Microsoft Visio (https://www.microsoft.com/en-us/.).

DECISION POINT

It was clear to the manager (and all employees) which complaints, if rectified, would cover most of the process failure problems in the restaurant. First, slow service will be addressed by training the existing staff, adding another server, and improving the food preparation process. Removing some decorative furniture from the dining area and spacing the tables better will solve the problem with cramped tables. The Pareto chart shows that these two problems, if rectified, will account for almost 70 percent of the complaints.

Online Resources

Active Model 2.1 provides additional insights on this Pareto chart example and its extensions.

Tutor 2.3 in OM Explorer provides a new example on creating Pareto charts.



Vlad Zymovin/Shutterstock

People having lunch in packed restaurants on a hot day.

FIGURE 2.11 ▶
Bar Chart

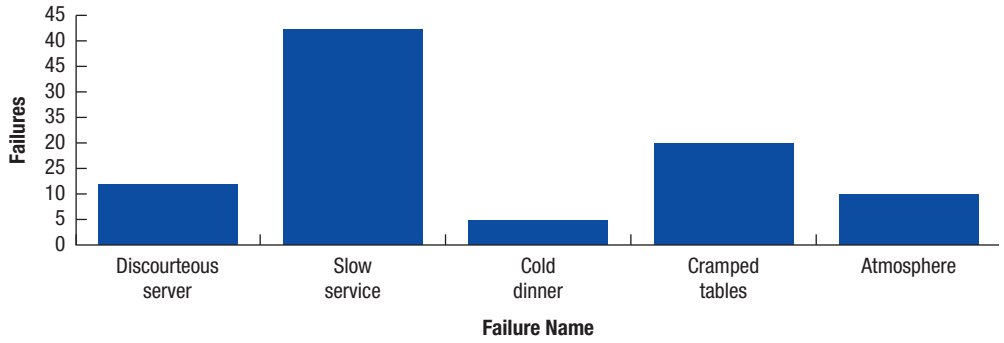
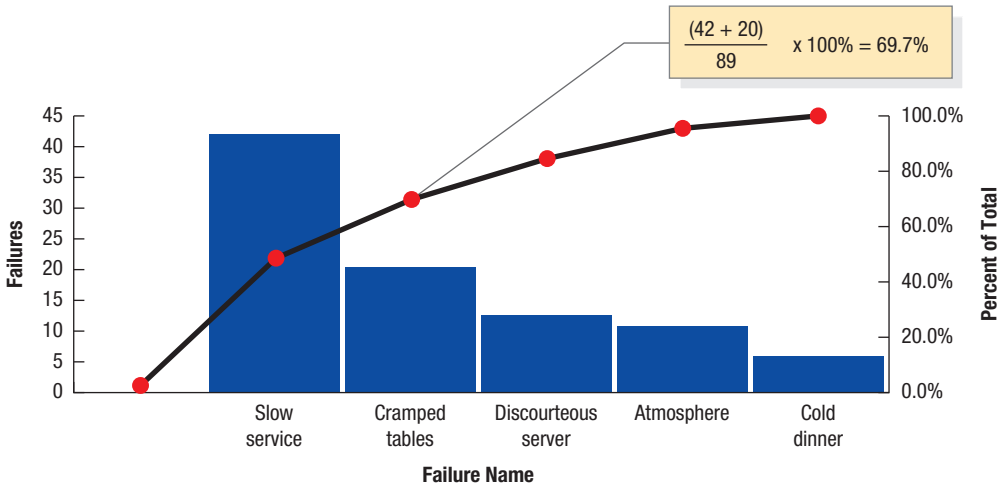


FIGURE 2.12 ▶
Pareto Chart



scatter diagram
A plot of two variables showing whether they are related.

Scatter Diagrams Sometimes managers suspect that a certain factor is causing a particular process failure. A **scatter diagram**, which is a plot of two variables showing whether they are related, can be used to verify or negate the suspicion. Each point on the scatter diagram represents one data observation. For example, the manager of a castings shop may suspect that casting defects are a function of the diameter of the casting. A scatter diagram could be constructed by plotting the number of defective castings found for each diameter of casting produced. After the diagram is completed, any relationship between diameter and number of process failures will be clear.

cause-and-effect diagram
A diagram that relates a key performance problem to its potential causes.

Cause-and-Effect Diagrams An important aspect of process analysis is linking each metric to the inputs, methods, and process steps that build a particular attribute into the service or product. One way to identify a design problem is to develop a **cause-and-effect diagram** that relates a key performance problem to its potential causes. First developed by Kaoru Ishikawa, the diagram helps management trace disconnects directly to the operations involved. Processes that have no bearing on a particular problem are not shown on the diagram.

The cause-and-effect diagram sometimes is called a *fishbone diagram*. The main performance gap is labeled as the fish's "head," the major categories of potential causes as structural "bones," and the likely specific causes as "ribs." When constructing and using a cause-and-effect diagram, an analyst identifies all the major categories of potential causes for the problem. These might be personnel, machines, materials, and processes. For each major category, the analyst lists all the likely causes of the performance gap. Under personnel might be listed "lack of training," "poor communication," and "absenteeism." Creative thinking helps the analyst identify and properly classify all suspected causes. The analyst then systematically investigates the causes listed on the diagram for each major category, updating the chart as new causes become apparent. The process of constructing a cause-and-effect diagram calls management and worker attention to the primary factors affecting process failures. Example 2.3 demonstrates the use of a cause-and-effect diagram by a firm manufacturing air conditioners.

EXAMPLE 2.3 Analysis of Inadequate Production of Headers

A process improvement team is working to improve the production output of Johnson Manufacturing's header cell. Johnson manufactures a key component, headers, used in commercial air conditioners. A header is part of the circulatory system of a commercial air conditioner that moves coolant between various components such as the evaporator coil and the condenser coil. Currently, the header production

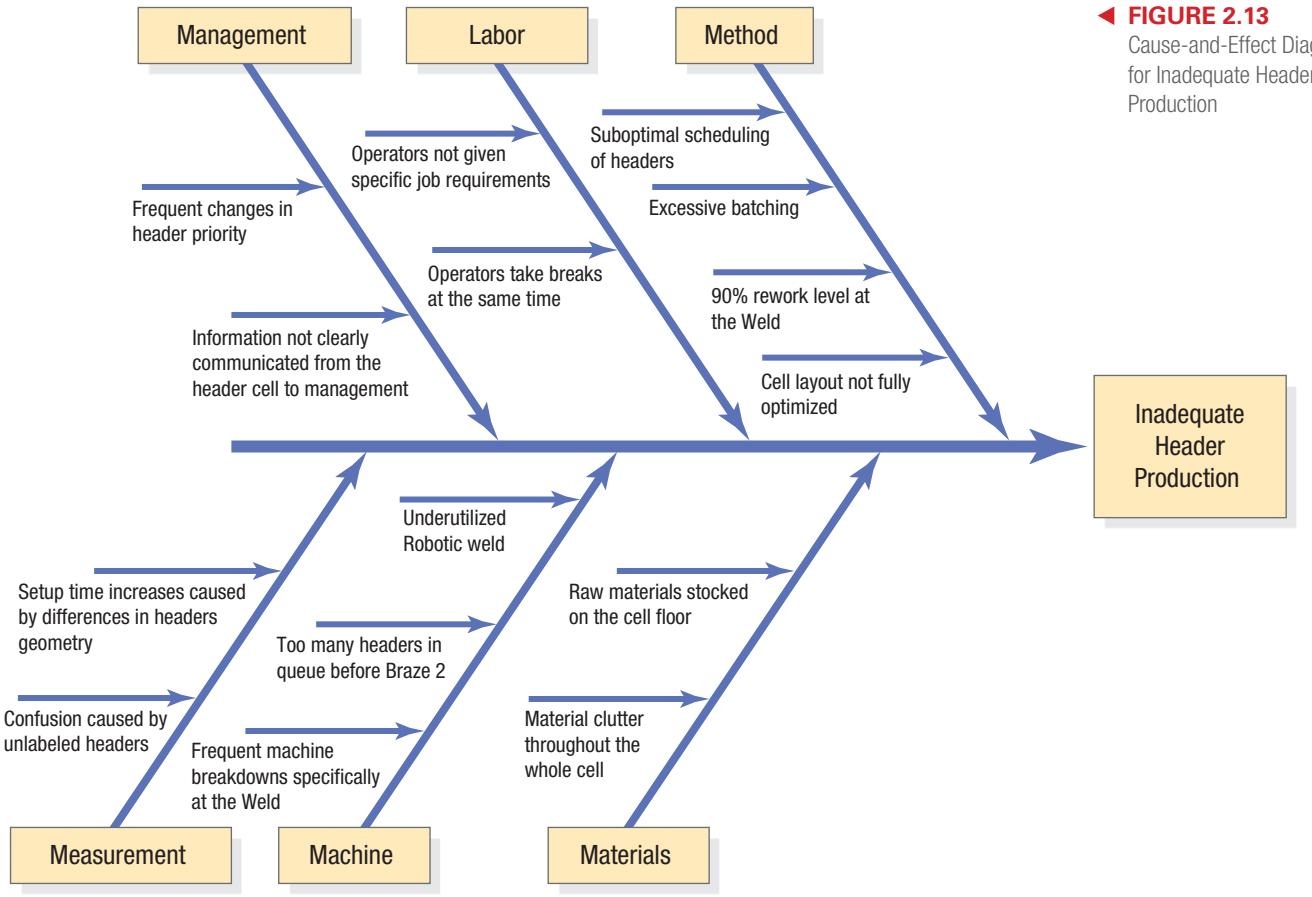
cell is scheduled separately from the main work in the plant. Often, individual headers are not sequenced to match the product they go into on the final assembly line in a timely fashion, and so the product can sit in queue waiting for a header.

SOLUTION

As a first step, the team conducted extensive onsite observations across the six processing steps within the cell, followed by the transport of the finished header to the air conditioner assembly area for installation into an air conditioner unit. The six processing steps included:

1. Cut copper pipes to the appropriate length.
2. Punch vent and stub holes into the copper log.
3. Weld a steel supply valve onto the top of the copper log.
4. Braze end caps and vent plugs to the copper log.
5. Braze stub tubes into each stub hole in the copper log.
6. Add plastic end caps to protect the newly created header.

To analyze all the possible causes of the problem, the team constructed a cause-and-effect diagram (Figure 2.13). The main problem, inadequate header production, is the head of the diagram. The team brainstormed all possible causes, and together they identified several major categories: management, labor, method, measurement, machine, and materials—or the 6 Ms. Several suspected causes were identified for each major category.



◀ **FIGURE 2.13**
Cause-and-Effect Diagram for Inadequate Header Production

DECISION POINT

The improvement team noted several immediate issues that were slowing down production of headers. These issues included operators batching individual jobs (method branch) into groups to save walking time, which was further exacerbated by the availability of raw materials stocked on the shop floor (materials branch) and the lack of specific job requirement (management branch). Further, there were many instances of individual tasks not being done correctly, and thus having to be redone—such as the 90 percent rework rate at weld (method branch). The next step in this process improvement was to eliminate the raw material on the floor, improve quality at the weld machine, and move each header individually using a header-specific cart.

graphs
Representations of data in a variety of pictorial forms, such as line charts and pie charts.

Graphs Visualizing data in user-friendly ways can greatly enhance process analysis. **Graphs** represent data in a variety of pictorial formats, such as line charts and pie charts. *Line charts* represent data sequentially with data points connected by line segments to highlight trends in the data. Line charts are used in control charts (see Chapter 3, "Quality and Performance") and forecasting (see Chapter 8, "Forecasting"). Pie charts represent process factors as slices of a pie; the size of each slice is in proportion to the number of occurrences of the factor. Pie charts are useful for showing data from *a group of factors* that can be represented as percentages totaling 100 percent.

Each of the tools for improving quality may be used independently, but their power is greatest when they are used together. In solving a process-related problem, managers often must act as detectives, sifting data to clarify the issues involved and deducing the causes. We call this process *data snooping*. Example 2.4 demonstrates how the tools for improving quality can be used for data snooping.

EXAMPLE 2.4 Identifying Causes of Poor Headliner Process Failures

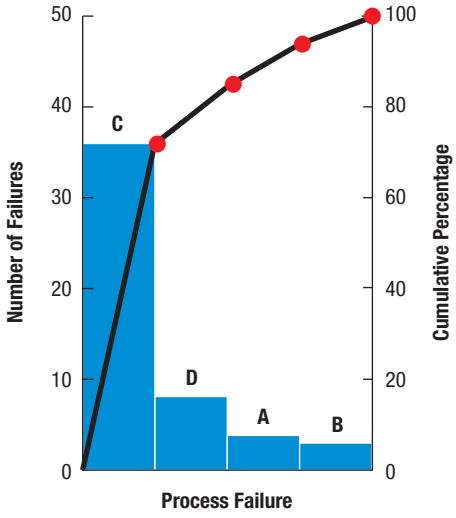
The Wellington Fiber Board Company produces headliners, the fiberglass components that form the inner roof of passenger cars. Management wanted to identify which process failures were most prevalent and to find the cause.

Step 1. Checklist

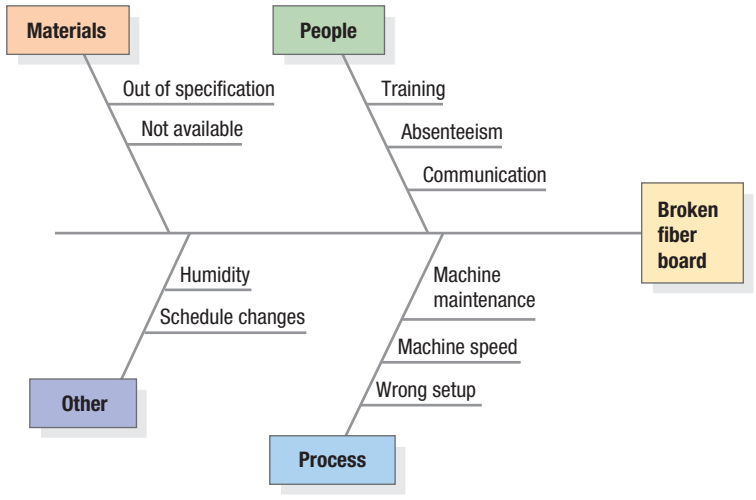
Headliner failures

Process failure	Tally	Total
A. Tears in fabric	IIII	4
B. Discolored fabric	III	3
C. Broken fiber board	𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 I	36
D. Ragged edges	𝍸 II	7
		Total 50

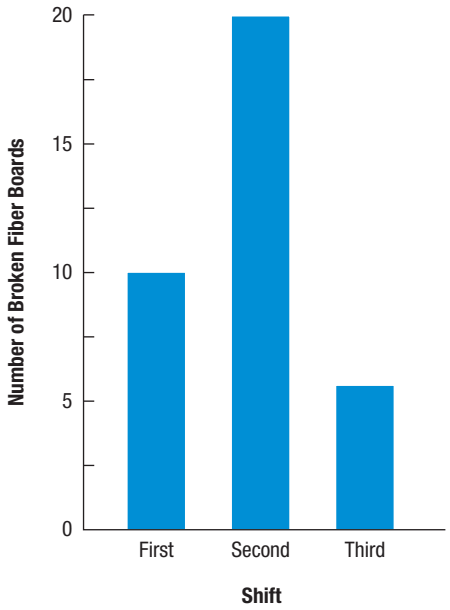
Step 2. Pareto Chart



Step 3. Cause-and-Effect Diagram



Step 4. Bar Chart



▲ **FIGURE 2.14**
Application of the Tools for Improving Quality

SOLUTION

Figure 2.14 shows the sequential application of several tools for improving quality.

Step 1. A checklist of different types of process failures was constructed from last month's production records.

Step 2. A Pareto chart prepared from the checklist data indicated that broken fiber board accounted for 72 percent of the process failures.

Step 3. A cause-and-effect diagram for broken fiber board identified several potential causes for the problem. The one strongly suspected by the manager was employee training.

Step 4. The manager reorganized the production reports into a bar chart according to shift, because the personnel on the three shifts had varied amounts of experience.

DECISION POINT

The bar chart indicated that the second shift, with the least experienced workforce, had most of the process failures. Further investigation revealed that workers were not using proper procedures for stacking the fiber boards after the press operation, which caused cracking and chipping. The manager set up additional training sessions focused on board handling. Although the second shift was not responsible for all the process failures, finding the source of many of the failures enabled the manager to improve the performance of her operations.

A simulation model goes one step further than static data analysis tools, because it can show how the process dynamically changes over time. **Process simulation** is the act of reproducing the behavior of a process, using a model that describes each step. Once the process is modeled, the analyst can make changes in the model to measure the impact on certain metrics, such as response time, waiting lines, resource utilization, and the like. To learn more about how simulation works, see online Supplement E, "Simulation."

process simulation
The act of reproducing the behavior of a process, using a model that describes each step.

Redesigning and Managing Process Improvements

A doctor pinpoints an illness after a thorough examination of the patient, and then the doctor recommends treatments based on the diagnosis; so it is with processes. After a process is defined, metrics data are collected, and disconnects are identified, the process analyst or design team puts together a set of changes that will improve the process. At this step, people directly involved in the process are brought in to get their ideas and inputs.

Questioning and Brainstorming

Sometimes, ideas for reengineering or improving a process become apparent after defining the process and carefully examining the areas of substandard performance, handoffs between departments, and steps where customer contact is high. Example 2.4 illustrated how such documentation pointed to a better way of handling the fiber boards through better training. In other cases, the better solution is less evident. Ideas can be uncovered (because there is always a better way) by asking six questions about each step in the process, and a final series of questions about the process as a whole:

1. *What* is being done?
2. *When* is it being done?
3. *Who* is doing it?
4. *Where* is it being done?
5. *How* is it being done?
6. *How* well does it do on the various metrics of importance?

Answers to these questions are challenged by asking still another series of questions. *Why* is the process even being done? *Why* is it being done where it is being done? *Why* is it being done when it is being done?

Creativity can also be stimulated by **brainstorming**, letting a group of people knowledgeable about the process propose ideas for change by saying whatever comes to mind. A facilitator records the ideas on a flipchart, so that all can see. Participants are discouraged from evaluating any of the ideas generated during the session. The purpose is to encourage creativity and to get as many ideas as possible, no matter how far-fetched the ideas may seem. The participants of a brainstorming session need not be limited to the design team as long as they have seen or worked with the process. For instance, Baptist Memorial Hospital in Memphis, Tennessee, holds "huddle meetings" at least three times a day seeking out process improvements. The meetings bring together the hospital's

brainstorming
Letting a group of people, knowledgeable about the process, propose ideas for change by saying whatever comes to mind.

house supervisor, housekeeping supervisor, and key nurses. Improvements have been dramatic, and resulted in it being ranked among the top five hospitals in Tennessee.

A growing number of big companies are also taking advantage of the Internet and specially designed software to run brainstorming sessions that allow people at far-flung locations to "meet" online and hash out solutions to particular problems. The technology lets employees see, and build on, one another's ideas, so that one person's seed of a notion can grow into a practical plan.

After the brainstorming session is over, the design team moves into the "get real" phase: They evaluate the different ideas. The team identifies the changes that give the best payoffs for process redesign. The redesign could involve issues of capacity, technology, or even location, all of which are discussed in more detail in the following chapters.

The redesigned process is defined once again, this time as the "after" view of the process. Expected payoffs are carefully estimated, along with risks. For changes involving investments, the time value of money must be considered (see online Supplement F, "Financial Analysis"). The impact on people (skills, degree of change, training requirements, and resistance to change) must also be factored into the evaluation of the new design.

Benchmarking

benchmarking

A systematic procedure that measures a firm's processes, services, and products against those of industry leaders.

Benchmarking can be another valuable source for process redesign. **Benchmarking** is a systematic procedure that measures a firm's processes, services, and products against those of industry leaders. Companies use benchmarking to better understand how outstanding companies do things so that they can improve their own processes.

Benchmarking focuses on setting quantitative goals for improvement. *Competitive* benchmarking is based on comparisons with a direct industry competitor. *Functional* benchmarking compares areas such as administration, customer service, and sales operations with those of outstanding firms in any industry. For instance, Xerox benchmarked its distribution function against L.L. Bean's because L.L. Bean is renowned as a leading retailer in distribution efficiency and customer service. *Internal* benchmarking involves using an organizational unit with superior performance as the benchmark for other units. This form of benchmarking can be advantageous for firms that have several business units or divisions. All forms of benchmarking are best applied in situations where you are looking for a long-term program of continuous improvement.

Typical measures used in benchmarking include cost per unit, service upsets (breakdowns) per customer, processing time per unit, customer retention rates, revenue per unit, return on investment, and customer satisfaction levels.

Collecting benchmarking data can sometimes be a challenge. Internal benchmarking data are surely the most accessible. One way of benchmarking is always available—tracking the performance of a process over time. Functional benchmarking data are often collected by professional associations or consulting firms. Several corporations and government organizations have agreed to share and standardize performance benchmarks. The American Productivity and Quality Center, a nonprofit organization, created thousands of measures, as Figure 2.15 illustrates. A full range of metrics can be explored at www.apqc.org. Another source is the Supply Chain Council, which has defined key metrics in its Supply Chain Operations Reference (SCOR) model (see Chapter 14, "Supply Chain Integration").

Implementing

Implementing a beautifully redesigned process is only the beginning to continually monitoring and improving processes. Metrics goals must be continually evaluated and reset to fit changing requirements. Avoid the following seven mistakes when managing processes:[4]

1. *Not Connecting with Strategic Issues.* Is particular attention being paid to core processes, competitive priorities, impact of customer contact and volume, and strategic fit during process analysis?
2. *Not Involving the Right People in the Right Way.* Does process analysis closely involve the people performing the process, or those closely connected to it as internal customers and suppliers?
3. *Not Giving the Design Teams and Process Analysts a Clear Charter, and Then Holding Them Accountable.* Does management set expectations for change and maintain pressure for results? Does it allow paralysis in process-improvement efforts by requiring excessive analysis?
4. *Not Being Satisfied Unless Fundamental "Reengineering" Changes Are Made.* Is the radical change from process reengineering the expectation? If so, the cumulative effect of many small improvements that could be made incrementally could be lost. Process management efforts should not be limited to downsizing or to reorganization only, even though jobs may be eliminated or the structure changed. It should not be limited to big technological innovation projects, even though technological change occurs often.

[4]Geary A. Rummler and Alan P. Brache, *Improving Performance*, 2nd ed. (San Francisco: Jossey-Bass, 1995), 126–133.

Customer Relationship Process

- Total cost of "enter, process, and track orders" per $1,000 revenue
- System costs of process per $100,000 revenue
- Value of sales order line item not fulfilled due to stockouts, as percentage of revenue
- Percentage of finished goods sales value that is returned
- Average time from sales order receipt until manufacturing or logistics is notified
- Average time in direct contact with customer per sales order line item
- Energy consumed in transporting product
- Total distance traveled for products
- Greenhouse gas emissions

Order Fulfillment Process

- Value of plant shipments per employee
- Finished goods inventory turnover
- Reject rate as percentage of total orders processed
- Percentage of orders returned by customers due to quality problems
- Standard customer lead time from order entry to shipment
- Percentage of orders shipped on time
- Use of non-renewable energy sources
- Use of toxic ingredients
- Safe and healthy work environment

New Service/Product Development Process

- Percentage of sales due to services/products launched last year
- Cost of "generate new services/products" process per $1,000 revenue
- Ratio of projects entering the process to projects completing the process
- Time to market for existing service/product improvement project
- Time to market for new service/product project
- Time to profitability for existing service/product improvement project

Supplier Relationship Process

- Cost of "select suppliers and develop/maintain contracts" process per $1,000 revenue
- Number of employees per $1,000 of purchases
- Percentage of purchase orders approved electronically
- Average time to place a purchase order
- Total number of active vendors per $1,000 of purchases
- Percentage of value of purchased material that is supplier certified
- Amount of toxic chemicals used in supplies production process
- Energy consumed in transporting raw materials and parts
- Total distance traveled for raw materials and parts
- Greenhouse gas emissions
- Supplier's use of toxic chemicals in production process
- Percentage of child labor used by supplier

Support Process

- Systems cost of finance function per $1,000 revenue
- Percentage of finance staff devoted to internal audit
- Total cost of payroll processes per $1,000 revenue
- Number of accepted jobs as percentage of job offers
- Total cost of "source, recruit, and select" process per $1,000 revenue
- Average employee turnover rate

◀ FIGURE 2.15
Illustrative Benchmarking Metrics by Type of Process

5. *Not Considering the Impact on People.* Are the changes aligned with the attitudes and skills of the people who must implement the redesigned process? It is crucial to understand and deal with the *people side* of process changes.
6. *Not Giving Attention to Implementation.* Are processes redesigned but never implemented? A great job of flowcharting and benchmarking is of only academic interest if the proposed changes are not implemented. Sound project management practices are required.
7. *Not Creating an Infrastructure for Continuous Process Improvement.* Is a measurement system in place to monitor key metrics over time? Is anyone checking to see whether anticipated benefits of a redesigned process are actually being realized?

Failure to manage processes is failure to manage the business. Managers must make sure that their organization spots new performance gaps in the continual search for process improvements. Process redesign efforts need to be part of periodic reviews and even annual plans. Measurement is the particular focus of the next chapter. It covers how a performance tracking system is the basis for feedback and improvement efforts. The essence of a learning organization is the intelligent use of such feedback.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
2.1 Understand the process structure in services and how to position a service process on the customer-contact matrix.	The section "Process Structure in Services" shows at the process level the key contextual variables associated with service processes and how they relate to each other. There is a key figure in this section: Figure 2.2 brings together three key elements: (1) the degree of customer contact, (2) customization, and (3) process characteristics. It shows how the degree of customer contact and customization are linked with process divergence and line flows.	
2.2 Understand the process structure in manufacturing and how to position a manufacturing process on the product-process matrix.	See the section "Process Structure in Manufacturing," which focuses on the manufacturing processes. Figure 2.3 brings together three key elements: (1) volume, (2) product customization, and (3) process characteristics. The key drivers are customization and volume, which are linked with line flows and the extent of repetitive work. See the video "Manufacturing Process Structure Choices" to understand how SOME BURROS Mexican Restaurant, WT Graphix Custom Embroidery and Silk Screening, and Crayola make tradeoffs between customization and volume in designing their processes.	
2.3 Explain the major process strategy decisions and their implications for operations.	"Process Strategy Decisions" explains three major process strategy decisions shown in Figure 2.1. Apart from process structure, these include customer involvement, resource flexibility, and capital intensity. Note that customer involvement has advantages and disadvantages, resource flexibility applies to both workforce and equipment, and economies of scope in certain situations can break the inverse relationship between resource flexibility and capital intensity.	**OM Explorer Tutor:** Break-Even for Equipment Selection **POM for Windows:** Break-Even Analysis
2.4 Discuss how process decisions should strategically fit together.	See "Strategic Fit" for a detailed discussion of ways managers should understand how the four major process decisions tie together in service and manufacturing firms, so as to spot ways of improving poorly designed processes.	
2.5 Compare and contrast the two commonly used strategies for change, and understand a systematic way to analyze and improve processes.	The section "Strategies for Change" explains two different but complementary philosophies for process design and change: (1) process reengineering and (2) process improvement. The Six Sigma DMAIC model for process improvement then shows a systematic way in which processes can be defined, measured, analyzed, improved, and controlled.	
2.6 Discuss how to define, measure, and analyze processes.	The section "Defining, Measuring, and Analyzing the Process" discusses three major techniques for effectively defining and measuring processes, including (1) flowcharts, (2) work measurement techniques, and (3) process charts. Review the Solved Problems for examples of flowchart, process chart, and Pareto chart construction. The time study method, elemental standard data method, predetermined data method, work sampling method, and learning curve analysis are briefly described in the "Work Measurement Techniques" section. Pareto charts and cause-and-effect diagrams help you to analyze and understand the causes of performance gaps.	**Cases:** Custom Molds, Inc.; José's Authentic Mexican Restaurant **OM Explorer Solvers:** Learning Curve Analysis; Measuring Output Rates; Process Charts; Pareto Charts **OM Explorer Tutors:** Process Charts; Pareto Charts **POM for Windows:** Learning Curve Analysis; Measuring Output Rates **Supplement I:** Learning Curve Analysis
2.7 Identify the commonly used approaches for effectively improving and controlling processes.	The section "Redesigning and Managing Process Improvements" discusses how the process analyst puts together a set of changes that will make the process better. Then seven mistakes to avoid when managing processes are discussed at the end. There must be a continual search for process improvements.	

Key Terms

assemble-to-order strategy 81
automation 83
back office 78
bar chart 97
batch process 80
benchmarking 102
Black Belt 90
brainstorming 101
capital intensity 76
cause-and-effect diagram 98
checklist 96
continuous-flow process 80
customer contact 77
customer involvement 76
design-to-order strategy 80
economies of scope 84
elemental standard data 93
fixed automation 84
flexible (or programmable) automation 84
flexible flow 78
flexible workforce 82
flowchart 91
focused factories 87
front office 78
graphs 100
Green Belt 90
histogram 97
hybrid office 78
industrial robot 84
job process 80
layout 76
learning curve 94
line flow 78
line process 80
make-to-order strategy 81
make-to-stock strategy 81
mass customization 81
mass production 81
Master Black Belt 90
metrics 90
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plants within plants (PWPs) 86
postponement 81
predetermined data method 94
process analysis 75
process chart 95
process choice 79
process divergence 77
process failure 96
process improvement 88
process simulation 101
process strategy 75
process structure 76
reengineering 88
resource flexibility 76
scatter diagram 98
service blueprint 92
swim lane flowchart 91
time study 93
work sampling 94

Solved Problem 1

Create a flowchart for the following telephone-ordering process at a retail chain that specializes in selling books and music CDs. It provides an ordering system via the telephone to its time-sensitive customers besides its regular store sales.

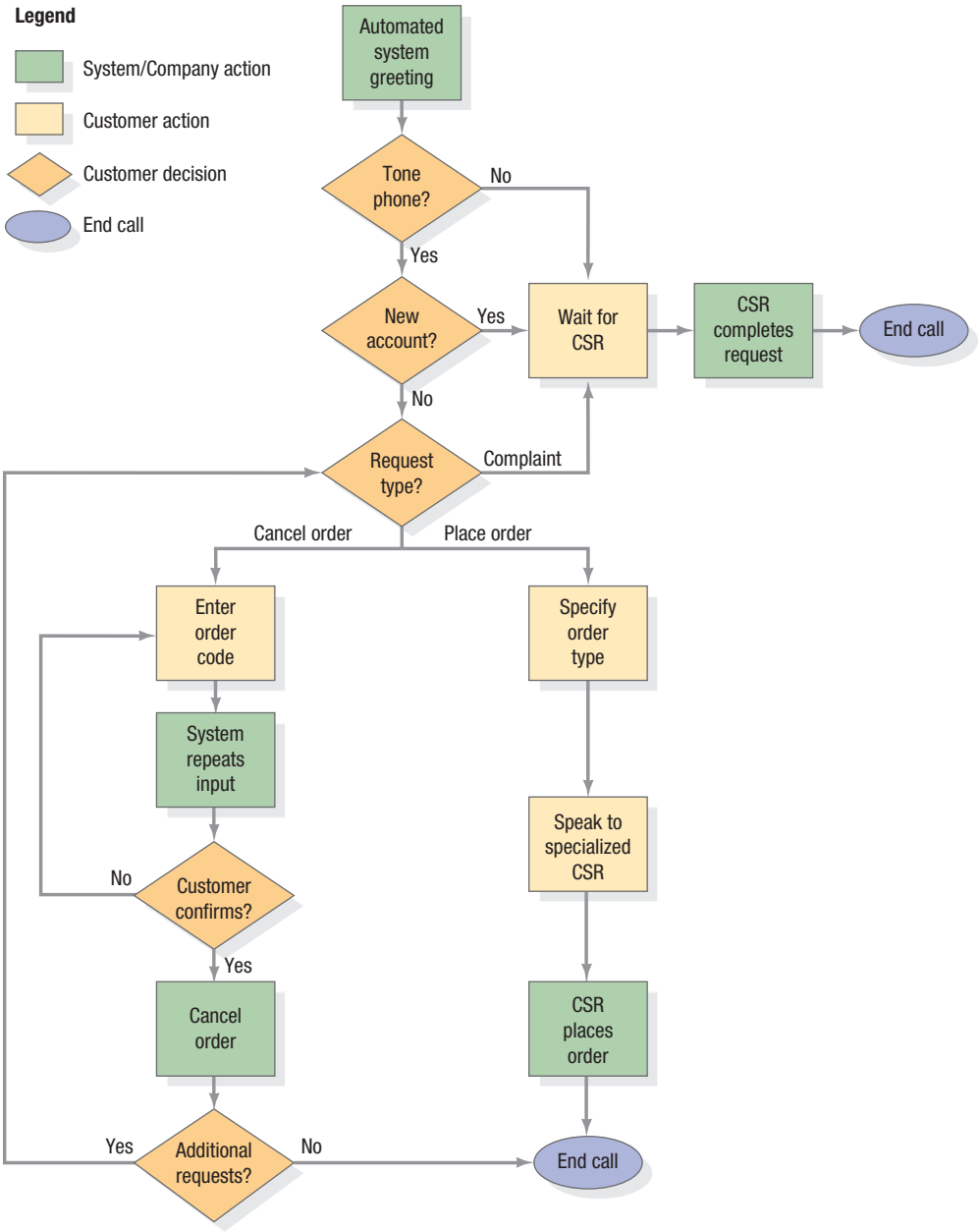
First, the automated system greets customers and identifies whether they have a tone or pulse phone. Customers choose 1 if they have a tone phone; otherwise, they wait for the first available service representative to process their request. If customers have a tone phone, they complete their request by choosing options on the phone. First, the system checks to see whether customers have an existing account. Customers choose 1 if they have an existing account or choose 2 if they want to open a new account. Customers wait for the service representative to open a new account if they choose 2.

Next, customers choose between the options of making an order, canceling an order, or talking to a customer representative for questions and/or complaints. If customers choose to make an order, then they specify the order type as a book or a music CD, and a specialized customer representative for books or music CDs picks up the phone to get the order details. If customers choose to cancel an order, then they wait for the automated response. By entering the order code via phone, customers can cancel the order. The automated system says the name of the ordered item and asks for the confirmation of the customer. If the customer validates the cancellation of the order, then the system cancels the order; otherwise, the system asks the customer to input the order code again. After responding to the request, the system asks whether the customer has additional requests; if not, the process terminates.

SOLUTION

Figure 2.16 shows the flowchart.

FIGURE 2.16 ▶
Flowchart of Telephone Ordering Process



Solved Problem 2

An automobile service is having difficulty providing oil changes in the 29 minutes or less mentioned in its advertising. You are to analyze the process of changing automobile engine oil. The subject of the study is the service mechanic. The process begins when the mechanic directs the customer's arrival and ends when the customer pays for the services.

SOLUTION

Figure 2.17 shows the completed process chart. The process is broken into 21 steps. A summary of the times and distances traveled is shown in the upper-righthand corner of the process chart.

The times add up to 28 minutes, which does not allow much room for error if the 29-minute guarantee is to be met and the mechanic travels a total of 420 feet.

Process:	Changing engine oil
Subject:	Mechanic
Beginning:	Direct customer arrival
Ending:	Total charges, receive payment

Insert Step

Append Step

Remove Step

Summary

Activity	Number of Steps	Time (min)	Distance (ft)
Operation ●	7	16.50	
Transport ➡	8	5.50	420
Inspect ■	4	5.00	
Delay ◗	1	0.70	
Store ▼	1	0.30	

Step No.	Time (min)	Distance (ft)	●	➡	■	◗	▼	Step Description
1	0.80	50.0		X				Direct customer into service bay
2	1.80		X					Record name and desired service
3	2.30				X			Open hood, verify engine type, inspect hoses, check fluids
4	0.80	30.0		X				Walk to customer in waiting area
5	0.60		X					Recommend additional services
6	0.70					X		Wait for customer decision
7	0.90	70.0		X				Walk to storeroom
8	1.90		X					Look up filter number(s), find filter(s)
9	0.40				X			Check filter number(s)
10	0.60	50.0		X				Carry filter(s) to service pit
11	4.20		X					Perform under-car services
12	0.70	40.0		X				Climb from pit, walk to automobile
13	2.70		X					Fill engine with oil, start engine
14	1.30				X			Inspect for leaks
15	0.50	40.0		X				Walk to pit
16	1.00				X			Inspect for leaks
17	3.00		X					Clean and organize work area
18	0.70	80.0		X				Return to auto, drive from bay
19	0.30						X	Park the car
20	0.50	60.0		X				Walk to customer waiting area
21	2.30		X					Total charges, receive payment

◀ FIGURE 2.17
Process Chart for Changing Engine Oil

Solved Problem 3

What improvement can you make in the process shown in Figure 2.17?

SOLUTION

Your analysis should verify the following three ideas for improvement. You may also be able to come up with others.

a. **Move Step 17 to Step 21.** Customers should not have to wait while the mechanic cleans the work area.

b. **Store Small Inventories of Frequently Used Filters in the Pit.** Steps 7 and 10 involve travel to and from the storeroom. If the filters are moved to the pit, a copy of the reference material must also be placed in the pit. The pit will have to be organized and well lighted.

c. **Use Two Mechanics.** Steps 10, 12, 15, and 17 involve running up and down the steps to the pit. Much of this travel could be eliminated. The service time could be shortened by having one mechanic in the pit working simultaneously with another working under the hood.

Solved Problem 4

Vera Johnson and Merris Williams manufacture vanishing cream. Their packaging process has four steps: (1) mix, (2) fill, (3) cap, and (4) label. They have had the reported process failures analyzed, which shows the following:

Process failure		Frequency
Lumps of unmixed product		7
Over- or underfilled jars		18
Jar lids did not seal		6
Labels rumpled or missing		29
	Total	60

Draw a Pareto chart to identify the vital failures.

SOLUTION

Defective labels account for 48.33 percent of the total number of failures:

$$\frac{29}{60} \times 100\% = 48.33\%$$

Improperly filled jars account for 30 percent of the total number of failures:

$$\frac{18}{60} \times 100\% = 30.00\%$$

The cumulative percent for the two most frequent failures is

$$48.33\% + 30.00\% = 78.33\%$$

Lumps represent $\frac{7}{60} \times 100\% = 11.67\%$ of failures; the cumulative percentage is

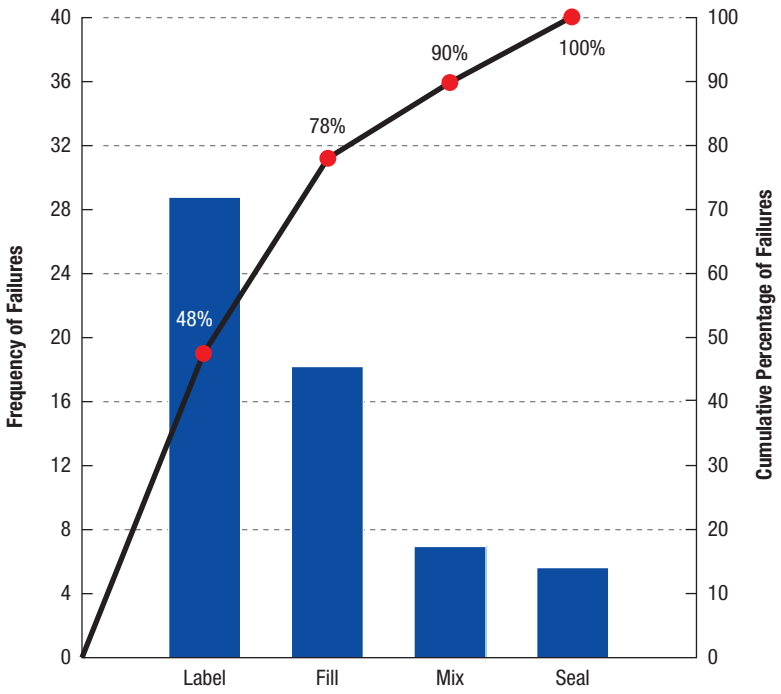
$$78.33\% + 11.67\% = 90.00\%$$

Defective seals represent $\frac{6}{60} \times 100\% = 10\%$ of failures; the cumulative percentage is

$$10\% + 90\% = 100.00\%$$

The Pareto chart is shown in Figure 2.18.

FIGURE 2.18 ▶
Pareto Chart



Discussion Questions

1. What processes at manufacturing firms are really service processes that involve considerable customer contact? Can customer contact be high, even if the process only has internal customers?
2. Consider this sign seen in a local restaurant: "To-go orders do NOT include complimentary chips and salsa. If you have any questions, see our management, NOT our employees." What impact does this message have on its employees, their service processes, and customer satisfaction? Contrast this approach with the one taken by a five-star restaurant. Are the differences primarily due to different competitive priorities?
3. How do the process strategies of eBay and McDonald's differ, and how do their choices relate to customer-introduced variability?
4. Medical technology can outfit a patient with an artificial heart or cure vision defects with the touch of a laser. However, hospitals still struggle with their back-office processes, such as getting X-ray files from radiology on the fourth floor to the first-floor view boxes in the emergency room without having to send a runner. More than 90 percent of the estimated 30 billion health transactions each year are conducted by telephone, fax, or mail. To what extent, and how, can information technology

improve productivity and quality for such processes? Remember that some doctors are not ready to give up their pads and pencils, and many hospitals have strong lines drawn around its departments, such as pharmacy, cardiology, radiology, and pediatrics.

5. Consider the range of processes in the financial services industry. What position on the customer-contact matrix would the process of selling financial services to municipalities occupy? The process of preparing monthly fund balance reports? Explain why they would differ.
6. Assume you had your hair styled in a hair salon after making an online booking. Calculate a combined score for the overall customer contact after considering each of the five dimensions of customer contact in Table 2.1. Use a seven-point scale, where 1= very low and 7= very high. For example, online booking will have low customer contact score because the customer is not present. Did you use equal weightings in calculating the combined score? Why or Why not? Where would you position the process in customer-contact matrix? Is it properly aligned? Why or Why not?
7. Continuous improvement recognizes that many small improvements add up to sizeable benefits. Will continuous improvement take a company at the bottom of an industry to the top? Explain.
8. The Hydro-Electric Company (HEC) has three sources of power. A small amount of hydroelectric power is generated by damming wild and scenic rivers; a second source of power comes from burning coal, with emissions that create acid rain and contribute to global warming; the third source of power comes from nuclear fission. HEC's coal-fired plants use obsolete pollution-control technology, and an investment of several hundred million dollars would be required to update it. Environmentalists urge HEC to promote conservation and purchase power from suppliers that use the cleanest fuels and technology.

   However, HEC is already suffering from declining sales, which have resulted in billions of dollars invested in idle equipment. Its large customers are taking advantage of laws that permit them to buy power from low-cost suppliers. HEC must cover the fixed costs of idle capacity by raising rates charged to its remaining customers or face defaulting on bonds (bankruptcy). The increased rates motivate even more customers to seek low-cost suppliers, the start of a death spiral for HEC. To prevent additional rate increases, HEC implements a cost-cutting program and puts its plans to update pollution controls on hold.

   Form sides and discuss the ethical, environmental, and political issues and trade-offs associated with HEC's strategy.
9. Paul O'Neill, former U.S. Treasury secretary, estimated that arguably half of the $2 trillion a year that Americans spend on health care is needlessly wasted. Brainstorm up to 10 blue-sky ideas to solve the following problems:
   a. A typical retail pharmacy spends 20 percent of its time playing telephone tag with doctors, trying to find out the intent for a given prescription.
   b. After the person responsible for filling the prescription determines what she thinks she is supposed to do, errors can be made even in filling the prescription. For example, administering an adult dose (rather than the dose for a premature baby) of heparin in a preemie ICU is fatal.
   c. Drugs get distributed at a hospital on a batch basis. For example, carts can be filled on Monday, Wednesday, and Friday. A huge volume of drugs can come back on Monday because they are not consumed on the wards between Friday and Monday, patient conditions changed, or the doctor decided on a different intervention. A technician spends the rest of the day restocking the shelves with the returns and 40 percent of the intravenous materials prepared on Friday morning are poured down the drain.
   d. Sometimes the administration of the drug was not done on the agreed-upon schedule, because the nurses were busy doing something else.
   e. For every bed in an acute care hospital system, someone falls during the year. Most falls occur after 11 P.M. and before 6 A.M. Sometimes a bone is fractured, leading to immobilization and then pneumonia.
   f. One in every 14 people who go to a U.S. hospital contract an infection in the hospital.

Problems

The OM Explorer, POM for Windows, and Active Model software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software replaces entirely the manual calculations.

Process Strategy Decisions

Problems 1, 2, and 3 apply break-even analysis (discussed in Supplement A, "Decision Making") to process decisions.

1. Dr. Gulakowicz is an orthodontist. She estimates that adding two new chairs will increase fixed costs by $150,000, including the annual equivalent cost of the capital investment and the salary of one more technician. Each new patient is expected to bring in $3,000 per year in additional revenue, with variable costs estimated at $1,000 per patient. The two new chairs will allow Dr. Gulakowicz to expand her practice by as many as 200 patients annually. How many patients would have to be added for the new process to break even?
2. Two different manufacturing processes are being considered for making a new product. The first process is

less capital intensive, with fixed costs of only $50,000 per year and variable costs of $700 per unit. The second process has fixed costs of $400,000 but has variable costs of only $200 per unit.

a. What is the break-even quantity beyond which the second process becomes more attractive than the first?

b. If the expected annual sales for the product is 800 units, which process would you choose?

3. Gömböc shapes are interesting mathematical shapes attracting attention from mathematics enthusiasts. These blocks involve a complex manufacturing and molding process. A manufacturer is evaluating three machines that can be used for producing these shapes. The annual capital and variable costs associated with each machine are provided in the accompanying table.

Types of Machines	Annual Cost of Capital Required	Variable Costs per Machine
Machine 1	£25,000	£3
Machine 2	£15,000	£5
Machine 3	£10,000	£15

At what quantity range will each option be preferred?

Defining, Measuring, and Analyzing the Process

4. Consider the Custom Molds, Inc., case at the end of this chapter. Prepare a flowchart of the mold fabrication process and the parts manufacturing process, showing how they are linked.

5. Do Problem 4 using a process chart spreadsheet of your own design, one that differs from the *Process Chart* Solver in OM Explorer. It should have one or more columns to record information or metrics that you think are relevant, be they external customer contacts, time delays, completion times, percent rework, costs, capacity, or demand rates. Your entries should show what information you would collect, even though only part of it is available in the case.

6. Founded in 1970, ABC is one of the world's largest insurance companies with locations in 28 countries. Given the following description, flowchart the new policy setup process as it existed in 1970:

Individual customers who wanted to set up a new policy would visit one of ABC's 70 branch offices or make contact with an agent. They would then fill out an application and sometimes attach a check. The branch office then sent the application package through company mail to the XYZ division in London. In addition, a customer might also fill out the application at home and send it directly to any number of ABC locations, which would then transfer it to the London operation. Once received, XYZ separated the various parts of the application, then scanned and digitized it. The electronic image was then retrieved from a server and delivered to an associate's desktop client computer. The associate was responsible for entering the information on the form into the appropriate database. If the information supplied on the application was complete, a confirmation notice was automatically printed and sent to the customer. If the information was incomplete, then another associate, trained to deal with customers on the telephone, would call the customer to obtain the additional information. If something was wrong on the confirmation notice received, the customer would either call a toll-free number or send in a letter describing the problem. The Customer Problem Resolution division dealt with problems arising at this point. An updated confirmation notice was sent to the customer. If the information was correct, the application transaction was complete.

7. Do Problem 6 using a process chart spreadsheet of your own design, one that differs from the *Process Chart* Solver in OM Explorer. It should have one or more columns to record information or metrics that you think should be collected to analyze the process (see Problem 5).

8. Prepare a flowchart of the field service division process at DEF, as described here. Start from the point where a call is received and end when a technician finishes the job.

DEF was a multibillion dollar company that manufactured and distributed a wide variety of electronic, photographic, and reprographic equipment used in many engineering and medical system applications. The Field Service Division employed 475 field service technicians, who performed maintenance and warranty repairs on the equipment sold by DEF. Customers would call DEF's National Service Center (NSC), which received about 3,000 calls per day. The NSC staffed its call center with about 40 call-takers. A typical incoming service call was received at the NSC and routed to one of the call-takers, who entered information about the machine, the caller's name, and the type of problem into DEF's mainframe computer. In some cases, the call-taker attempted to help the customer fix the problem. However, call-takers were currently only able to avoid about 10 percent of the incoming emergency maintenance service calls. If the service call could not be avoided, the call-taker usually stated the following script: "Depending upon the availability of our technicians, you should expect to see a technician sometime between now and (now +X)." ("X" was the target response time based on the model number and the zone.) This information was given to the customer because many customers wanted to know when a tech would arrive on site.

Call-takers entered service call information on DEF's computer system, which then sent the information electronically to the regional dispatch center assigned to that customer location. (DEF had four regional dispatch centers with a total of about 20 dispatchers.) Service call information was printed on a small card at the dispatch center. About every hour, cards were ripped off the printer and given to the dispatcher assigned to that customer location. The dispatcher placed each card on a magnetic board under the name of a tech that the dispatcher believed would be the most likely candidate for the service call, given the location of the machine,

the current location of the tech, and the tech's training profile. After completing a service call, techs called the dispatcher in the regional dispatch center, cleared the call, and received a new call assigned by the dispatcher. After getting the service call from a dispatcher, a tech called the customer to give an expected time of arrival, drove to the customer site, diagnosed the problem, repaired the machine if parts were available in the van, and then telephoned the dispatcher for the next call. If the tech did not have the right parts for a repair, the tech informed the NSC, and the part was express mailed to the customer; the repair was done the next morning.

9. Big Bob's Burger Barn would like to graphically depict the interaction among its lunch-ordering customers and its three employees. Customers come into the restaurant and eat there rather than drive through and eat in the car. Using the brief process descriptions below, develop a service blueprint.

Fry Employee: receive customer order from counter employee, retrieve uncooked food, drop food into fry vat, wrap cooked food into special packaging, place wrapped items on service counter.

Grill Employee: receive customer order from counter employee, retrieve uncooked food, place food onto grill, build sandwich with requested condiments, deliver sandwich to Counter Employee.

Counter Employee: take order from customer, transmit appropriate orders to Fry and Grill Employee, transact payment, retrieve drinks, wrap sandwich, package order, and deliver order to customer.

10. As part of a COVID-19 response team, you have to put together a group of volunteers to cook hot meals for 300 health workers at a local hospital. The menu consists of the following items: flavored rice, tomato soup, vegetable salad, chocolate cake, and a bottle of fresh juice. All items except the chocolate cake and the fresh juice will be prepared inside a nearby tent with cooking facilities. For ease of distribution, the prepared meals will be packed in cardboard boxes which will be stored in reusable crates. Construct a flowchart and a process chart for the temporary kitchen. What inputs in terms of materials, human effort, and equipment are involved? Estimate the number of volunteers, food items, and packaging material required for this operation.

11. Assume you are working as an intern in the accounts payable department of a construction company. As an intern, you have to process the invoices you receive from suppliers on a weekly basis. You receive an average of 200 invoices per week. Suppliers send their invoices by post and email. The business processes are largely manual in nature with technology used only for making payment and accounting purposes. Before making payments, you have to complete the following steps: print out the purchase order if sent digitally (3 minutes each); identify the purchase order number and retrieve the actual purchase order from the purchasing ledger (3 minutes each); retrieve the goods received document from the stores office ledger and undertake a three-way match between invoice, purchase order, and goods receipt document (5 minutes each), if all the values match, approve the invoice, submit it to the procurement manager for approval (2 minutes each); inform supplier about the status via phone/email about the invoice status (5 minutes each).

a. Make a process chart for the above activity, assuming that it is a one-person operation.

b. Estimate how long will it take to process 200 invoices. Assume that you are paid $15 per hour. How much will it cost to process 200 invoices?

c. Consider each of the following process changes. Which changes would reduce the time and cost of the current process?

- All the relevant documents are scanned and stored as PDFs in a predetermined folder.
- There is a mismatch between the document values.
- You are using an integrated ERP system that does the three-way matching.
- You are scanning the approved invoice and emailing it to the procurement manager.
- You are providing access to the invoice approval process so that a supplier can view the status online.

d. Would any of these changes be likely to reduce the effectiveness of the mailing? If so, which ones? Why?

e. Would the changes that increase time and cost be likely to increase the effectiveness of the mailing? Why or why not?

12. Diagrams of two self-service gasoline stations, both located on corners, are shown in Figure 2.19(a) and (b). Both have two rows of four pumps and a booth at which an attendant receives payment for the gasoline. At neither station is it necessary for the customer to pay in advance. The exits and entrances are marked on the diagrams. Analyze the flows of cars and people through each station.

a. Which station has the more efficient flows from the standpoint of the customer?

b. Which station is likely to lose more potential customers who cannot gain access to the pumps because another car is headed in the other direction?

c. At which station can a customer pay without getting out of the car?

13. The management of the Just Like Home Restaurant has asked you to analyze some of its processes. One of these processes is making a single-scoop ice cream cone. Cones can be ordered by a server (for table service) or by a customer (for takeout).

Figure 2.20 illustrates the process chart for this operation.

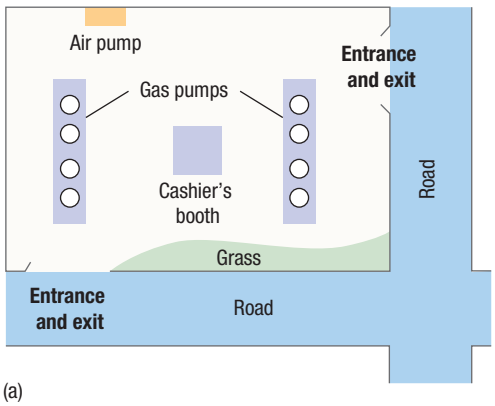
- The ice cream counter server earns $10 per hour (including variable fringe benefits).
- The process is performed 10 times per hour (on average).
- The restaurant is open 363 days a year, 10 hours a day.

a. Complete the Summary (top-right) portion of the chart.

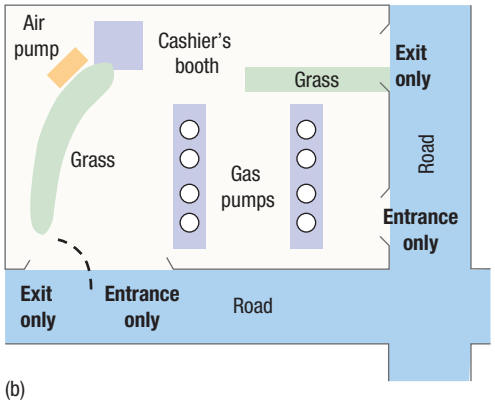
b. What is the total labor cost associated with the process?

c. How can this operation be made more efficient? Make a process chart using OM Explorer's *Process Charts* Solver of the improved process. What are the annual labor savings if this new process is implemented?

14. While undertaking a degree in operations management, you are interested in applying for internships in this field. These jobs are advertised in job portals such as Monster, business networking portals such as LinkedIn, and in many cases through word of mouth. You are also planning to use novel approaches such as a



(a)



(b)

▲ **FIGURE 2.19**
Two Self-Service Gasoline Stations

video curriculum vitae (CV). To land up in a job position of your choice, you have to understand the activities involved as an operations intern, search for opportunities, develop your CV, cover letter, create a social networking profile, and also reach out to friends and families for contacts apart from the university placement cell. You need to customize the CV and cover letter based on the opportunity and, in many cases, there will be no acknowledgment from employers. Prepare a list of process chart steps and place them in an efficient sequence.

15. At the Department of Motor Vehicles (DMV), the process of getting license plates for your car begins when you enter the facility and take a number. You walk 50 feet to the waiting area. During your wait, you count about 30 customers waiting for service. You notice that many customers become discouraged and leave. When a number is called, if a customer stands, the ticket is checked by a uniformed person, and the customer is directed to the available clerk. If no one stands, several minutes are lost while the same number is called repeatedly. Eventually, the next number is called, and more often than not, that customer has left, too. The DMV clerk has now been idle for several minutes but does not seem to mind.

After 4 hours, your number is called and checked by the uniformed person. You walk 60 feet to the clerk, and the process of paying city sales taxes is completed in 4 minutes. The clerk then directs you to the waiting area for paying state personal property tax, 80 feet away. You take a different number and sit down with some different customers who are just renewing licenses. There is a 1-hour, 40-minute wait this time, and after a walk of 25 feet you pay property taxes in a process that takes 2 minutes. Now that you have paid taxes, you are eligible to pay registration and license fees. That department is 50 feet away, beyond the employees' cafeteria.

FIGURE 2.20 ▶
Process Chart for Making Ice Cream Cones

Process:	Making one ice cream cone
Subject:	Server at counter
Beginning:	Walk to cone storage area
Ending:	Give it to server or customer

Insert Step
Append Step
Remove Step

Summary

Activity	Number of Steps	Time (min)	Distance (ft)
Operation ●			
Transport ➡			
Inspect ■			
Delay ◗			
Store ▼			

Step No.	Time (min)	Distance (ft)	●	➡	■	◗	▼	Step Description
1	0.20	5.0		X				Walk to cone storage area
2	0.05		X					Remove empty cone
3	0.10	5.0		X				Walk to counter
4	0.05		X					Place cone in holder
5	0.20	8.0		X				Walk to sink area
6	0.50					X		Ask dishwasher to wash scoop
7	0.15	8.0		X				Walk to counter with clean scoop
8	0.05		X					Pick up empty cone
9	0.10	2.5		X				Walk to flavor ordered
10	0.75		X					Scoop ice cream from container
11	0.75		X					Place ice cream in cone
12	0.25				X			Check for stability
13	0.05	2.5		X				Walk to order placement area
14	0.05		X					Give server or customer the cone

The registration and license customers are called in the same order in which personal property taxes were paid. There is only a 10-minute wait and a 3-minute process. You receive your license plates, take a minute to complain to the license clerk about the wait, and leave exactly 6 hours after arriving.

Make a process chart using OM Explorer's *Process Charts* Solver to depict this process, and suggest improvements.

16. Refer to the process chart for the automobile oil change in Solved Problem 2. Calculate the annual labor cost if:

- The mechanic earns $40 per hour (including variable fringe benefits).
- The process is performed twice per hour (on average).
- The shop is open 300 days a year, 10 hours a day.

a. What is the total labor cost associated with the process?

b. If steps 7, 10, 12, and 15 were eliminated, estimate the annual labor savings associated with implementing this new process.

17. A time study of an employee assembling peanut valves resulted in the following set of observations. What is the standard time, given a performance rating of 95 percent and an allowance of 20 percent of the total normal time?

Average Time (seconds)	Observations
15	14
20	12
25	15

18. An initial time study was done on a process with the following results (in minutes). Based on the data obtained so far, assuming an allowance of 20 percent of the normal time, what do you estimate for the time per customer served, based on this preliminary sample?

Element	Performance Rating	Obs 1	Obs 2	Obs 3	Obs 4	Obs 5
Element 1	70	4	3	5	4	3
Element 2	110	8	10	9	11	10
Element 3	90	6	8	7	7	6

19. A work sampling study was conducted to determine the proportion of the time a worker is idle. The following information was gathered on a random basis.

Day	Number of Times Worker Idle	Total Number of Observations
Monday	17	44
Tuesday	18	56
Wednesday	14	48
Thursday	16	60

a. Based on these preliminary results, what percent of the time is the worker working?

b. If idle time is judged to be excessive, what additional categories might you add to a follow-up work sampling study to identify the root causes?

20. A contractor is preparing a bid to install swimming pools at a new housing addition. The estimated time to build the first pool is 35 hours. The contractor estimates an 85 percent learning rate. Without using the computer:

a. How long do you estimate the time required to install the second pool?

b. How long do you estimate the time required to install the fourth pool?

21. Return to Problem 20. Using OM Explorer's *Learning Curves* Solver, how long do you estimate the time required to install the fifth pool? What is your estimate of the total time for all five pools?

22. On RainTite Window's manual assembly line, a new employee can usually assemble the first window unit in 30 minutes. Management assumes a 90 percent learning rate.

a. How long should a new employee take to assemble the second window if management is correct in their assumption? How long should the 16th window take?

b. On RainTite's semiautomated line, a new employee takes 45 minutes to assemble the first window; however, the learning rate is 75 percent. At how many windows produced will the semiautomated line's employee take less time to produce a window than an employee on the manual line?

23. A hospital emergency service department was analyzing the factors that were contributing to failing performance against response time targets set for urgent care response calls. It listed the main issues that prevented the ambulance from bringing the patient back to the hospital on time.

Problem	Frequency
Ambulance driver unable to locate the patient	22
Road traffic	30
Ambulance performance issues	8
Staff availability	8
Equipment issues	12
Uncooperative patient	14
Delayed support from other agencies such as fire and police	6
Total	100

a. Use a Pareto chart to identify the "vital few" patient transport problems. Comment on potential root causes of these problems and identify any especially egregious quality failures.

b. To understand the root cause of the problem, the hospital management requested the ambulance crew to maintain a log of specific difficulties. After a week, the log included the following entries: drunk patient, caller unaware of the location, incorrect address provided, vehicle had mechanical issues, unable to fit patient on a stretcher due to body size, and map system does not have real-time traffic updates.

Organize these causes into a cause-and-effect diagram.

24. Smith, Schroeder, and Torn (SST) is a short-haul household furniture moving company. SST's labor force, selected from the local community college football team,

is temporary and part time. SST is concerned with recent complaints, as tabulated on the following tally sheet.

Complaint	Tally
Broken glass	𝍸 𝍸 |||
Delivered to wrong address	𝍸 ||||
Furniture rubbed together while on truck	𝍸 𝍸 𝍸 𝍸
Late delivery	𝍸
Late arrival for pickup	𝍸 𝍸 𝍸 |||
Missing items	𝍸 𝍸 𝍸 𝍸 𝍸 |
Nicks and scratches from rough handling	𝍸 𝍸
Soiled upholstery	𝍸 |||

a. Draw a bar chart and a Pareto chart using OM Explorer to identify the most serious moving problems.

b. The manager of Smith, Schroeder, and Torn is attempting to understand the root causes of complaints. He has compiled the following list of issues that occurred during problem deliveries:

truck broke down, ran out of packing boxes, multiple deliveries in one day caused truck to be late, no furniture pads, employee dropped several items, driver got lost en route to address, ramp into truck was bent, no packing tape, new employee doesn't know how to pack, moving dolly has broken wheel, and employee late to work

Organize these causes into a cause-and-effect diagram.

25. Rick DeNeefe, manager of the Golden Valley Bank credit authorization department, recently noticed that a major competitor was advertising that applications for equity loans could be approved within 2 working days. Because fast credit approval was a competitive priority, DeNeefe wanted to see how well his department was doing relative to the competitor's. Golden Valley stamps each application with the date and time it is received and again when a decision is made. A total of 104 applications were received in March. The time required for each decision, rounded to the nearest hour, is shown in the table. Golden Valley's employees work 8 hours per day.

Decision Process Time (hours)	Frequency
8	8
11	19
14	28
17	10
20	25
23	4
26	10
Total	104

a. Draw a bar chart for these data.

b. Analyze the data. How is Golden Valley Bank doing with regard to this competitive priority?

26. A business school undertook research to investigate the reasons for high-level absenteeism and lack of engagement from its students. It conducted a group discussion with students to uncover the key reasons that could be classified into the following categories.

Complaint	Frequency
Subject not taught interestingly	45
Content is outdated	20
Health issues of students	15
Timing is not convenient	10
Little encouragement from teachers to participate	10

a. Draw a Pareto chart to identify the significant reasons for poor engagement.

b. Categorize the following identified problems into a cause-and-effect diagram: study material, people, delivery style, and health of students.

27. Oregon Fiber Board makes roof liners for the automotive industry. The manufacturing manager is concerned about product quality. She suspects that one particular failure, tears in the fabric, is related to production-run size. An assistant gathers the following data from production records.

Run	Size	Failures (%)	Run	Size	Failures (%)
1	1,000	3.5	11	6,500	1.5
2	4,100	3.8	12	1,000	5.5
3	2,000	5.5	13	7,000	1.0
4	6,000	1.9	14	3,000	4.5
5	6,800	2.0	15	2,200	4.2
6	3,000	3.2	16	1,800	6.0
7	2,000	3.8	17	5,400	2.0
8	1,200	4.2	18	5,800	2.0
9	5,000	3.8	19	1,000	6.2
10	3,800	3.0	20	1,500	7.0

a. Draw a scatter diagram for these data.

b. Does there appear to be a relationship between run size and percent failures? What implications do these data have for Oregon Fiber Board's business?

28. Transport Research Laboratory, a UK-based global company, undertook a research to identify factors that contributed to the increasing number of road accidents. In its report titled "The effects of drivers' speed on the frequency of road accidents," it gathered the following data on the accident frequency (per link per year) and mean speed (miles/hour) in London.

Accident Frequency	Mean Speed (miles/hour)
0.75	20
1.25	25
1.5	28
2	30
2.5	32
3	35

Source: http://www.20splentyforuk.org.uk/UsefulReports/TRLREports/trl421SpeedAccidents.pdf

a. Draw a scatter diagram for these data.

b. Is there a relationship between mean speed and accident frequency?

c. Do you think this relationship can be applied to regions outside London?

29. The operations manager for Superfast Airlines at Chicago's O'Hare Airport noticed an increase in the number of delayed flight departures. She brainstormed possible causes with her staff:

- Aircraft late to gate
- Acceptance of late passengers
- Passengers arriving late at gate
- Passenger processing delays at gate
- Late baggage to aircraft
- Other late personnel or unavailable items
- Mechanical failures

Draw a cause-and-effect diagram to organize the possible causes of delayed flight departures into the following major categories: equipment, personnel, material, procedures, and other factors beyond managerial control. Provide a detailed set of causes for each major cause identified by the operations manager, and incorporate them in your cause-and-effect diagram.

30. A leading domestic gas meter manufacturer was facing a wide range of quality issues and observed wastage at several stages of the supply chain. It analyzed performance data of the process over a period of one month. The table presents the results.

Type of Wastage	Number of Occurrences
Assembly components not conforming to quality	345
Product damage during work in progress	140
Rejection after final assembly	55
Rejection from customer	40
Damage due to improper material handling in warehouse	75

Draw a Pareto chart to identify the key issues the business must focus on to improve the situation.

31. Polar Magnets Limited is a global supplier of neodymium magnets. Based in Japan, it manufactures magnets of various sizes and shapes such as circular, rectangular, cylindrical, and spherical. Recently, it introduced a new ring-shaped magnet with a diameter of 25 mm and a pull strength of 6.5 kg. The manufacturing size tolerance is +/− 0.1 mm, the pull strength is 6.5 kg with a tolerance of +/− 200 g. To ensure that the new range is in line with the specification, an analyst gathered data of a random sample of 100 magnets.

a. Draw a histogram for these data.

b. Magnets with pull strength less than 5.8 kg or more than 6.2 kg are considered to be out of specification. Based on the sample data, what percentage of the magnets will be out of specification?

Pull Weight of the Magnet (kg)									
6.05	6.22	6.14	6.51	6.19	6.73	6.25	6.45	6.51	6.44
6.01	6.06	6.79	6.51	6.54	6.95	6.16	6.5	6.03	6.43
6.2	6.37	6.44	6.69	6.78	6.05	6.68	6.47	6.86	6.4
6.97	6.91	6.82	6.22	6.79	6.41	6.14	6.96	6.65	6.97
6.15	6.68	6.7	6.6	6.36	6.25	6.23	6.02	6.81	6.52
6.71	6.45	6.31	6.9	6.1	6.31	6.21	6.1	6.02	6.09
6.34	6.33	6.85	6.4	6.52	6.56	6.96	6.96	6.58	6.31
6.06	6.14	6.9	6.66	6.63	6.06	6.94	6.22	6.23	6.82
6.58	6.99	6.4	6.36	6.32	6.7	6.38	6.4	6.34	6.12
6.3	6.08	6.52	6.24	6.98	6.64	6.42	6.42	6.18	6.78

32. This problem should be solved as a team exercise.

Shaving is a process that many men perform each morning. Assume that the process begins at the bathroom sink with the shaver walking (say, 5 feet) to the cabinet (where his shaving supplies are stored) to pick up bowl, soap, brush, and razor. He walks back to the sink, runs the water until it gets warm, lathers his face, shaves, and inspects the results. Then he rinses the razor; dries his face; walks over to the cabinet to return the bowl, soap, brush, and razor; and comes back to the sink to clean it up and complete the process.

a. Develop a process chart for shaving. (Assume suitable values for the time required for the various activities involved in the process.)

b. Brainstorm to generate ideas for improving the shaving process. Having fewer than 20 ideas is unacceptable. (Do not try to evaluate the ideas until the group has compiled as complete a list as possible. Otherwise, judgment will block creativity.)

33. Busybee Fabricators are manufacturers of high-quality steel chests used for storing car repair tools. All chests are subjected to rigorous quality checks prior to dispatch. As a quality assurance professional, you have been tasked to examine the reasons for rejects and present your findings to the business process improvement team. Upon examining the reasons for rejections, each reject has been attached to a specific category as labeled below.

Wheels not attached to the chest	A	17
Missing handles	B	9
Ball-bearing slides not functioning properly	C	9
Locking mechanism does not work	D	9
Dents and scratches at the back of the chest	E	6

For 50 chests that had been rejected in the last quarter, the summary statement showed the following:

C	B	A	D	D	A	B	C	B	D
A	E	A	C	D	A	C	A	A	A
C	D	A	E	B	C	B	D	A	C
D	A	A	C	A	B	E	A	E	C
A	B	E	D	A	E	B	A	D	B

a. Prepare a tally sheet (or checklist) listing the various reasons for rejection.

b. Develop a Pareto chart to identify the more significant types of rejection.

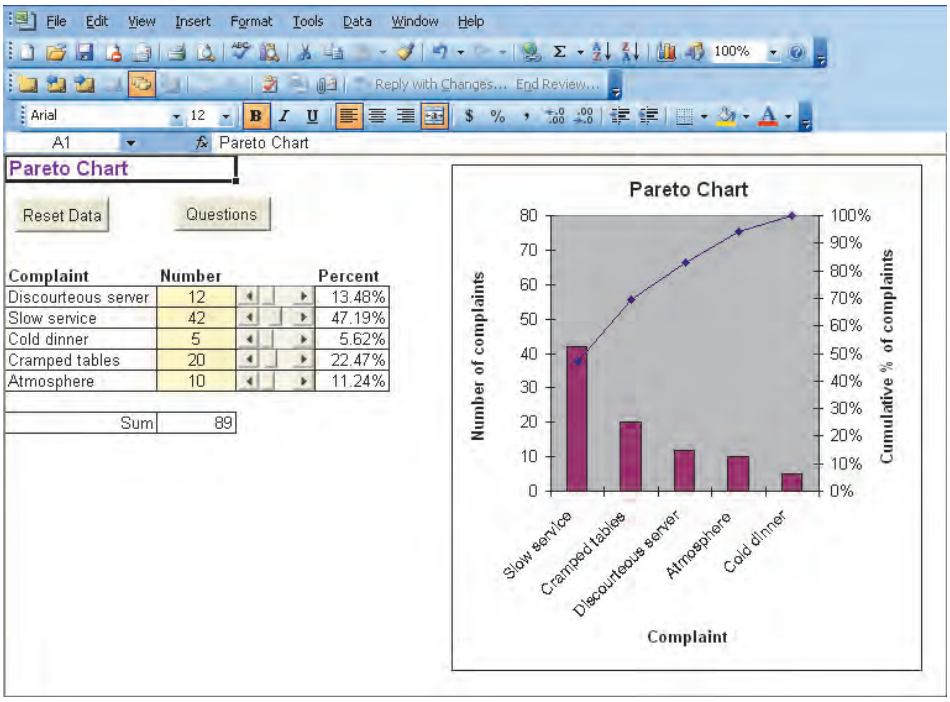
c. Examine the causes of the most significant type of defect, using a cause-and-effect diagram.

Active Model Exercise

This Active Model is available online. Continuing on with Example 2.2, it allows you to evaluate the structure of a Pareto chart.

QUESTIONS

1. What percentage of overall complaints does discourteous service account for?
2. What percentage of overall complaints do the three most common complaints account for?
3. How does it affect the chart if we eliminate discourteous service?



CASE Custom Molds, Inc.

Custom Molds, Inc., manufactures custom-designed molds for plastic parts and produces custom-made plastic connectors for the electronics industry. Located in Tucson, Arizona, Custom Molds was founded by the father-and-son team of Tom and Mason Miller in 1997. Tom Miller, a mechanical engineer, had more than 20 years of experience in the connector industry with AMP, Inc., a large multinational producer of electronic connectors. Mason Miller graduated from the Arizona State University in 1996 with joint degrees in chemistry and chemical engineering.

The company was originally formed to provide manufacturers of electronic connectors with a source of high-quality, custom-designed molds for producing plastic parts. The market consisted mainly of the product design and development divisions of those manufacturers. Custom Molds worked closely with each customer to design and develop molds to be used in the customer's product development processes. Thus, virtually every mold had to meet exacting standards and was somewhat unique. Orders for multiple molds would arrive when customers moved from the design and pilot-run stage of development to large-scale production of newly designed parts.

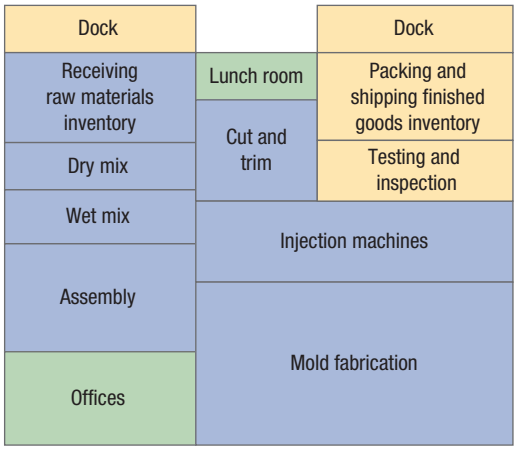
As the years went by, Custom Molds's reputation grew as a designer and fabricator of precision molds. Building on this reputation, the Millers decided to expand into the limited manufacture of plastic parts. Ingredient-mixing facilities and injection-molding equipment were added, and by the mid-2000s, Custom Molds developed its reputation to include being a supplier of high-quality plastic parts. Because of limited capacity, the company concentrated its sales efforts on supplying parts that were used in limited quantities for research and development efforts and in preproduction pilot runs.

Production Processes

By 2017, operations at Custom Molds involved two distinct processes: one for fabricating molds and one for producing plastic parts. Although different, in many instances these two processes were linked, as when a customer would have Custom Molds both fabricate a mold and produce the necessary parts to support the customer's research and design efforts. All fabrication and production operations were housed in a single facility. The layout was characteristic of a typical job shop, with like processes and similar equipment grouped in various places in the plant. Figure 2.21 shows a layout of the plant floor. Multiple pieces of various types of high-precision machinery, including milling, turning, cutting, and drilling equipment, were located in the mold-fabrication area.

Fabricating molds is a skill-oriented, craftsman-driven process. When an order is received, a design team, comprising a design engineer and 1 of 13 master machinists, reviews the design specifications. Working closely with the customer, the team establishes the final specifications for the mold and gives them to the master machinist for fabrication. It is always the same machinist who was assigned to the design team. At the same time, the purchasing department is given a copy of the design specifications, from which it orders the appropriate raw materials and special tooling. The time needed to receive the ordered materials is usually 3 to 4 weeks. When the materials are received for a particular mold, the plant master scheduler reviews the workload of the assigned master machinist and schedules the mold for fabrication.

Fabricating a mold takes from 2 to 4 weeks, depending on the amount of work the machinist already has scheduled. The fabrication process itself takes only 3 to 5 days. Upon completion, the mold is sent to the testing and inspection area, where it is used to produce a small number of parts on one of the injection-molding machines. If the parts meet the design specifications established by the design team, the mold is passed on to be cleaned and polished. It is then packed and shipped to the customer. One day is spent inspecting and testing the mold and a second day cleaning, polishing, packing, and shipping it to the customer. If the parts made by the mold do not meet design specifications, the mold is returned to the master machinist for retooling and the process starts over. Currently, Custom Molds has a published lead time of 9 weeks for delivery of custom-fabricated molds.



▲ **FIGURE 2.21**
Plant Layout

The manufacturing process for plastic parts is somewhat different from that for mold fabrication. An order for parts may be received in conjunction with an order for a mold to be fabricated. In instances where Custom Molds has previously fabricated the mold and maintains it in inventory, an order may be just for parts. If the mold is already available, the order is reviewed by a design engineer, who verifies the part and raw material specifications. If the design engineer has any questions concerning the specifications, the customer is contacted and any revisions to specifications are mutually worked out and agreed upon.

Upon acceptance of the part and raw material specifications, raw material orders are placed and production is scheduled for the order. Chemicals and compounds that support plastic-parts manufacturing are typically ordered and received within 1 week. Upon receipt, the compounds are first dry-mixed and blended to achieve the correct composition. Then the mixture is wet-mixed to the desired consistency (called *slurry*) for injection into molding machines. When ready, the slurry is transferred to the injection-molding area by an overhead pipeline and deposited in holding tanks adjacent to the injection machines. The entire mixing process takes only 1 day.

When the slurry is staged and ready, the proper molds are secured—from inventory or from the clean and polish operation if new molds were fabricated for the order—and the parts are manufactured. Although different parts require different temperature and pressure settings, the time to produce a part is relatively constant. Custom Molds has the capacity to produce 5,000 parts per day in the injection-molding department; historically, however, the lead time for handling orders in this department has averaged 1 week. Upon completion of molding, the parts are taken to the cut and trim operation, where they are disconnected and leftover flashing is removed. After being inspected, the parts may be taken to assembly or transferred to the packing and shipping area for shipment to the customer. If assembly of the final parts is not required, the parts can be on their way to the customer 2 days after being molded.

Sometimes, the final product requires some assembly. Typically, this entails attaching metal leads to plastic connectors. If assembly is necessary, an additional 3 days are needed before the order can be shipped. Custom Molds is currently quoting a 3-week lead time for parts not requiring fabricated molds.

The Changing Environment

In early 2021, Tom and Mason Miller began to realize that the electronics industry they supplied, along with their own business, was changing. Electronics manufacturers had traditionally manufactured their own component parts to reduce costs and ensure a timely supply of parts. But this trend had changed. Manufacturers were developing strategic partnerships with parts suppliers to ensure the timely delivery of high-quality, cost-effective parts. This approach allowed funds to be diverted to other uses that could provide a larger return on investment.

The impact on Custom Molds could be seen in sales figures over the past 3 years. The sales mix was changing. Although the number of orders per year for mold fabrication remained virtually constant, orders for multiple molds were declining, as shown in the accompanying table.

	NUMBER OF ORDERS		
Order Size	Molds 2018	Molds 2019	Molds 2020
1	80	74	72
2	60	70	75
3	40	51	55
4	5	6	5
5	3	5	4
6	4	8	5
7	2	0	1
8	10	6	4
9	11	8	5
10	15	10	5
Total orders	230	238	231

The reverse was true for plastic parts, for which the number of orders per year had declined, but for which the order sizes were becoming larger, as illustrated in the next table.

	NUMBER OF ORDERS		
Order Size	Parts 2018	Parts 2019	Parts 2020
50	100	93	70
100	70	72	65
150	40	30	35
200	36	34	38
250	25	27	25
500	10	12	14
750	1	3	5
1,000	2	2	8
3,000	1	4	9
5,000	1	3	8
Total orders	286	280	277

During this same period, Custom Molds began having delivery problems. Customers were complaining that parts orders were taking 4 to 5 weeks instead of the stated 3 weeks and that the delays were disrupting production schedules. When asked about the situation, the master scheduler said that determining when a particular order could be promised for delivery was difficult. Bottlenecks were occurring during the production process, but where or when they would occur could not be predicted. The bottlenecks always seemed to be moving from one operation to another.

Tom Miller thought that he had excess labor capacity in the mold-fabrication area. So, to help push through those orders that were behind schedule, he assigned one of the master machinists the job of identifying and expediting those late orders. However, that tactic did not seem to help much. Complaints about late deliveries were still being received. To add to the problems, two orders had been returned recently because of the number of defective parts. The Millers knew that something had to be done. The question was, "What?"[5]

QUESTIONS

1. What are the major issues facing Tom and Mason Miller?
2. What are the competitive priorities for Custom Molds's processes and the changing nature of the industry?
3. What alternatives might the Millers pursue? What key factors should they consider as they evaluate these alternatives?

[5] *Source:* This case was prepared by Dr. Brooke Saladin, Wake Forest University, as a basis for classroom discussion. Copyright © Brooke Saladin. Reprinted by permission.

CASE José's Authentic Mexican Restaurant

"Two bean tacos, a chicken burrito grande, and a side order of Spanish rice, please." Ivan Karetski called his table's order into the kitchen as he prepared the beverage orders. Business was brisk. Karetski liked it that way. Lots of customers meant lots of tips and, as a struggling graduate student, the extra income was greatly appreciated. Lately, however, his tips had been declining.

José's is a small, 58-seat restaurant that offers a reasonably broad range of Mexican food prepared and presented in a traditional Mexican style. It is located in New England in a mature business district on the edge of a large metropolitan area. The site is adjacent to a central artery and offers limited free off-street parking. The restaurant's interior decoration promotes the Mexican theme: The walls appear to be made of adobe and are draped with serapes, the furniture is Spanish–Mexican style, and flamenco guitar and mariachi alternate as background music.

Patrons enter the restaurant through a small vestibule that opens directly into the dining area; there is no separate waiting area. Upon arrival, patrons are greeted by a host and either seated directly or apprised of the expected wait. Seating at José's is usually immediate except for Friday and Saturday nights, when waits of as long as 45 minutes can be encountered. Because space inside for waiting is very limited, patrons must remain outside until their party is called. José's does not take reservations.

After seating patrons, the host distributes menus and fills glasses with water. If standards are being met, the server assigned to the table greets the patrons within 1 minute of their being seated. The server introduces himself or herself, announces the daily specials, and takes the beverage orders. After delivering the beverages, the server takes the meal orders.

The menu consists of 23 main entrees assembled from eight basic stocks (chicken, beef, beans, rice, corn tortillas, flour tortillas, tomatoes, and lettuce) and a variety of other ingredients (fruits, vegetables, sauces, herbs, and spices). Before the dining hours begin, the cook prepares the basic stocks so that they can be quickly combined and finished off to complete the requested meals. The typical amount of time needed to complete a meal once it has been ordered is 12 minutes. A good portion of this time is for final cooking, so several meals may be in preparation at the same time. As can be imagined, one of the skills a good cook needs is to be able to schedule production of the various meals ordered at a table so that they are ready at approximately the same time. Once all the meals and any side dishes have been completed by the cook, the server checks to see that all meals are correct and pleasing to the eye, corrects any mistakes, and adds any finishing touches. When everything is in order, the server assembles them on a tray and delivers them to the table. From this point on, the server keeps an eye on the table to detect when any additional service or assistance is needed.

When the diners at the table appear to be substantially finished with their main meal, the server approaches, asks if he can clear away any dishes, and takes any requests for dessert or coffee. When the entire meal has been completed, the server presents the bill and shortly thereafter collects payment. José's accepts cash or major credit cards but no checks.

Karetski believes that his relationship with the cook is important. Because the cook largely controls the quality of the food, Karetski wants to stay on good terms with him. He treats the cook with respect, tries to place the items on his order slip in the sequence of longest preparation time, and makes sure to write clearly so that the orders are easy to read. Although it is not his job, he helps out by fetching food stocks from the refrigerator or the storage area when the cook is busy and by doing some of the food preparation himself. The cook has been irritable lately, complaining of the poor quality of some of the ingredients that have been delivered. Last week, for example, he received lettuce that appeared wilted and chicken that was tough and more bone than meat. During peak times, it can take more than 20 minutes to get good meals delivered to the table.

Karetski had been shown the results of a customer survey that management conducted last Friday and Saturday during the evening mealtime. The accompanying table shows a summary of the responses.

Customer Survey Results

Were you seated promptly?	Yes: 70	No: 13
Was your server satisfactory?	Yes: 73	No: 10
Were you served in a reasonable time?	Yes: 58	No: 25
Was your food enjoyable?	Yes: 72	No: 11
Was your dining experience worth the cost?	Yes: 67	No: 16

As Karetski carried the tray of drinks to the table, he wondered whether the recent falloff in tips was due to anything that he could control.[6]

QUESTIONS

1. How should process outcomes and quality be defined at this restaurant?
2. What are the restaurant's costs of process failures?
3. Use some of the tools for process analysis to assess the situation at José's.

[6] *Source:* This case was prepared by Larry Meile, Boston College, as a basis for classroom discussion. Reprinted by permission.

VIDEO CASE Process Strategy and Analysis at Cleveland Clinic

Cleveland Clinic is one of the nation's most respected research and academic hospitals, garnering top ratings annually in *U.S. News and Word Reports* rankings of healthcare providers for more than two decades. Headquartered in Cleveland, Ohio, the organization has more than 260 facilities throughout the United States and the world and is focused on providing superior patient safety and quality as evidenced in its clinicians' commitment to providing patients with the best care anywhere.

One of its top facilities in Cleveland, Fairview Hospital, is particularly well known as a clinical "Center of Excellence," enjoying national recognition for its birthing services, cancer center, emergency and Level II trauma, heart center, and surgery. Founded in 1892, Fairview Hospital is a faith-based community hospital with 488 licensed beds and is fully accredited by The Joint Commission, the nation's premier healthcare accrediting agency. The hospital performs about 11,000 surgical procedures annually. General surgeries have the highest volumes at about 3,000 procedures annually, followed closely by Obstetrics/Gynecological, Urological, and Orthopedics as the most frequently performed procedures.

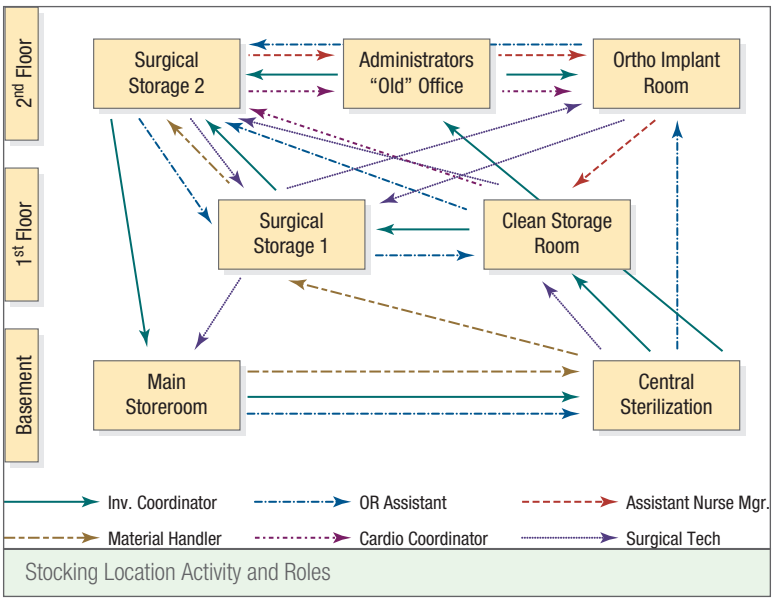
Recently, the Inventory Management Transformation team within the Supply Chain Management corporate organization, performed work flow assessments at Fairview Hospital utilizing Six Sigma Process Improvement concepts. Skilled and licensed clinical staff, such as registered nurses in the Surgery Department, were required to spend a great deal of time walking around their units to inspect and inventory critical surgical supplies. Could the design of the process be the culprit? The staff annually required over 18,400 unique supplies provided by 327 unique vendors, with a value of close to $20 million, spread over numerous storage locations. An enterprise initiative to support clinicians performing at the height of their licensure recognized that time away from direct patient care for this skilled clinical staff could have an adverse impact on patient safety and wished to minimize this risk.

As noted in Figure 2.6, a Six Sigma Process Improvement project includes the following five steps:

1. Define: Outlines the scope and boundaries of the process to be examined
2. Measure: Selects the metrics for collecting data about the area of interest
3. Analyze: Discovers gaps between actual and expected performance
4. Improve: Generates ideas for improving the process, based on the gathered metrics
5. Control: Observes how well the chosen improvement process is working after implementation

To better understand the workflows and the amount of clinical time dedicated to daily supply procurement, the supply chain team conducted a "time and motion" study of the Fairview Surgery Department to measure different activities. The goal was to understand the current state of responsibilities and time commitments required for all supply chain functions within Materials Management staff, central sterilization technicians, Fairview surgery nurses and Fairview surgery inventory personnel. For the skilled and licensed staff, the team narrowed the scope to observing the time it took to inspect and inventory the required supply items each day. This included mapping not only travel time, but also locations of supplies routinely needed for medical and surgical care.

The study started with questioning and brainstorming with staff to understand the work being done, who was doing it, the frequency of each task, locations, and relative value in the greater scheme of job duties. An example of this work was the daily inspection of hardware needed for trauma surgeries, such as broken bones. On a daily basis, an assistant nurse manager had to physically inspect a large steel cabinet in the "administrators old office" that contained the essential hardware items for surgical procedures. This cabinet was located on the second floor, as noted in the Stocking Location Activity and Roles "before" diagram shown below. Similar to a hardware store, the cabinet contains multiple drawers filled with various sizes of small screws, pins, rods, and plates of a wide variety of configurations. Performing the inspection is a standard inventory review task, but does not require someone with a nursing degree and years of surgical experience to determine which product needs replenishment. Yet this was exactly what was happening.



Stocking Location Activity and Roles

Additionally, the study revealed that the daily time commitments within these workflows equaled four full-time equivalent employees of work, spread across a total workforce of approximately 190 staff. This was time that was being taken away from patient care and safety, both mission-critical imperatives for the hospital staff.

To measure staff movements, the project team mapped the actual travel activity. As shown in the graphic below, the arrows indicate the paths skilled and licensed personnel had to travel to secure inventory items. Not only did these trips require travel between multiple floors of the hospital, but the staff also had to move between multiple locations on those floors. The team knew that any time spent in transit was time not available for patient care.

As analysis began, the team brainstormed on ideas for improving the process. Was there a way to reorganize the supply procurement process for improved efficiency and increased patient safety? How would such a reorganization impact clinical and licensed staff workflow? If the staff were no longer tasked with procuring the necessary items each day, who would fill this role instead?

The chart below shows which personnel were observed and how much time they spent on non-value-added duties as part of this study, in terms of full-time equivalent (FTE) employees. For instance, the assistant nurse manager was spending over half her shift on inventory (material)-related tasks.

Staff	Department	Current Materials Duties	Future
		FTEs	FTEs
Assistant Nurse Manager Operational and administrative support. Training staff, assigning tasks, scheduling shifts, assessing performance.	Surgical Service	0.55	
Cardiothoracic Coordinator Provides professional nursing care and support the Cardiovascular Service.	Surgical Services	0.45	
Lead Surgical Technician X2 Procedural set-up and support, Equipment/Supply Management, facilitation as needed.	Surgical Services	1.30	
CS/SPD Supervisor Surgical Instrumentation and Case Cart supply management.	Central Sterilization	0.50	
Materials Handler Inventory Management ordering and replenishment.	Materials Management	0.30	
Inventory Coordinator Procedural support, critical Supply and Implant Management, facilitation.	Surgical Service	0.85	4.00
Total		**3.95**	**4.00**

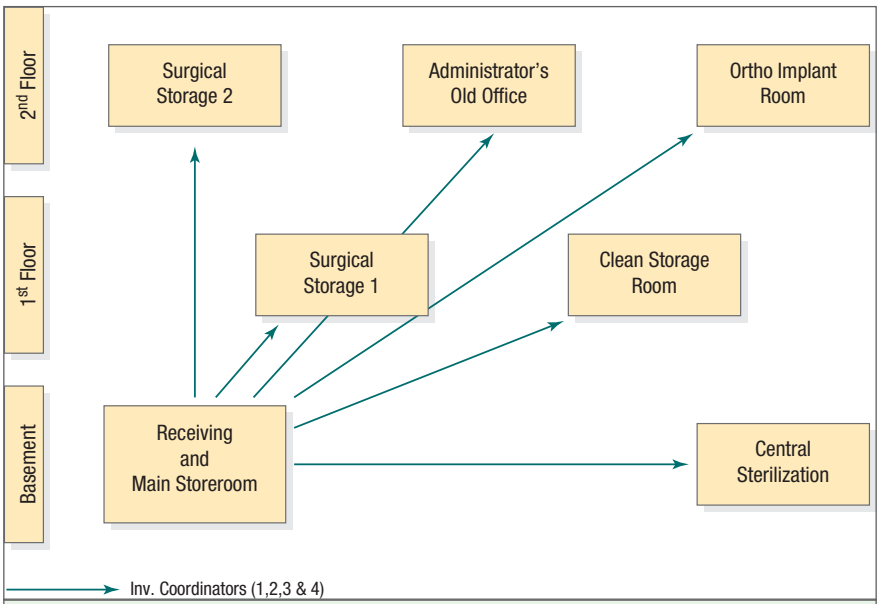
As the team focused on ways to improve the process, they knew they needed to remove non-value-added activities from the purview of clinicians so they could spend their time on patient care responsibilities.

As a result of the time and motion study analysis, Fairview Hospital's Surgery Department established a new staff workflow model under the control of the Materials Management Department, shown below, that required a realignment of the existing surgical inventory coordinator to report to the supply chain organization and take over those duties that were formerly handled by the hospital staff shown in the chart above. Three additional supply chain staff were hired by the Materials Management Team to support the entire Surgery Department. The hiring of these staff relieved the clinicians of the tasks of checking surgical hardware inventory, and implementation of this solution across the Cleveland Clinic enterprise, to date, has returned over 22,000 clinical work hours back to the nurses for increased time spent with patients under their care. While it did not reduce costs as additional supply chain staff had to be hired, the project brought standard work, tools, and inventory management expertise to the Surgery Department, and allowed clinicians to perform within the scope of their training and expertise.



Photo courtesy of Cleveland Clinic/Don Gerda

A caregiver at the Cleveland Clinic scans a product for replenishment, allowing clinicians more time to spend on their patients.



Future State Routes: Stocking Location Activity

Fairview Hospital also incorporated "periodic automatic adjustment" of inventory levels to determine the quantity of supplies that should be on hand at all times for the Surgery Department. This reorganization gave the supply chain organization the opportunity to optimize stocking levels, saving the organization over $2 million in 2019 alone.

As part of the last step of the Six Sigma process, Control, the Supply Chain organization leveraged the Inventory Management Transformation Center of Excellence. This group is charged with developing and managing approaches to exercise control over inventory movement, expiration dates, and consolidating supply chain roles and responsibilities to bolster the organization's "Patient First" goals. For high-dollar inventory items, this team has added RFID tags to track serial numbers and expiration dates and generate automatic reordering of those items as they are used in procedures.

QUESTIONS

1. In addition to the time and motion study the Cleveland Clinic followed, what other work measurement techniques might have been used? Why?
2. Which data analysis tools and metrics might have been used to quantify what the project team observed in the daily travel workflow?
3. After reviewing the various process strategy and analysis techniques in this chapter, what else could Cleveland Clinic do to make the Six Sigma process improvement project even more effective?

3

QUALITY AND PERFORMANCE

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

3.1 Define the four major costs of quality and their relationship to the role of ethics in determining the overall costs of delivering products and services.

3.2 Explain the basic principles of total quality management (TQM) and Six Sigma.

3.3 Understand how acceptance sampling and process performance approaches interface in a supply chain.

3.4 Describe how to construct process control charts and use them to determine whether a process is out of statistical control.

3.5 Explain how to determine whether a process is capable of producing a service or product to specifications.

3.6 Describe International Quality Documentation Standards and the Baldrige Performance Excellence Program.

3.7 Understand the systems approach to total quality management.

Lego



LH Images/Alamy Stock Photo

Lego family within the park Legoland Windsor UK.

Who has not played with Lego toys? Countless number of children and adults over the past half century have used the Lego bricks to build cars, airplanes, action figures, tall buildings, and intricate art sculptures, to name just a few. These interlocking bricks, called "automatic binding bricks," stand the test of time and function flawlessly over decades to retain their shape, smooth finish, and an ability to bear high stress and still be linked with and disassembled from other bricks. How do they do it? It is achieved through their relentless focus on never taking shortcuts on quality, which is reflected in the Lego group's motto of "only the best is good enough."

Lego in Danish means "play well." Starting out as a wooden toy manufacturing company in Denmark in 1936, they migrated over 50% of their production to plastic toys by 1951. The modern brick design with the locking ability that allows the bricks to become a universal system for creative play was patented in 1958. Other innovations, such as Duplo for younger children, mini-figures, and Lego theme kits, followed over the course of years to make Lego one of the most valued brands—one that is highly visible, with eight Lego theme parks all over the globe, more than 125 retail stores, video and board games, books and magazines, children's clothing, movies, and Lego-based television shows.

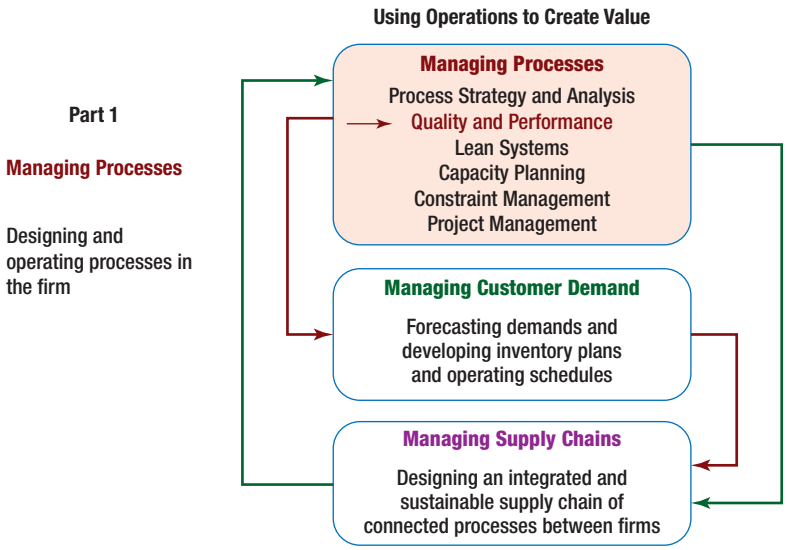
Manufacturing plants located in Czech Republic, Denmark, Hungary, Mexico, and China inject molten plastic into injection molding machines to produce up to 36 billion bricks a year to exacting quality standards. The molds designed by Lego engineers have a tolerance of 18 micrometers to ensure that bricks can stay connected. Inspectors check the output of molds to eliminate significant variation in color and thickness. Machines perform additional drop, torque, tension, compression, bite, impact, and measurement tests to ensure the safety and durability of the product. Only 18 bricks out of a million fail to meet quality standards, which are uniformly enforced irrespective of the global production location through knowledge sharing and use of standardized equipment at each manufacturing plant. During the automated packaging process, a precise number of bricks are dropped into polypropylene bags, which are then weighed to make sure that each bag has the right contents. At the end of the process, these bags are placed into boxes, and packaging operators check that the machines have not made any mistakes and add other necessary pieces before sealing a box. The process uses up to half a million environmentally friendly "green" boxes per year, which are subsequently shipped all over the world.

This single-minded focus on quality and attention to the tiniest details of designing, raw material sourcing, and manufacturing the product has created a company with an iconic brand that continues to maintain its grip on the imagination and wallets of its many happy and satisfied customers.[1]

[1] *Sources:* Tracey V. Wilson, "How Lego Bricks Work" (June 28, 2006), HowStuffWorks.com, https://entertainment.howstuffworks.com/lego.htm (June 18, 2020); Michael Venables, "How Lego Makes Safe, Quality, Diverse and Irresistible Toys Everyone Wants: Part Two" (April 20, 2013), *Forbes*, https://www.forbes.com/sites/michaelvenables/2013/04/20/how-lego-makes-the-safe-quality-diverse-and-irresistible-toys-we-all-want-part-two/#49e519106118 (June 18, 2020); https://en.wikipedia.org/wiki/Lego (June 18, 2020).

The challenge for businesses today is to satisfy their customers through the exceptional performance of their processes and products. Lego is one example of a company that met the challenge by designing and managing its manufacturing processes to provide customers with high-quality products and total satisfaction. Evaluating process performance is important if this is to happen. It is also necessary for managing supply chains.

Quality and performance should be everybody's concern. Therefore, in this chapter, we first address the costs of quality and then focus on total quality management and Six Sigma, two philosophies and supporting tools that many companies embrace to evaluate and improve quality and performance. We subsequently describe how acceptance sampling and process performance approaches interface in a supply chain, and the role played by process variation in determining whether a process is in statistical control or not. We finally conclude with techniques that can be used to measure and improve quality such that the product or service meets the customers' needs and specifications.



Costs of Quality

When a process fails to satisfy a customer, the failure is considered a **defect**. For example, according to the California Academy of Family Physicians, defects for the processes in a doctor's practice are defined as "anything that happened in my office that should not have happened, and that I absolutely do not want to happen again." Obviously, this definition covers process failures that the patient sees, such as poor communication and errors in prescription dosages. It also includes failures the patient does not see, such as incorrect charting.

defect
Any instance when a process fails to satisfy its customer.

Closely tied to the notion of defects is the question of determining how much quality is enough. There is a greater societal effect that also must be factored into decision making involving the production of services or products that often requires balancing the costs of quality with the overall benefits to society. For example, in the health care industry, aiming for zero complications in cardiac surgery might sound good; however, if it comes at the cost of turning down high-risk patients, is society being served in the best way? Or how much time, energy, and money should go into delivering vaccines or preventing complications? These are questions that often do not have clear answers.

Many companies spend significant time, effort, and expense on systems, training, and organizational changes to improve the quality and performance of their processes. They believe that it is important to be able to gauge current levels of performance so that any process gaps can be determined. Gaps reflect potential dissatisfied customers and additional costs for the firm. Most experts estimate that the costs of quality range from 20 to 30 percent of gross sales. These costs can be broken down into four major categories: (1) prevention, (2) appraisal, (3) internal failure, and (4) external failure. The American Society for Quality, also commonly known as ASQ (http://asq.org/learn-about-quality/cost-of-quality/overview/overview.html), provides several examples of these four types of costs. In addition, there is a fifth category of costs associated with unethical behavior in making quality decisions, and which can be significantly higher than all the other four costs combined.

Prevention Costs

Prevention costs are associated with preventing defects before they happen. They include the costs of redesigning the process to remove the causes of poor performance, redesigning the service or product to make it simpler to produce, training employees in the methods of continuous improvement, and working with suppliers to increase the quality of purchased items or contracted services. To prevent problems from happening, firms must invest additional time, effort, and money. Some examples of where these investments are needed include (1) *product or service requirements*, which involve establishment of specifications for incoming materials, processes, finished products, and services; (2) *quality planning,* which involves creation of plans for quality, reliability, operations, production, and inspection; (3) *quality assurance*, which involves creation and maintenance of a well-defined quality system; and (4) *training* that is focused on the development, preparation, and maintenance of quality-related programs.

prevention costs
Costs associated with preventing defects before they happen.

Appraisal Costs

appraisal costs
Costs incurred when the firm assesses the performance level of its processes.

Appraisal costs are incurred when the firm assesses the level of performance of its processes. As the costs of prevention increase and performance improves, appraisal costs decrease because fewer resources are needed for quality inspections and the subsequent search for causes of any problems that are detected. Some examples of appraisal costs include (1) *verification*, which involves checking of incoming materials, process setups, and products against agreed upon specifications; (2) *quality audits* aimed at confirming that the quality system is functioning correctly; and (3) *supplier rating*, which is the assessment and approval of suppliers of products and services.

Internal Failure Costs

internal failure costs
Costs resulting from defects that are discovered during the production of a service or product.

Internal failure costs result from defects that are discovered during the production of a service or product. Defects fall into three main categories: (1) *rework or rectification*, which is incurred if some aspect of a service must be performed again or if a defective item must be rerouted to some previous operation(s) to correct the defect; (2) *scrap*, which is incurred if a defective item is unfit for further processing and cannot be repaired, used, or sold; and (3) *waste*, which involves performance of unnecessary work or holding stock as a result of errors or poor communication and organization.

External Failure Costs

external failure costs
Costs that arise when a defect is discovered after the customer receives the service or product.

External failure costs arise when a defect is discovered after the customer receives the service or product. Dissatisfied customers talk about bad service or products to their friends, who in turn tell others. If the problem is bad enough, consumer protection groups may even alert the media. The potential impact on future profits is difficult to assess, but without doubt external failure costs erode market share and profits. Encountering defects and correcting them after the product is in the customer's hands is costly. Examples of external failure costs include costs that are associated with (1) *repairs and servicing* of both returned products and those actually being used by customers; (2) *complaints*, which involve all costs and work associated with handling and servicing customers' complaints; (3) *returns*, which involves transportation of rejected or recalled products; and (4) *warranty service and litigation* costs, where a **warranty** is a written guarantee that the producer will replace or repair defective parts or perform the service to the customer's satisfaction. Usually, a warranty is given for some specified period. For example, television repairs may be guaranteed for 90 days and new automobiles for 5 years or 50,000 miles, whichever comes first. Warranty costs must be considered in the design of new services or products.

warranty
A written guarantee that the producer will replace or repair defective parts or perform the service to the customer's satisfaction.

Ethical Failure Costs

ethical failure costs
Societal and monetary costs associated with *deceptively* passing defective services or products to internal or external customers such that it jeopardizes the well-being of stockholders, customers, employees, partners, and creditors.

The costs of quality go far beyond the out-of-pocket costs associated with training, appraisal, scrap, rework, warranties, litigation, or the lost sales from dissatisfied customers. **Ethical failure costs** are the societal and monetary costs associated with *deceptively* passing defective services or products to internal or external customers such that it jeopardizes the well-being of stockholders, customers, employees, partners, and creditors.

As a practical matter, ethical costs arise from internal or external failures. The main difference is that somebody tries to "cover them up" and knowingly passes the defects along to the customer, knowing that they can do harm. What makes the nature of ethical failure costs different from internal failure or external failure costs already mentioned is the punitive costs of litigation once the ethical lapses are discovered, the extraordinary magnitude of the fines and penalties, the loss of goodwill that can literally damage the firm for a long time, and the hidden costs of employee morale and attitude. Ethical costs are tied to deception and shifting the blame to other partners in the supply chain, and go beyond the internal or external failure costs associated with fixing the quality problems in an organization. Mattel—with brands like Fisher Price, Barbie Dolls, and Hot Wheels, among others—had to issue multiple product recalls in 2007 due to the presence of cheaper but toxic lead paint in its toys. Problems also existed with loosely attached small magnets in its toys, which if swallowed could cause injuries to children. Despite exerting downward pressures on costs, Mattel initially denied knowledge and responsibility for the use of lead paint, and instead placed the blame on the suppliers to its manufacturing plants in China. But later on, after stockholder lawsuits claiming the withholding of timely information and misleading financial statements, and also government and media pressure, Mattel instituted stringent inspection and quality programs to prevent the recurrence of such incidents. As a result, Mattel has significantly repaired its corporate image over the past decade.

Deceptive business practices are a source of major concern for service or product quality. Deceptive business practice involves three elements: (1) The conduct of the provider is intentional and motivated by a desire to exploit the customer; (2) the provider conceals the truth based upon what is actually known to the provider; and (3) the transaction is intended to generate a disproportionate economic benefit to the provider at the expense of the customer. This behavior is unethical, diminishes the quality of the customers' experience, and may impose a substantial cost on society. Quality is all about increasing the satisfaction of customers. When a firm engages in unethical behavior and the customer finds out about it, the customer is unlikely to favorably assess the quality of his or her experience with that firm or to return as a customer. Under these conditions, employees of firms that attempt to profit by deceiving customers are less likely to be motivated to put forth their best effort to create true value for customers; they erode a firm's ability to compete now and in the future. Therefore, ethical behavior falls on the shoulders of all employees of an organization. Many firms like Patagonia, Starbucks, and the retailer H&M go the extra mile to ensure that they source their materials from suppliers that follow ethical business practices.

Overall, management must put in place the appropriate processes and approaches to manage the quality costs of prevention, assessment, internal failure, external failure, and ethical failure. Developing the cultural environment for ethical behavior is not cost free. Employees must be educated in how ethics interfaces with their jobs. The firm may organize an ethics task force or an ethics public relations group to provide an interface between the firm and society. Documentation may be required.



UPI/Alamy Stock Photo

Polly Pocket play sets and Batman action figures are seen in a basket at Kinder Haus Toy store in Arlington, Virginia. Mattel recalled 9 million Chinese made toys, including Polly Pocket play sets, Batman action figures, Fisher-Price toys and some die cast cars because of the presence of lead paint or their use of tiny magnets that could cause a choking hazard.

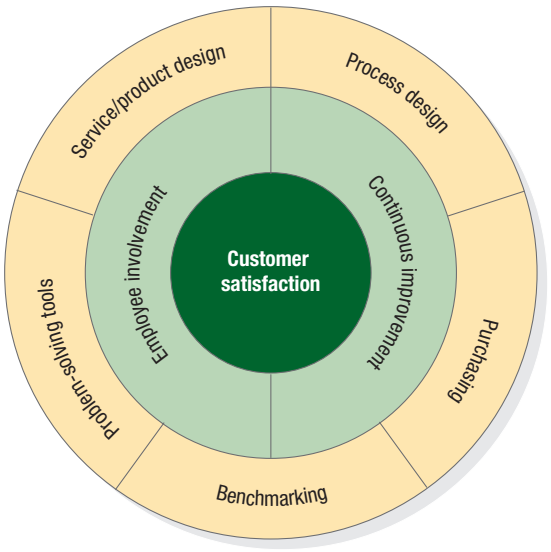
Total Quality Management and Six Sigma

We now turn to a discussion of total quality management and Six Sigma, two philosophies companies use to evaluate and improve quality and process performance along technical, service, and ethical dimensions.

Total Quality Management

Total quality management (TQM) is a philosophy that stresses three principles for achieving high levels of process performance and quality. These principles are related to (1) customer satisfaction, (2) employee involvement, and (3) continuous improvement in performance. As Figure 3.1 indicates, TQM also involves a number of other important elements. We have covered tools and process analysis techniques useful for process problem solving, redesign, and improvement in Chapter 2 "Process Strategy and Analysis." Service or product design and purchasing are covered later in this text. Here, we just focus on the three main principles of TQM, which must always be guided and supported by management commitment and leadership in creating a quality-driven organization.

▼ **FIGURE 3.1**
TQM Wheel



Customer Satisfaction Customers, internal or external, are satisfied when their expectations regarding a service or product have been met or exceeded. Often, customers use the general term **quality** to describe their level of satisfaction with a service or product. Quality has multiple dimensions in the mind of the customer, which cut across the nine competitive priorities we introduced in Chapter 1, "Using Operations to Create Value." One or more of the following five definitions apply at any one time.

- **Conformance to Specifications.** Although customers evaluate the service or product they receive, it is the processes that produced the service or product that are really being judged. In this case, a process failure would be the process's inability to meet certain advertised or implied performance standards. Conformance to specifications may relate to consistent quality, on-time delivery, or delivery speed.
- **Value.** Another way customers define quality is through value, or how well the service or product serves its intended purpose at a price customers are willing to pay. The service or product development process plays a role here, as do the firm's competitive priorities relating to top-quality versus low-cost operations. The two factors must be balanced to produce value for the customer. How much value a service or product has in the mind of the customer depends on the customer's expectations before purchasing it.

total quality management (TQM)
A philosophy that stresses three principles for achieving high levels of process performance and quality: (1) customer satisfaction, (2) employee involvement, and (3) continuous improvement in performance.

quality
A term used by customers to describe their general satisfaction with a service or product.

- **Fitness for Use.** When assessing how well a service or product performs its intended purpose, the customer may consider the convenience of a service, the mechanical features of a product, or other aspects such as appearance, style, durability, reliability, craftsmanship, and serviceability. For example, you may define the quality of the entertainment center you purchased on the basis of how easy it was to assemble and its appearance and styling.
- **Support.** Often the service or product support provided by the company is as important to customers as the quality of the service or product itself. Customers get upset with a company if its financial statements are incorrect, responses to its warranty claims are delayed, its advertising is misleading, or its employees are not helpful when problems are incurred. Good support once the sale has been made can reduce the consequences of quality failures.
- **Psychological Impressions.** People often evaluate the quality of a service or product on the basis of psychological impressions: atmosphere, image, or aesthetics. In the provision of services where the customer is in close contact with the provider, the appearance and actions of the provider are especially important. Nicely dressed, courteous, friendly, and sympathetic employees can affect the customer's perception of service quality.

Attaining quality in all areas of a business is a difficult task. To make things even more difficult, consumers change their perceptions of quality. In general, a business's success depends on the accuracy of its perceptions of consumer expectations and its ability to bridge the gap between those expectations and operating capabilities. Good quality pays off in higher profits. High-quality services and products can be priced higher and yield a greater return. Poor quality erodes the firm's ability to compete in the marketplace and increases the costs of producing its service or product.

Employee Involvement One of the important elements of TQM is employee involvement, as shown in Figure 3.1. A program in employee involvement includes changing organizational culture and encouraging teamwork.

- **Cultural Change.** One of the main challenges in developing the proper culture for TQM is to define *customer* for each employee. In general, customers are internal or external. *External customers* are the people or firms who buy the service or product. Some employees, especially those having little contact with external customers, may have difficulty seeing how their jobs contribute to the whole effort.

  It is helpful to point out to employees that each employee also has one or more *internal customers*—employees in the firm who rely on the output of other employees. All employees must do a good job of serving their internal customers if external customers ultimately are to be satisfied. They will be satisfied only if each internal customer demands value be added that the external customer will recognize and pay for. The notion of internal customers applies to all parts of a firm and enhances cross-functional coordination. For example, accounting must prepare accurate and timely reports for management, and purchasing must provide high-quality materials on time for operations.

  In TQM, everyone in the organization must share the view that quality control is an end in itself. Errors or defects should be caught and corrected at the source, not passed along to an internal or external customer. For example, a consulting team should make sure its billable hours are correct before submitting them to the accounting department. This philosophy is called **quality at the source**. In addition, firms should avoid trying to "inspect quality into the product" by using inspectors to weed out unsatisfactory services or defective products after all operations have been performed. By contrast, in some manufacturing firms, workers have the authority to stop a production line if they spot quality problems.

quality at the source

A philosophy whereby defects are caught and corrected where they were created.

- **Teams.** Employee involvement is a key tactic for improving processes and quality. One way to achieve employee involvement is by the use of **teams**, which are small groups of people who have a common purpose, set their own performance goals and approaches, and hold themselves accountable for success. The three approaches to teamwork most often used are (1) problem-solving teams, (2) special-purpose teams, and (3) self-managed teams. All three use some amount of **employee empowerment**, which moves responsibility for decisions further down the organizational chart—to the level of the employee actually doing the job.

teams

Small groups of people who have a common purpose, set their own performance goals and approaches, and hold themselves accountable for success.

employee empowerment

An approach to teamwork that moves responsibility for decisions further down the organizational chart—to the level of the employee actually doing the job.

The value of employee involvement and empowerment in creating high-quality products can be seen at the Santa Cruz Guitar Company in Managerial Practice 3.1.

MANAGERIAL PRACTICE 3.1 Improving Quality Through Employee Involvement at Santa Cruz Guitar Company

Founded in 1976, the Santa Cruz Guitar Company produces acoustic guitars that are well recognized by famous artists such as Eric Clapton, Tony Rice, Warren Haynes, and Elvis Costello. The company is a small-scale manufacturer that produces about 500 to 700 guitars per year and emphasizes small production numbers in order to focus on instrument quality. In the competitive marketplace of musical instruments, the sole order winning competitive priority is top quality, which is represented by the sound of the instrument. Ironically, the company does not have a formal process of quality assurance through a dedicated department. Instead, the quality of the guitars is entrusted to employees at all levels. Every instrument is built as a team, and the company practices total quality management along with following the management principles of W. Edwards Deming.

The process of making a guitar is divided into seven steps, with each step requiring various degrees of inspection at all levels. The guitar-making process starts with selecting the wood. Each wood type is obtained from a few trusted suppliers located around the world. The tops are from Germany, the back and side materials are from India or Brazil, and so forth. The shop floor where the woods are treated is kept at a constant 47 percent humidity, which is optimum for maintaining the equilibrium of moisture conditions. For cutting the treated wood, the company invested in an expensive machine that relieves the craftsmen from performing repetitive tasks. While many artisan and luxury brand products claim to be 100 percent handcrafted, Santa Cruz Guitar Company made this choice so that the craftsmen can concentrate on more delicate processes that are best suited for human hands. It also keeps them highly motivated, and helps to reduce repetitive stress injuries. The craftsmen then take the fine-cut wood and bend the sides to the desired shapes using their hands. This process is best performed by human hands because sides that are shaped by machines have a tendency to spring back when they are being forced into molds. Next, the guitar top and back are cut to shape, and braced. The thicknesses of the top and the braces have the most influence on the final sound of the guitar. The craftsmen will tap the top of each finished piece to hear the tone and adjust the thickness of the wooden support braces attached under the top until the tone is perfect. The craftsmen document what they did while building the top, and if a guitar produces an exceptional sound, the craftsman making that guitar will be asked to check his or her notes, and the knowledge thus gained will be shared with others. The neck of the guitar requires consistent quality conforming to the tight customer specifications. Therefore, this process is carried out using machines. The guitar pieces are finished with 12 protective layers of lacquer and then assembled. A technician will play the guitar for the first time, and adjust the neck or string height and make sure that the instrument provides optimized playability to the customer.



Patrick Tehan/San Jose Mercury News/MCT/Newscom

A worker constructs an instrument at the Santa Cruz Guitar Company in Santa Cruz, California.

The company empowers workers to take quality initiatives at every step of the process, and this is possible due to their employee-supportive culture. Workers are encouraged to take external courses or practice their skills by allowing them to build two instruments a year for personal use. Craftsmen continuously explore new techniques in building guitars, and make quality improvement suggestions. The company also encourages the craftsmen to go out and open their own guitar brand business. While this may increase competition in the market and pose potential threats, the firm puts trust in furthering the welfare of its employees to enhance process quality. Promoting pride in workmanship, open communication with supervisors, and employee empowerment altogether make Santa Cruz Guitar Company an inspired and productive manufacturer of high-quality musical instruments.[2]

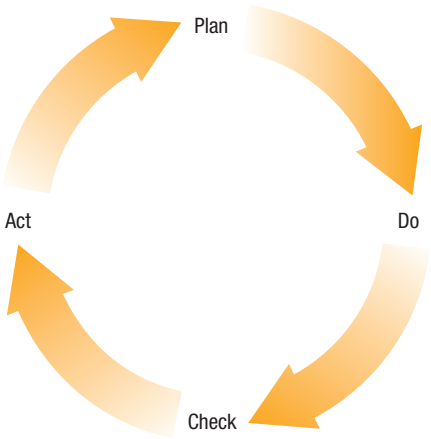
Continuous Improvement Based on a Japanese concept called *kaizen*, **continuous improvement** is the philosophy of continually seeking ways to improve processes. Continuous improvement involves identifying benchmarks of excellent practice and instilling a sense of employee ownership in the process. The focus of continuous improvement projects is to reduce waste, such as reducing the length of time required to process requests for loans at a bank, the amount of scrap generated at a milling machine, or the number of employee injuries at a construction site. The basis of the continuous improvement philosophy is the belief that virtually any aspect of a process can be improved and that the people most closely associated with a process are in the best position to identify the changes that should be made. The idea is not to wait until a massive problem occurs before acting.

continuous improvement
The philosophy of continually seeking ways to improve processes based on a Japanese concept called *kaizen*.

Employees should be given problem-solving tools, such as the statistical process control (SPC) methods we discuss later in this chapter, and a sense of ownership of the process to be improved.

[2] *Sources:* L. T. Foo, "Good Vibrations: Ingrained Quality Practices Mirror Deming's 14 Points," *Quality Progress* (2008), http://asq.org/quality-progress/2008/02/quality-managementment/good-vibrations.html; Santa Cruz Guitar Company (February 18, 2017), http://www.santacruzguitar.com/our-story/ (June 16, 2020); https://en.wikipedia.org/wiki/Santa_Cruz_Guitar_Company.

▼ **FIGURE 3.2**
Plan-Do-Check-Act-Cycle



A sense of operator ownership emerges when employees feel a responsibility for the processes and methods they use and take pride in the quality of the service or product they produce. It comes from participation on work teams and in problem-solving activities, which instill in employees a feeling that they have some control over their workplace and tasks.

Most firms actively engaged in continuous improvement train their work teams to use the **plan-do-check-act cycle** for problem solving. Another name for this approach is the Deming wheel, named after the renowned statistician W. Edwards Deming who taught quality improvement techniques to the Japanese after World War II. Figure 3.2 shows this cycle, which lies at the heart of the continuous improvement philosophy. The cycle comprises the following steps:

plan-do-check-act cycle
A cycle, also called the Deming wheel, used by firms actively engaged in continuous improvement to train their work teams in problem solving.

1. *Plan.* The team selects a process (an activity, method, machine, or policy) that needs improvement. The team then documents the selected process, usually by analyzing related data; sets qualitative goals for improvement; and discusses various ways to achieve the goals. After assessing the benefits and costs of the alternatives, the team develops a plan with quantifiable measures for improvement.
2. *Do.* The team implements the plan and monitors progress. Data are collected continuously to measure the improvements in the process. Any changes in the process are documented, and further revisions are made as needed.
3. *Check.* The team analyzes the data collected during the *do* step to find out how closely the results correspond to the goals set in the *plan* step. If major shortcomings exist, the team reevaluates the plan or stops the project.
4. *Act.* If the results are successful, the team documents the revised process so that it becomes the standard procedure for all who may use it. The team may then instruct other employees in the use of the revised process.

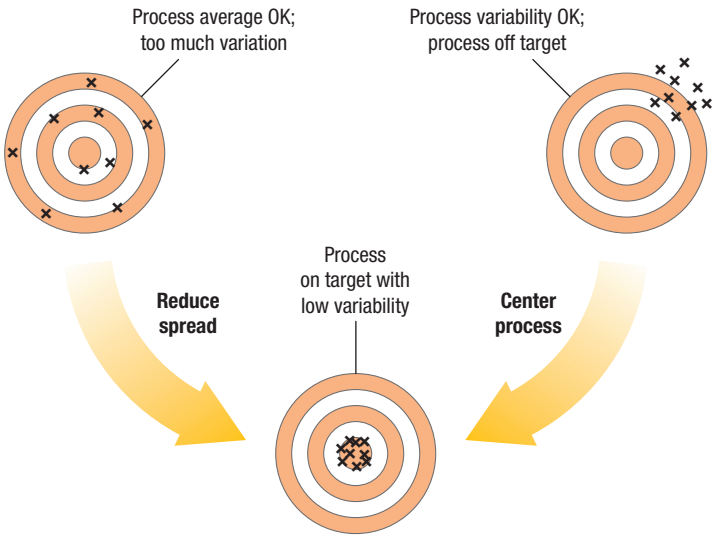
Problem-solving projects often focus on those aspects of processes that do not add value to the service or product. Value is added in processes such as machining a part or serving a customer through a Web page. No value is added in activities such as inspecting parts for defects or routing requests for loan approvals to several different departments. The idea of continuous improvement is to reduce or eliminate activities that do not add value and, thus, are wasteful.

Six Sigma

Six Sigma
A comprehensive and flexible system for achieving, sustaining, and maximizing business success by minimizing defects and variability in processes.

The **Six Sigma** philosophy allows managers to think analytically about processes and their underlying quality. It relies heavily on the principles of TQM, and is a comprehensive and flexible system for achieving, sustaining, and maximizing business success by minimizing defects and variability in processes. Six Sigma has a different focus than TQM does: It is driven by a close understanding of customer needs; the disciplined use of facts, data, and statistical analysis; and diligent attention to managing, improving, and reinventing business processes. Figure 3.3 shows how Six Sigma focuses on reducing variation in processes as well as centering processes on their target measures of performance. Either flaw—too much variation or an off-target process—degrades performance of the process. For example, a mortgage loan department of a bank might advertise loan approval decisions in 2 days. If the actual performance ranges from 1 to 5 days, with an average of 2 days, those customers who had to wait longer than 2 days would be upset. Process variability causes customer dissatisfaction. Similarly, if actual performance consistently produced loan decisions in 3 days, all customers would be dissatisfied. In this case, the process is consistent, but off the target. Six Sigma is a rigorous approach to align processes with their target performance measures with low variability.

▼ **FIGURE 3.3**
Six Sigma Approach Focuses on Reducing Spread and Centering the Process



The name Six Sigma, originally developed by Motorola for its manufacturing operations, relates to the goal of achieving low rates of defective output by developing processes whose mean output for a performance measure is $\pm$ 6 standard deviations (sigma) from the limits of the design specifications for the service or product. We will discuss variability and its implications on the capability of a process to perform at acceptable levels when we present the tools of statistical process control.

Although Six Sigma was rooted in an effort to improve manufacturing processes, credit General Electric with popularizing the application of the approach to non-manufacturing processes such as sales, human resources,

customer service, and financial services. The concept of eliminating defects is the same, although the definition of "defect" depends on the process involved. For example, a human resource department's failure to meet a hiring target counts as a defect. Using the DMAIC approach within the Six Sigma Improvement model highlighted in Chapter 2, "Process Strategy and Analysis," Six Sigma process improvement specialists with black belts have been able to mentor employees and successfully apply Six Sigma to improve a host of service processes, including financial services, human resource processes, marketing processes, and health care administrative processes.



ClassicStock/Alamy Stock Photo

Harley Davidson Motorcycle Assembly Line in York, Pennsylvania. Harley Davidson uses Statistical Process Control to enhance the quality of its motorcycles in different areas of the plant where the motorcycles are assembled.

Acceptance Sampling

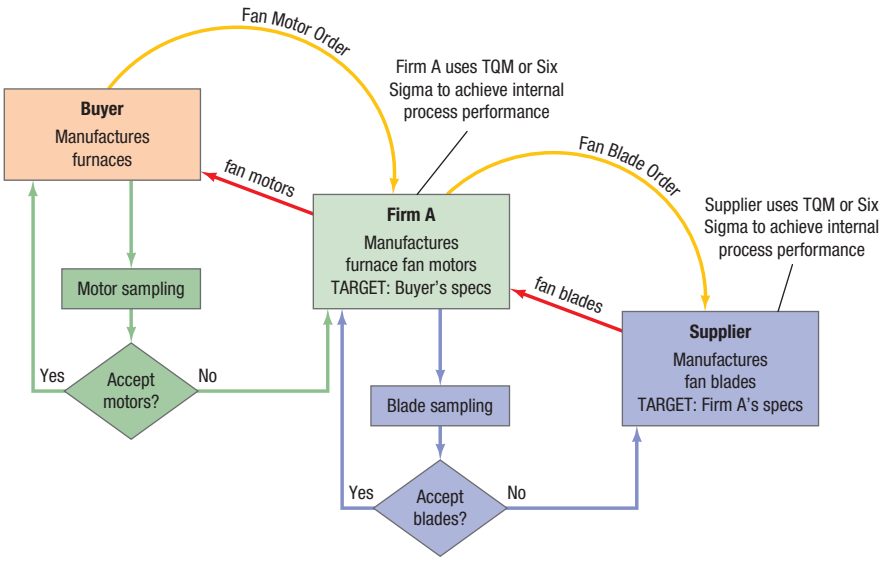
Before any internal process can be evaluated for performance, the inputs to that process must be of good quality. **Acceptance sampling**, which is the application of statistical techniques to determine if a quantity of material from a supplier should be accepted or rejected based on the inspection or test of one or more samples, limits the buyer's risk of rejecting good-quality materials (and unnecessarily delaying the production of goods or services) or accepting bad-quality materials (and incurring downtime due to defective materials or passing bad products to customers). Relative to the specifications for the material the buyer is purchasing, the buyer specifies an **acceptable quality level (AQL)**, which is a statement of the proportion of defective items (outside of specifications) that the buyer will accept in a shipment. These days, that proportion is getting very small, often measured in parts per ten-thousand. The idea of acceptance sampling is to take a sample, rather than testing the entire quantity of material, because that is often less expensive. Therein lies the risk—the sample may not be representative of the entire lot of goods from the supplier. The basic procedure is straightforward.

acceptance sampling
The application of statistical techniques to determine whether a quantity of material should be accepted or rejected based on the inspection or test of a sample.

acceptable quality level (AQL)
The quality level desired by the consumer.

1. A random sample is taken from a large quantity of items and tested or measured relative to the specifications or quality measures of interest.
2. If the sample passes the test (low number of defects), the entire quantity of items is accepted.
3. If the sample fails the test, either (a) the entire quantity of items is subjected to 100 percent inspection and all defective items repaired or replaced, or (b) the entire quantity is returned to the supplier.

In a supply chain, any company can be both a producer of goods purchased by another company and a consumer of goods or raw materials supplied by another company. Figure 3.4 shows a flowchart of how acceptance sampling and internal process performance (TQM or Six Sigma) interface in a supply chain. From the perspective of the supply chain, the buyer's specifications for various dimensions of quality become the targets the supplier shoots for in a supply contract. The supplier's internal processes must be up to the task; TQM or Six Sigma can help achieve



▲ **FIGURE 3.4**
Interface of Acceptance Sampling and Process Performance Approaches in a Supply Chain

the desired performance. The buyer's sampling plan will provide a high probability of accepting AQL (or better). Online Supplement G, "Acceptance Sampling Plans," shows how to design an acceptance sampling plan that meets the level of risk desired.

Measuring quality of a process and monitoring its progress over time can be a complex task that involves a multitude of steps and decisions, as the following Managerial Challenge demonstrates.

MANAGERIAL CHALLENGE Accounting

Star Industries, Inc., manufactures highly engineered products for both the electric transmission and wireless communication industries. Rebecca Davis, corporate controller, oversees the accounting and budgeting functions for the company. Last year she directed a major overhaul of a number of internal processes, including payroll accounting and customer billing. The overhaul included new equipment and technologies as well as new manual procedures for the staff. Now that the new processes had about a year to iron out the glitches, she needed to know how many, if any, improvements were made. The motivation for the process improvement project was to reduce costly inefficiencies in payroll and to reduce the lead time to bill customers. The latter improvement was aimed at improving revenue flows and cash position.

Rebecca realized that she needed the help of someone who could develop budgets and had the skills to track budget expenses, analyze data, and audit ongoing processes. She hired Jamal Johnson, who recently graduated with a degree in accounting, to assume the role of budget analyst. Jamal began by studying the payroll accounting process. It consisted of a number of repetitive procedures that included the proper authorization of overtime, approval of time records, and checks on the calculation of gross pay and payroll deductions. Auditors could periodically sample individual employee pay records to verify the documentation of the required authorizations and approvals. A missing authorization or approval would constitute a process defect. Jamal wondered how big the sample should be? How often should it be taken? Over time, how would he know if the process is getting better or getting worse?

The customer billing process has revenue implications and therefore has high status in the accounting department. Jamal realized that the important statistic in this process is the time between the point that goods are provided and the point that the customers are billed; reducing that time is a key step in speeding up collections. Auditors could randomly draw samples of invoices and measure the amount of time between delivery date and billing date. In this case, what would be considered a defect? How big should the sample be, and how often should a sample be taken? Finally, over time, how can he be sure that the process is running as planned? The remainder of this chapter will provide Jamal guidance in answering his questions.

Statistical Process Control

Regardless of whether a firm is producing a service or a product, it is important to ensure that the firm's processes are providing the quality that customers want. A key element of TQM or Six Sigma is building the capability to monitor the performance of processes so that corrective action can be initiated in a timely fashion. Evaluating the performance of processes requires a variety of data-gathering approaches. We already discussed checklists, histograms and bar charts, Pareto charts, scatter diagrams, cause-and-effect diagrams, and graphs (see Chapter 2, "Process Strategy and Analysis"). All of these tools can be used with TQM or Six Sigma. Here, we focus on the powerful statistical tools that can be used to monitor and manage repetitive processes.

statistical process control (SPC)
The application of statistical techniques to determine whether a process is delivering what the customer wants.

Statistical process control (SPC) is the application of statistical techniques to determine whether a process is delivering what customers want. In SPC, tools called "control charts" are used primarily to detect defective services or products or to indicate that the process has changed and that services or products will deviate from their design specifications, unless something is done to correct the situation. SPC can also be used to inform management of improved process changes. Examples of process changes that can be detected by SPC include the following:

- A decrease in the average number of complaints per day at a hotel
- A sudden increase in the proportion of defective gear boxes
- An increase in the time to process a mortgage application
- A decline in the number of scrapped units at a milling machine
- An increase in the number of claimants receiving late payment from an insurance company

Let us consider the last situation. Suppose that the manager of the accounts payable department of an insurance company notices that the proportion of claimants receiving late payments

rose from an average of 0.01 to 0.03. The first question is whether the rise is a cause for alarm or just a random occurrence. Statistical process control can help the manager decide whether further action should be taken. If the rise in the proportion is not just a random occurrence, the manager should seek explanations of the poor performance. Perhaps the number of claims significantly increased, causing an overload on the employees in the department. The decision might be to hire more personnel. Or perhaps the procedures being used are ineffective or the training of employees is inadequate. SPC is an integral part of TQM and Six Sigma.

Variation of Outputs

No two services or products are exactly alike because the processes used to produce them contain many sources of variation, even if the processes are working as intended. Nonetheless, it is important to minimize the variation in outputs because frequently variation is what the customer sees and feels. Suppose a physicians' clinic submits claims on behalf of its patients to a particular insurance company. In this situation, the physicians' clinic is the customer of the insurance company's bill payment process. In some cases, the clinic receives payment in 4 weeks, and in other cases 20 weeks. The time to process a request for payment varies because of the load on the insurance company's processes, the medical history of the patient, and the skills and attitudes of the employees. Meanwhile, the clinic must cover its expenses while it waits for payment. Regardless of whether the process is producing services or products, nothing can be done to eliminate variation in output completely; however, management should investigate the *causes* of the variation in order to minimize it.



Ian Shaw/Alamy Stock Photo

Wine production is an example of a situation in which complete inspection is not an option. Here a quality inspector draws a sample of white wine from a stainless steel maturation tank.

Performance Measurements Performance can be evaluated in two ways. One way is to measure **variables**—that is, service or product characteristics, such as weight, length, volume, or time, that can be *measured*. The advantage of using performance variables is that if a service or product misses its performance specifications, the inspector knows by how much. The disadvantage is that such measurements typically involve special equipment, employee skills, exacting procedures, and time and effort.

variables

Service or product characteristics, such as weight, length, volume, or time, that can be measured.

Another way to evaluate performance is to measure **attributes**; service or product characteristics that can be quickly *counted* for acceptable performance. This method allows inspectors to make a simple "yes or no" decision about whether a service or product meets the specifications. Attributes often are used when performance specifications are complex and measurement of variables is difficult or costly. Some examples of attributes that can be counted are the number of insurance forms containing errors that cause underpayments or overpayments, the proportion of airline flights arriving within 15 minutes of scheduled times, and the number of stove-top assemblies with spotted paint.

attributes

Service or product characteristics that can be quickly counted for acceptable performance.

The advantage of counting attributes is that less effort and fewer resources are needed than for measuring variables. The disadvantage is that, even though attribute counts can reveal that process performance has changed, they do not indicate by how much. For example, a count may determine that the proportion of airline flights arriving within 15 minutes of their scheduled times declined, but the result does not show how much beyond the 15-minute allowance the flights are arriving. For that, the actual deviation from the scheduled arrival, a variable, would have to be measured.

Sampling The most thorough approach to inspection is to examine each service or product at each stage of the process for quality. This method, called *complete inspection*, is used when the costs of passing defects to an internal or external customer outweigh the inspection costs. Firms often use automated inspection equipment that can record, summarize, and display data. Many companies find that automated inspection equipment can pay for itself in a reasonably short time.



Juice Images/Alamy Stock Photo

Performance measurement is the key to quality improvement. Here a quality inspector measures the diameter of holes in a machined part.

sampling plan
A plan that specifies a sample size, the time between successive samples, and decision rules that determine when action should be taken.

sample size
A quantity of randomly selected observations of process outputs.

A well-conceived **sampling plan** can approach the same degree of protection as complete inspection. A sampling plan specifies a **sample size**, which is a quantity of randomly selected observations of process outputs, the time between successive samples, and decision rules that determine when action should be taken. Sampling is appropriate when inspection costs are high because of the special knowledge, skills, procedures, and expensive equipment that are required to perform the inspections, or because the tests are destructive.

Sampling Distributions Relative to a performance measure, a process will produce output that can be described by a *process distribution*, with a mean and variance that will be known only with a complete inspection with 100 percent accuracy. The purpose of sampling, however, is to estimate a variable or attribute measure for the output of the process without doing a complete inspection. That measure is then used to assess the performance of the process itself. For example, the time required to process specimens at an intensive care unit lab in a hospital (a variable measure) will vary. If you measured the time to complete an analysis of a large number of patients and plotted the results, the data would tend to form a pattern that can be described as a process distribution. With sampling, we try to estimate the parameters of the process distribution using statistics such as the sample mean and the sample range or standard deviation.

1. The *sample mean* is the sum of the observations divided by the total number of observations:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

where

x_i = observation of a quality characteristic (such as time)

n = total number of observations

$\bar{x}$ = mean

2. The *range* is the difference between the largest observation in a sample and the smallest. The *standard deviation* is the square root of the variance of a distribution. An estimate of the process standard deviation based on a sample is given by

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad \text{or} \quad \sigma = \sqrt{\frac{\sum_{i=1}^{n} x^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}}{n-1}}$$

where

σ = standard deviation of a sample

n = total number of observations in the sample

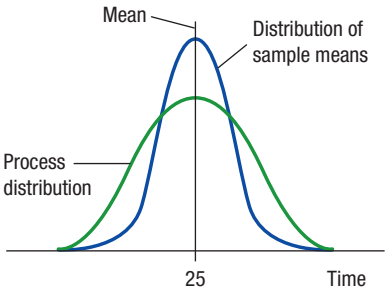
$\bar{x}$ = mean

x_i = observation of a quality characteristic

Relatively small values for the range or the standard deviation imply that the observations are clustered near the mean.

These sample statistics have their own distribution, which we call a *sampling distribution*. For example, in the lab analysis process, an important performance variable is the time it takes to get results to the critical care unit. Suppose that management wants results available in an average of 25 minutes. That is, it wants the process distribution to have a mean of 25 minutes. An inspector periodically taking a sample of five analyses and calculating the sample mean could use it to determine how well the process is doing. Suppose that the process is actually producing the analyses with a mean of 25 minutes. Plotting a large number of these sample means would show that they have their own sampling distribution with a mean centered on 25 minutes, as does the process distribution mean, but with much less variability. The reason is that the sample means offset the highs and lows of the individual times in each sample. Figure 3.5 shows the relationship between the sampling distribution of sample means and the process distribution for the analysis times.

▼ **FIGURE 3.5**
Relationship Between the Distribution of Sample Means and the Process Distribution



Some sampling distributions (e.g., for means with sample sizes of 4 or more and proportions with sample sizes of 20 or more) can be approximated by the normal distribution, allowing the use of the normal tables (see Appendix 1, "Normal Distribution"). For example, suppose you wanted to determine the probability that a sample mean will be more than 2.0 standard deviations higher than the process mean. Go to Appendix 1 and note that the entry in the table for $z = 2.0$ standard deviations is 0.9772. Consequently, the probability is 1.0000 − 0.9772 = 0.0228, or 2.28 percent. The probability that the sample mean will be more than 2.0 standard deviations lower than the process mean is

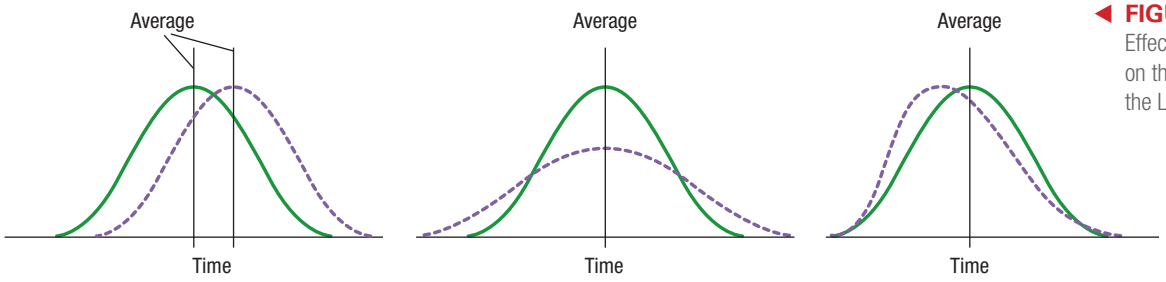
also 2.28 percent, because the normal distribution is symmetric to the mean. The ability to assign probabilities to sample results is important for the construction and use of control charts.

Common Causes The two basic categories of variation in output include common causes and assignable causes. **Common causes of variation** are the purely random, unidentifiable sources of variation that are unavoidable with the current process. A process distribution can be characterized by its *location*, *spread*, and *shape*. Location is measured by the *mean* of the distribution, while spread is measured by the *range* or *standard deviation.* The shape of process distributions can be characterized as either symmetric or skewed. A *symmetric* distribution has the same number of observations above and below the mean. A *skewed* distribution has a greater number of observations either above or below the mean. If process variability results solely from common causes of variation, a typical assumption is that the distribution is symmetric, with most observations near the center.

common causes of variation
The purely random, unidentifiable sources of variation that are unavoidable with the current process.

Assignable Causes The second category of variation, **assignable causes of variation**, also known as *special causes*, includes any variation-causing factors that can be identified and eliminated. Assignable causes of variation include an employee needing training or a machine needing repair. Let us return to the example of the lab analysis process. Figure 3.6 shows how assignable causes can change the distribution of output for the analysis process. The **green** curve is the process distribution when only common causes of variation are present. The **purple** dashed curves depict a change in the distribution because of assignable causes. In Figure 3.6(a), the **purple** dashed curve indicates that the process took more time than planned in many of the cases, thereby increasing the average time of each analysis. In Figure 3.6(b), an increase in the variability of the time for each case affected the spread of the distribution. Finally, in Figure 3.6(c), the **purple** dashed curve indicates that the process produced a preponderance of the tests in less-than-average time. Such a distribution is skewed, or no longer symmetric to the average value. A process is said to be in statistical control when the location, spread, or shape of its distribution does not change over time. After the process is in statistical control, managers use SPC procedures to detect the onset of assignable causes so that they can be addressed.

assignable causes of variation
Any variation-causing factors that can be identified and eliminated.



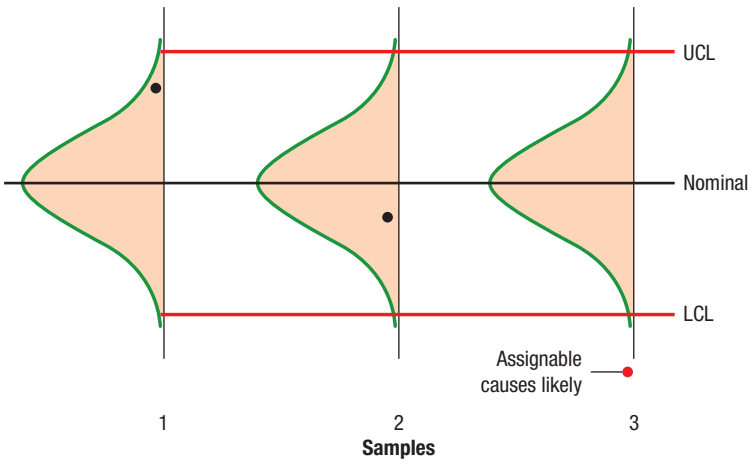
◀ **FIGURE 3.6**
Effects of Assignable Causes on the Process Distribution for the Lab Analysis Process

Control Charts

To determine whether observed variations are abnormal, we can measure and plot the performance measure taken from the sample on a time-ordered diagram called a **control chart**. A control chart has a nominal value, or central line, which can be the process's historic average or a target that managers would like the process to achieve, and two control limits based on the sampling distribution of the quality measure. The control limits are used to judge whether action is required. The larger value represents the *upper control limit* (UCL), and the smaller value represents the *lower control limit* (LCL). Figure 3.7 shows how the control limits relate to the sampling distribution. A sample statistic that falls between the UCL and the LCL indicates that the process is exhibiting common causes of variation. A statistic that falls outside the control limits indicates that the process is exhibiting assignable causes of variation.

control chart
A time-ordered diagram that is used to determine whether observed variations are abnormal.

▼ **FIGURE 3.7**
How Control Limits Relate to the Sampling Distribution: Observations from Three Samples

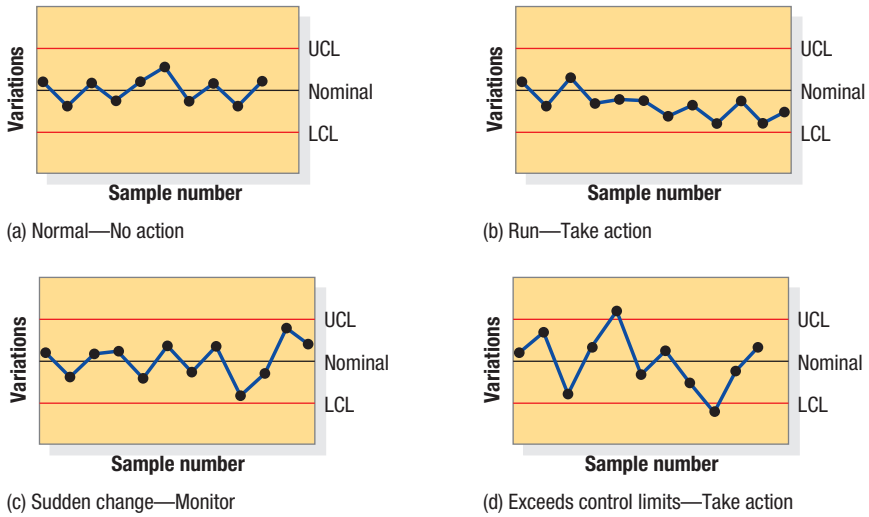


Observations falling outside the control limits do not always mean poor quality. For example, in Figure 3.7 the assignable cause may be a new billing process introduced to reduce the number of incorrect bills sent to customers. If the proportion of incorrect bills—that is, the performance measure from a sample of bills—falls *below* the LCL of the control chart, the new procedure likely changed the billing process for the better, and a new control chart should be constructed.

Managers or employees responsible for evaluating a process can use control charts in the following ways:

1. Take a random sample from the process and calculate a variable or attribute performance measure.
2. If the statistic falls outside the chart's control limits or exhibits unusual behavior, look for an assignable cause.
3. Eliminate the cause if it degrades performance; incorporate the cause if it improves performance. Reconstruct the control chart with new data.
4. Repeat the procedure periodically.

▼ **FIGURE 3.8**
Control Chart Examples



Sometimes, problems with a process can be detected even though the control limits have not been exceeded. Figure 3.8 contains four examples of control charts. Chart (a) shows a process that is in statistical control. No action is needed. However, chart (b) shows a pattern called a *run* or a sequence of observations with a certain characteristic. A typical rule is to take remedial action when five or more observations show a downward or upward trend, even if the points have not yet exceeded the control limits. Here, nine sequential observations are below the mean and show a downward trend. The probability is low that such a result could take place by chance.

Chart (c) shows that the process takes a sudden change from its normal pattern. The last four observations are unusual: The first drops close to the LCL, the next two rise toward the UCL, and the fourth remains above the nominal value. Managers or employees should monitor processes with such sudden changes even though the control limits have not been exceeded. Finally, chart (d) indicates that the process went out of control twice because two sample results fell outside the control limits. The probability that the process distribution has changed is high. We discuss more implications of being out of statistical control when we discuss process capability later in this chapter.

Control charts are not perfect tools for detecting shifts in the process distribution because they are based on sampling distributions. Two types of error are possible with the use of control charts. A **type I error** occurs when the conclusion is made that the process is out of control based on a sample result that falls outside the control limits, when in fact it was due to pure randomness. A **type II error** occurs when the conclusion is that the process is in control and only randomness is present, when actually the process is out of statistical control.

type I error
An error that occurs when the employee concludes that the process is out of control based on a sample result that falls outside the control limits, when in fact it was due to pure randomness.

type II error
An error that occurs when the employee concludes that the process is in control and only randomness is present, when actually the process is out of statistical control.

These errors can be controlled by the choice of control limits. The choice would depend on the costs of looking for assignable causes when none exist versus the cost of not detecting a shift in the process. For example, setting control limits at $\pm$ 3 standard deviations from the mean reduces the type I error, because chances are only 0.26 percent that a sample result will fall outside the control limits unless the process is out of statistical control. However, the type II error may be significant; more subtle shifts in the nature of the process distribution will go undetected because of the wide spread in the control limits. Alternatively, the spread in the control limits can be reduced to $\pm$ 2 standard deviations, thereby increasing the likelihood of sample results from a nonfaulty process falling outside the control limits to 4.56 percent. Now, the type II error is smaller, but the type I error is larger because employees are likely to search for assignable causes when the sample result occurred solely by chance. As a general rule, use wider limits when the cost for searching for assignable causes is large relative to the cost of not detecting a shift in the process distribution.

SPC methods are useful for both measuring the current process performance and detecting whether the process has changed in a way that will affect future performance. Consequently, we first discuss mean and range charts for variable measures of performance and then consider control charts for attributes measures.

Control Charts for Variables

Control charts for variables are used to monitor the mean and the variability of the process distribution.

***R*-chart**
A chart used to monitor process variability.

***R*-Chart** A range chart, or ***R*-chart**, is used to monitor process variability. To calculate the range of a set of sample data, the analyst subtracts the smallest from the largest measurement in each sample. If any of the ranges fall outside the control limits, the process variability is not in control.

The control limits for the R-chart are

$$\text{UCL}_R = D_4\overline{R} \quad \text{and} \quad \text{LCL}_R = D_3\overline{R}$$

where

$\overline{R}$ = average of several past R values and the central line of the control chart

D_3, D_4 = constants that provide 3 standard deviation (three-sigma) limits for a given sample size

Notice that the values for D_3 and D_4 shown in Table 3.1 change as a function of the sample size. Notice, too, that the spread between the control limits narrows as the sample size increases. This change is a consequence of having more information on which to base an estimate for the process range.

$\overline{x}$-Chart An **$\overline{x}$-chart** (read "x-bar chart") is used to see whether the process is generating output, on average, consistent with a target value set by management for the process or whether its current performance, with respect to the average of the performance measure, is consistent with its past performance. A target value is useful when a process is completely redesigned and past performance is no longer relevant. When the assignable causes of process variability have been identified and the process variability is in statistical control, the analyst can then construct an $\overline{x}$-chart. The control limits for the $\overline{x}$-chart are

$$\text{UCL}_{\bar{x}} = \overline{\overline{x}} + A_2\overline{R} \quad \text{and} \quad \text{LCL}_{\bar{x}} = \overline{\overline{x}} - A_2\overline{R}$$

$\overline{x}$-chart
A chart used to see whether the process is generating output, on average, consistent with a target value set by management for the process or whether its current performance, with respect to the average of the performance measure, is consistent with past performance.

TABLE 3.1 FACTORS FOR CALCULATING THREE SIGMA LIMITS FOR THE $\overline{x}$-CHART AND R-CHART

Size of Sample (n)	Factor for UCL and LCL for $\overline{x}$-Chart (A_2)	Factor for LCL for R-Chart (D_3)	Factor for UCL for R-Chart (D_4)
2	1.880	0	3.267
3	1.023	0	2.575
4	0.729	0	2.282
5	0.577	0	2.115
6	0.483	0	2.004
7	0.419	0.076	1.924
8	0.373	0.136	1.864
9	0.337	0.184	1.816
10	0.308	0.223	1.777

Source: NIST/SEMATECH e-Handbook of Statistical Methods, https://www.itl.nist.gov/div898/handbook/pmc/section3/pmc321.htm.

where

$\overline{\overline{x}}$ = central line of the chart, which can be either the average of past sample means or a target value set for the process

A_2 = constant to provide three-sigma limits for the sample mean

The values for A_2 are contained in Table 3.1. Note that the control limits use the value of $\overline{R}$; therefore, the $\overline{x}$-chart must be constructed *after* the process variability is in control.

To develop and use $\overline{x}$- and R-charts, do the following:

Step 1. Collect data on the variable quality measurement (such as time, weight, or diameter) and organize the data by sample number. Preferably, at least 20 samples of size n should be taken for use in constructing a control chart.

Step 2. Compute the range for each sample and the average range, $\overline{R}$, for the set of samples.

Step 3. Use Table 3.1 to determine the upper and lower control limits of the R-chart.

Step 4. Plot the sample ranges. If all are in control, proceed to step 5. Otherwise, find the assignable causes, correct them, and return to step 1.

Step 5. Calculate $\overline{x}$ for each sample and determine the central line of the chart, $\overline{\overline{x}}$.

Step 6. Use Table 3.1 to determine the parameters for $\text{UCL}_{\bar{x}}$ and $\text{LCL}_{\bar{x}}$ and construct the $\overline{x}$-chart.

Step 7. Plot the sample means. If all are in control, the process is in statistical control in terms of the process average and process variability. Continue to take samples and monitor the process. If any are out of control, find the assignable causes, address them, and return to step 1. If no assignable causes are found after a diligent search, assume that the out-of-control points represent common causes of variation and continue to monitor the process.

EXAMPLE 3.1 Using $\bar{x}$- and *R*-Charts to Monitor a Process

Online Resources

Tutor 3.1 in OM Explorer provides a new example to practice the use of *x*-bar and *R*-charts.

Active Model 3.1 provides additional insight on the *x*-bar and *R*-charts and their uses for the cylindrical bolt problem.

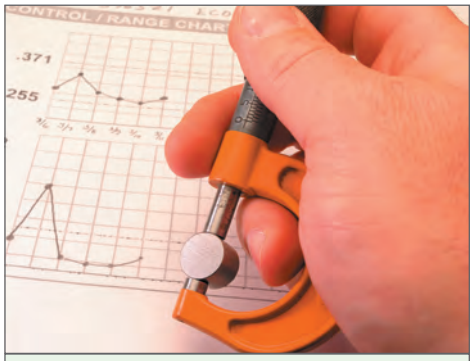
The management of West Allis Industries is concerned about the production of a special metal cylindrical bolt used by several of the company's largest customers. The diameter of the bolt is critical to the customers. Data from 5 samples appear in the accompanying table. The sample size is 4. Is the process in statistical control?

SOLUTION

Step 1. For simplicity, we use only 5 samples. In practice, more than 20 samples would be desirable. The data are shown in the following table.

DATA FOR THE $\bar{x}$- AND *R*-CHARTS: OBSERVATIONS OF BOLT DIAMETER (INCH)

		OBSERVATIONS				
Sample Number	1	2	3	4	*R*	$\bar{x}$
1	0.5014	0.5022	0.5009	0.5027	0.0018	0.5018
2	0.5021	0.5041	0.5024	0.5020	0.0021	0.5027
3	0.5018	0.5026	0.5035	0.5023	0.0017	0.5026
4	0.5008	0.5034	0.5024	0.5015	0.0026	0.5020
5	0.5041	0.5056	0.5034	0.5047	0.0022	0.5045
				Average	0.0021	0.5027



Lyroky/Alamy Stock Photo

An analyst measures the diameter of a part with a micrometer. After he measures the sample, he plots the range on the control chart.

Step 2. Compute the range for each sample by subtracting the lowest value from the highest value. For example, in sample 1 the range is 0.5027 − 0.5009 = 0.0018 inch. Similarly, the ranges for samples 2, 3, 4, and 5 are 0.0021, 0.0017, 0.0026, and 0.0022 inch, respectively. As shown in the table, $\bar{R} = 0.0021$.

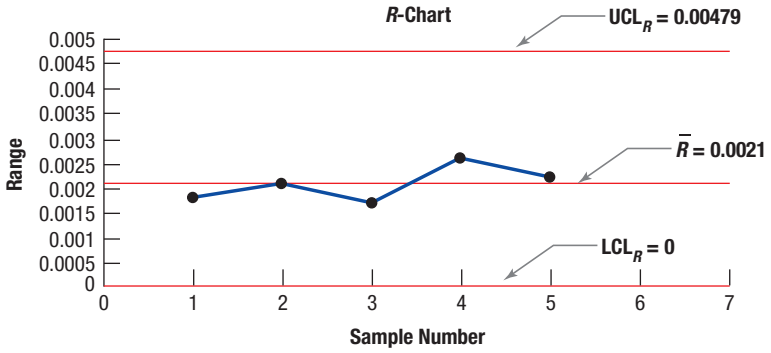
Step 3. To construct the *R*-chart, select the appropriate constants from Table 3.1 for a sample size of 4. The control limits are

$$UCL_R = D_4\bar{R} = 2.282(0.0021) = 0.00479 \text{ inch}$$

$$LCL_R = D_3\bar{R} = 0(0.0021) = 0 \text{ inch}$$

Step 4. Plot the ranges on the *R*-chart, as shown in Figure 3.9. None of the sample ranges falls outside the control limits. Consequently, the process variability is in statistical control. If any of the sample ranges fall outside the limits, or an unusual pattern appears (see Figure 3.9), we would search for the causes of the excessive variability, address them, and repeat step 1.

FIGURE 3.9 ▶
Range Chart from the OM Explorer $\bar{x}$- and *R*-Chart Solver, Showing That the Process Variability Is in Control



Step 5. Compute the mean for each sample. For example, the mean for sample 1 is

$$\frac{0.5014 + 0.5022 + 0.5009 + 0.5027}{4} = 0.5018 \text{ inch}$$

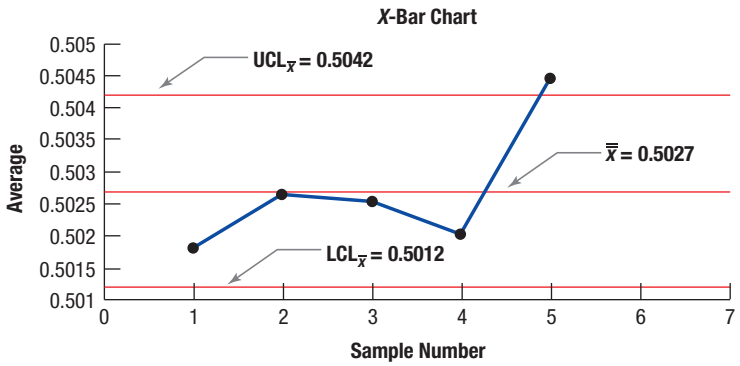
Similarly, the means of samples 2, 3, 4, and 5 are 0.5027, 0.5026, 0.5020, and 0.5045 inch, respectively. As shown in the table, $\bar{\bar{x}} = 0.5027$.

Step 6. Now, construct the $\bar{x}$-chart for the process average. The average bolt diameter is 0.5027 inch, and the average range is 0.0021 inch, so use $\bar{\bar{x}} = 0.5027$, $\bar{R} = 0.0021$, and A_2 from Table 3.1 for a sample size of 4 to construct the control limits:

$$\text{UCL}_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R} = 0.5027 + 0.729(0.0021) = 0.5042 \text{ inch}$$

$$\text{LCL}_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R} = 0.5027 - 0.729(0.0021) = 0.5012 \text{ inch}$$

Step 7. Plot the sample means on the control chart, as shown in Figure 3.10. The mean of sample 5 falls above the UCL, indicating that the process average is out of statistical control and that assignable causes must be explored, perhaps using a cause-and-effect diagram.



◀ **FIGURE 3.10**
The $\bar{x}$-chart from the OM Explorer $\bar{x}$- and R-Chart Solver for the Cylindrical Bolt, Showing that Sample 5 Is Out of Control

DECISION POINT

A new employee operated the lathe machine that makes the cylindrical bolt on the day sample 5 was taken. To solve the problem, management initiated a training session for the employee. Subsequent samples showed that the process was back in statistical control.

If the standard deviation of the process distribution is known, another form of the $\bar{x}$-chart may be used:

$$\text{UCL}_{\bar{x}} = \bar{\bar{x}} + z\sigma_{\bar{x}} \text{ and } \text{LCL}_{\bar{x}} = \bar{\bar{x}} - z\sigma_{\bar{x}}$$

where

$\sigma_{\bar{x}} = \sigma/\sqrt{n}$ = standard deviation of sample means

σ = standard deviation of the process distribution

n = sample size

$\bar{\bar{x}}$ = central line of the chart, which can be either the average of past sample means or a target value set for the process

z = normal deviate (number of standard deviations from the average)

The analyst can use an R-chart to be sure that the process variability is in control before constructing the $\bar{x}$-chart. The advantage of using this form of the $\bar{x}$-chart is that the analyst can adjust the spread of the control limits by changing the value of z. This approach can be useful for balancing the effects of type I and type II errors.

EXAMPLE 3.2 Designing an $\bar{x}$-Chart Using the Process Standard Deviation



keith morris/Alamy Stock Photo

A customer making a bank deposit in Boise, Idaho, USA.

The Sunny Dale Bank monitors the time required to serve customers at the drive-through window because it is an important quality factor in competing with other banks in the city. After analyzing the data gathered in an extensive study of the window operation, bank management determined that the mean time to process a customer at the peak demand period is 5 minutes, with a standard deviation of 1.5 minutes. Management wants to monitor the mean time to process a customer by periodically using a sample size of six customers. Assume that the process variability is in statistical control. Design an $\bar{x}$-chart that has a type I error of 5 percent. That is, set the control limits so that there is a 2.5 percent chance a sample result will fall below the LCL and a 2.5 percent chance that a sample result will fall above the UCL. After several weeks of sampling, two successive samples came in at 3.70 and 3.68 minutes, respectively. Is the customer service process in statistical control?

Online Resources

Active Model 3.2 provides additional insight on the *p*-chart and its uses for the booking services department.

Tutor 3.2 in OM Explorer provides a new example to practice the use of the *p*-chart.

SOLUTION

$$\bar{\bar{x}} = 5.0 \text{ minutes}$$

$$\sigma = 1.5 \text{ minutes}$$

$$n = 6 \text{ customers}$$

$$z = 1.96$$

The process variability is in statistical control, so we proceed directly to the $\bar{x}$-chart. The control limits are

$$\text{UCL}_{\bar{x}} = \bar{\bar{x}} + z\sigma/\sqrt{n} = 5.0 + 1.96(1.5)/\sqrt{6} = 6.20 \text{ minutes}$$

$$\text{LCL}_{\bar{x}} = \bar{\bar{x}} - z\sigma/\sqrt{n} = 5.0 - 1.96(1.5)/\sqrt{6} = 3.80 \text{ minutes}$$

The value for z can be obtained in the following way. The appendix on normal distribution gives the proportion of the total area under the normal curve from $-\infty$ to z. We want a type I error of 5 percent, or 2.5 percent of the curve above the UCL and 2.5 percent below the LCL. Consequently, we need to find the z-value in the table that leaves only 2.5 percent in the upper portion of the normal curve (or 0.9750 in the table). The value is 1.96. The two new samples are below the LCL of the chart, implying that the average time to serve a customer has dropped. Assignable causes should be explored to see what caused the improvement.

DECISION POINT

Management studied the time period over which the samples were taken and found that the supervisor of the process was experimenting with some new procedures. Management decided to make the new procedures a permanent part of the customer service process. After all employees were trained in the new procedures, new samples were taken and the control chart reconstructed.

Control Charts for Attributes

Two charts commonly used for performance measures based on attributes measures are the *p*- and *c*-chart. The *p*-chart is used for controlling the proportion of defects generated by the process. The *c*-chart is used for controlling the number of defects when more than one defect can be present in a service or product.

***p*-chart**
A chart used for controlling the proportion of defective services or products generated by the process.

***p*-Charts** The ***p*-chart** is a commonly used control chart for attributes. The performance characteristic is counted rather than measured, and the entire service or item can be declared good or defective. For example, in the banking industry, the attributes counted might be the number of nonendorsed deposits or the number of incorrect financial statements sent to customers. The method involves selecting a random sample, inspecting each item in it, and calculating the sample proportion defective, p, which is the number of defective units divided by the sample size.

Sampling for a *p*-chart involves a "yes or no" decision: The process output either is or is not defective. The underlying statistical distribution is based on the binomial distribution.

However, for large sample sizes, the normal distribution provides a good approximation to it. The standard deviation of the distribution of proportion defectives, σ_p, is

$$\sigma_p = \sqrt{\bar{p}(1 - \bar{p})/n}$$

where

n = sample size

$\bar{p}$ = central line on the chart, which can be either the historical average population proportion defective or a target value

We can use σ_p to arrive at the upper and lower control limits for a p-chart:

$$\text{UCL}_p = \bar{p} + z\sigma_p \quad \text{and} \quad \text{LCL}_p = \bar{p} - z\sigma_p$$

where

z = normal deviate (number of standard deviations from the average)

The chart is used in the following way. Periodically, a random sample of size n is taken, and the number of defective services or products is counted. The number of defectives is divided by the sample size to get a sample proportion defective, p, which is plotted on the chart. When a sample proportion defective falls outside the control limits, the analyst assumes that the proportion defective generated by the process has changed and searches for the assignable cause. Observations falling below the LCL_p indicate that the process may actually have improved. The analyst may find no assignable cause, because it is always possible that an out-of-control proportion occurred randomly. However, if the analyst discovers assignable causes, those sample data should not be used to calculate the control limits for the chart.

EXAMPLE 3.3 Using a *p*-Chart to Monitor a Process

The operations manager of the booking services department of Hometown Bank is concerned about the number of wrong customer account numbers recorded by Hometown personnel. Each week a random sample of 2,500 deposits is taken, and the number of incorrect account numbers is recorded. The results for the past 12 weeks are shown in the following table. Is the booking process out of statistical control? Use three-sigma control limits, which will provide a type I error of 0.26 percent.

Sample Number	Wrong Account Numbers	Sample Number	Wrong Account Numbers
1	15	7	24
2	12	8	7
3	19	9	10
4	2	10	17
5	19	11	15
6	4	12	3
			Total 147

SOLUTION

Step 1. Use these sample data to calculate $\bar{p}$

$$\bar{p} = \frac{\text{Total defectives}}{\text{Total number of observations}} = \frac{147}{12(2{,}500)} = 0.0049$$

$$\sigma_p = \sqrt{\bar{p}(1 - \bar{p})/n} = \sqrt{0.0049(1 - 0.0049)/2{,}500} = 0.0014$$

$$\text{UCL}_p = \bar{p} + z\sigma_p = 0.0049 + 3(0.0014) = 0.0091$$

$$\text{LCL}_p = \bar{p} - z\sigma_p = 0.0049 - 3(0.0014) = 0.0007$$

Step 2. Calculate each sample proportion defective. For sample 1, the proportion of defectives is 15/2,500 = 0.0060.

Step 3. Plot each sample proportion defective on the chart, as shown in Figure 3.11.

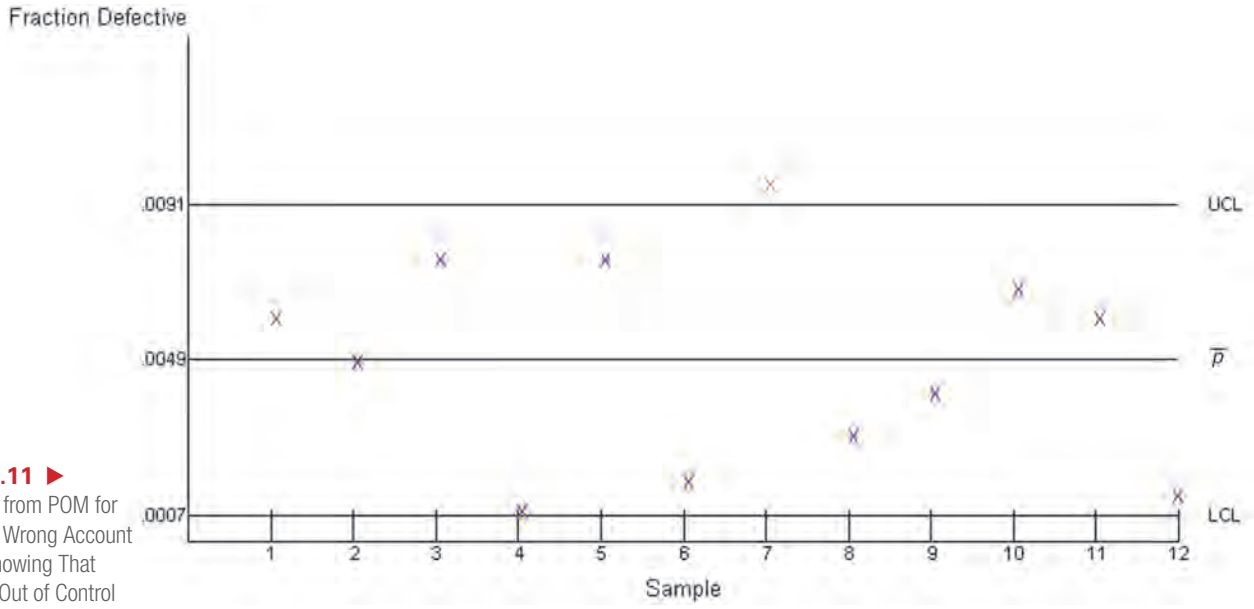


FIGURE 3.11 ▶
The *p*-Chart from POM for Windows for Wrong Account Numbers, Showing That Sample 7 Is Out of Control

Sample 7 exceeds the UCL; thus, the process is out of control and the reasons for the poor performance that week should be determined.

DECISION POINT

Management explored the circumstances when sample 7 was taken. The encoding machine used to print the account numbers on the checks was defective that week. The following week the machine was repaired; however, the recommended preventive maintenance on the machine was not performed for months prior to the failure. Management reviewed the performance of the maintenance department and instituted changes to the maintenance procedures for the encoding machine. After the problem was corrected, an analyst recalculated the control limits using the data without sample 7. Subsequent weeks were sampled, and the booking process was determined to be in statistical control. Consequently, the *p*-chart provides a tool to indicate when a process needs adjustment.

***c*-chart**
A chart used for controlling the number of defects when more than one defect can be present in a service or product.

***c*-Charts** Sometimes services or products have more than one defect. For example, a roll of carpeting may have several defects, such as tufted or discolored fibers or stains from the production process. Other situations in which more than one defect may occur include accidents at a particular intersection, bubbles in a television picture face panel, and complaints from a patron at a hotel. When management is interested in reducing the number of defects per unit or service encounter, another type of control chart, the ***c*-chart**, is useful.

The underlying sampling distribution for a *c*-chart is the Poisson distribution. The Poisson distribution is based on the assumption that defects occur over a continuous region on the surface of a product or a continuous time interval during the provision of a service. It further assumes that the probability of two or more defects at any one location on the surface or at any instant of time is negligible. The mean of the distribution is $\bar{c}$ and the standard deviation is $\sqrt{\bar{c}}$. A useful tactic is to use the normal approximation to the Poisson so that the central line of the chart is $\bar{c}$ and the control limits are

$$\text{UCL}_c = \bar{c} + z\sqrt{\bar{c}} \quad \text{and} \quad \text{LCL}_c = \bar{c} - z\sqrt{\bar{c}}$$

EXAMPLE 3.4 Using a *c*-Chart to Monitor Defects per Unit

The Woodland Paper Company produces paper for the newspaper industry. As a final step in the process, the paper passes through a machine that measures various product quality characteristics. When the paper production process is in control, it averages 20 defects per roll.

a. Set up a control chart for the number of defects per roll. For this example, use two-sigma control limits.

b. Five rolls had the following number of defects: 16, 21, 17, 22, and 24, respectively. The sixth roll, using pulp from a different supplier, had 5 defects. Is the paper production process in control?

SOLUTION

a. The average number of defects per roll is 20. Therefore

$$UCL_c = \bar{c} + z\sqrt{\bar{c}} = 20 + 2(\sqrt{20}) = 28.94$$

$$LCL_c = \bar{c} - z\sqrt{\bar{c}} = 20 - 2(\sqrt{20}) = 11.06$$

The control chart is shown in Figure 3.12.

b. Because the first five rolls had defects that fell within the control limits, the process is still in control. The sixth roll's five defects, however, fall below the LCL, and therefore, the process is technically "out of control." The control chart indicates that something good has happened.

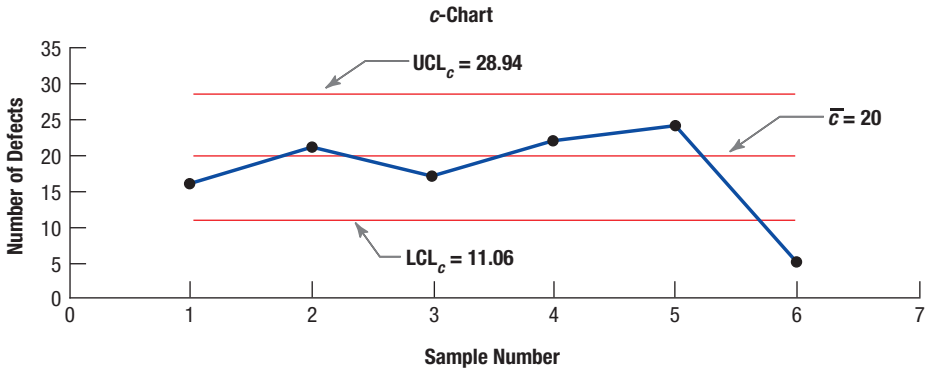
DECISION POINT

The supplier for the first five samples has been used by Woodland Paper for many years. The supplier for the sixth sample is new to the company. Management decided to continue using the new supplier for a while, monitoring the number of defects to see whether it stays low. If the number remains below the LCL for 20 consecutive samples, management will make the switch permanent and recalculate the control chart parameters.



H. Mark Weidman Photography/Alamy Stock Photo

A worker at a paper roll manufacturing facility.



◀ **FIGURE 3.12**
The *c*-Chart from the OM Explorer *c*-Chart Solver for Defects per Roll of Paper

Online Resource

Tutor 3.3 in OM Explorer provides a new example to practice the use of the *c*-chart.

Process Capability

Statistical process control techniques help managers achieve and maintain a process distribution that does not change in terms of its mean and variance. The control limits on the control charts signal when the mean or variability of the process changes. However, a process that is in statistical control may not be producing services or products according to their design specifications, because the control limits are based on the mean and variability of the *sampling distribution*, not the design specifications. **Process capability** refers to the ability of the process to meet the design specifications for a service or product. Design specifications often are expressed as a **nominal value**, or target, and a **tolerance**, or allowance above or below the nominal value.

For example, the administrator of an intensive care unit lab might have a nominal value for the turnaround time of results to the attending physicians of 25 minutes and a tolerance of ± 5 minutes because of the need for speed under life-threatening conditions. The tolerance gives an *upper specification* of 30 minutes and a *lower specification* of 20 minutes. The lab process must be capable of providing the results of analyses within these specifications; otherwise, it will produce a certain proportion of "defects." The administrator is also interested in detecting occurrences of turnaround times of less than 20 minutes because something might be learned that can be built into the lab process in the future. For the present, the physicians are pleased with results that arrive within 20 to 30 minutes.

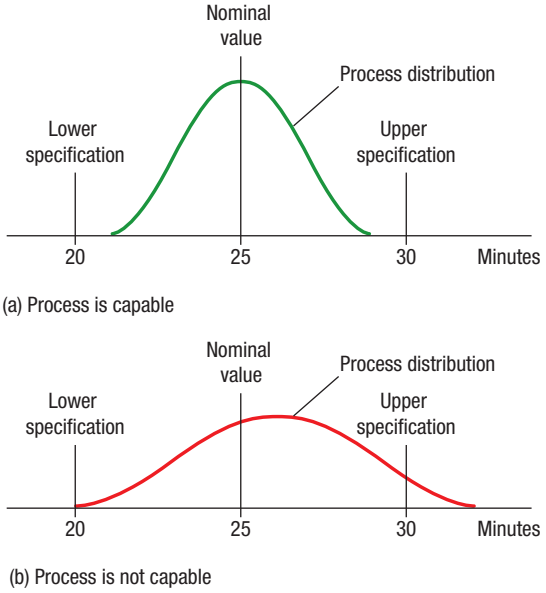
process capability
The ability of the process to meet the design specifications for a service or product.

nominal value
A target for design specifications.

tolerance
An allowance above or below the nominal value.

Defining Process Capability

Figure 3.13 shows the relationship between a process distribution and the upper and lower specifications for the lab process turnaround time under two conditions. In Figure 3.13(a), the process is capable because the extremes of the process distribution fall within the upper and lower



▲ **FIGURE 3.13**
The Relationship Between a Process Distribution and Upper and Lower Specifications

specifications. In Figure 3.13(b), the process is not capable because the lab process produces too many reports with long turnaround times.

Figure 3.13 shows clearly why managers are so concerned with reducing process variability. The less variability—represented by lower standard deviations—the less frequently bad output is produced. Figure 3.14 shows what reducing variability implies for a process distribution that is a normal probability distribution. The firm with two-sigma performance (the specification limits equal the process distribution mean $\pm$ 2 standard deviations) produces 4.56 percent defects, or 45,600 defects per million. The firm with four-sigma performance produces only 0.0063 percent defects, or 63 defects per million. Finally, the firm with six-sigma performance produces only 0.0000002 percent defects, or 0.002 defects per million.[3]

How can a manager determine quantitatively whether a process is capable? Two measures commonly are used in practice to assess the capability of a process: the process capability index and the process capability ratio.

Process Capability Index The **process capability index, C_{pk},** is defined as

$$C_{pk} = \text{Minimum of}\left[\frac{\bar{\bar{x}} - \text{Lower specification}}{3\sigma}, \frac{\text{Upper specification} - \bar{\bar{x}}}{3\sigma}\right]$$

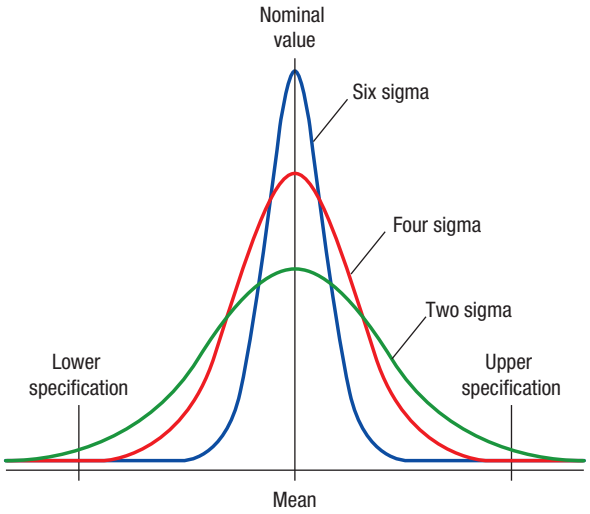
where

σ = standard deviation of the process distribution

The process capability index measures how well the process is centered and whether the variability is acceptable. As a general rule, most values of any process distribution fall within $\pm$ 3 standard deviations of the mean. Consequently, $\pm$ 3 standard deviations are used as the benchmark. Because the process capability index is concerned with how well the process distribution is centered relative to the specifications, it checks to see if the process average is at least 3 standard deviations from the upper and lower specifications. We take the minimum of the two ratios because it gives the *worst-case* situation.

The process capability index must be compared to a critical value to judge whether a process is capable. Firms striving to achieve three-sigma performance use a critical value for the ratio of 1.0. A firm targeting four-sigma performance will use 1.33 (or 4/3), a firm targeting five-sigma performance will use 1.67 (or 5/3), and a firm striving for six-sigma performance will use 2.00 (or 6/3). Processes producing services or products with less than three-sigma performance will have C_{pk} values less than 1.0.

If a process passes the process capability index test, we can declare the process is capable. Suppose a firm desires its processes to produce at the level of four-sigma performance. If C_{pk} is greater than or equal to the critical value of 1.33, we can say the process is capable. If C_{pk} is less than the critical value, either the process average is too close to one of the tolerance limits and is generating defective output, or the process variability is too large. To find out whether the variability is the culprit, we need another test.



▲ **FIGURE 3.14**
Effects of Reducing Variability on Process Capability

process capability index, C_{pk}
An index that measures the potential for a process to generate defective outputs relative to either upper or lower specifications.

process capability ratio, C_p
The tolerance width divided by 6 standard deviations.

Process Capability Ratio If a process fails the process capability *index* test, we need a quick test to see if the process variability is causing the problem. If a process is *capable*, it has a process distribution whose extreme values fall within the upper and lower specifications for a service or product. For example, if the process distribution is normal, 99.74 percent of the values fall within $\pm$ 3 standard deviations. In other words, the range of values of the quality measure generated by a process is approximately 6 standard deviations of the process distribution. Hence, if a process is capable at the three-sigma level, the difference between the upper and lower specification, called the *tolerance width*, must be greater than 6 standard deviations. The **process capability ratio, C_p,** is defined as

$$C_p = \frac{\text{Upper specification} - \text{Lower specification}}{6\sigma}$$

[3]Our discussion assumes that the process distribution has no assignable causes. Six Sigma programs, however, define defect performance with the assumption that the process average has moved 1.5 standard deviations. In such a case, there would be 3.4 defects per million. See http://www.isixsigma.com for the rationale behind that assumption.

Suppose management wants four-sigma capability in their processes, and a process just failed the process capability index test at that level. A C_p value of 1.33, say, implies that the variability of the process is at the level of four-sigma quality and that the process is capable of consistently producing outputs within specifications, assuming that the process is centered. Because C_p passed the test, but C_{pk} did not, we can assume that the problem is that the process is not centered adequately.

Using Continuous Improvement to Determine the Capability of a Process

To determine the capability of a process to produce outputs within the tolerances, use the following steps.

Step 1. Collect data on the process output, and calculate the mean and the standard deviation of the process output distribution.

Step 2. Use the data from the process distribution to compute process control charts, such as an $\bar{x}$- and an R-chart.

Step 3. Take a series of at least 20 consecutive random samples of size n from the process and plot the results on the control charts. If the sample statistics are within the control limits of the charts, the process is in statistical control. If the process is not in statistical control, look for assignable causes and eliminate them. Recalculate the mean and standard deviation of the process distribution and the control limits for the charts. Continue until the process is in statistical control.

Step 4. Calculate the process capability *index*. If the results are acceptable, the process is capable and document any changes made to the process; continue to monitor the output by using the control charts. If the results are unacceptable, calculate the process capability *ratio*. If the results are acceptable, the process variability is fine and management should focus on centering the process. If the results of the process capability ratio are unacceptable, management should focus on reducing the variability in the process until it passes the test. As changes are made, recalculate the mean and standard deviation of the process distribution and the control limits for the charts and return to step 3.

EXAMPLE 3.5 Assessing the Process Capability of the Intensive Care Unit Lab

The intensive care unit lab process has an average turnaround time of 26.2 minutes and a standard deviation of 1.35 minutes. The nominal value for this service is 25 minutes with an upper specification limit of 30 minutes and a lower specification limit of 20 minutes. The administrator of the lab wants to have four-sigma performance for her lab. Is the lab process capable of this level of performance?



Alexander Raths/123RF

A doctor examines a specimen through his microscope in a lab at St. Vincent's Hospital.

SOLUTION

The administrator began by taking a quick check to see if the process is capable by applying the process capability index:

$$\text{Lower specification calculation} = \frac{26.2 - 20.0}{3(1.35)} = 1.53$$

$$\text{Upper specification calculation} = \frac{30.0 - 26.2}{3(1.35)} = 0.94$$

$$C_{pk} = \text{Minimum of } [1.53, 0.94] = 0.94$$

Since the target value for four-sigma performance is 1.33, the process capability index told her that the process was not capable. However, she did not know whether the problem was the variability of the process, the centering of the process, or both. The options available to improve the process depended on what is wrong.

She next checked the process variability with the process capability ratio:

$$C_p = \frac{30.0 - 20.0}{6(1.35)} = 1.23$$

The process variability did not meet the four-sigma target of 1.33. Consequently, she initiated a study to see where variability was introduced into the process. Two activities, report preparation and specimen slide preparation, were identified as having inconsistent procedures. These procedures were modified to provide consistent performance. New data were collected and the average turnaround was

Online Resources

Active Model 3.3 provides additional insight on the process capability problem at the intensive care unit lab.

Tutor 3.4 in OM Explorer provides a new example to practice the process capability measures.

now 26.1 minutes with a standard deviation of 1.20 minutes. She now had the process variability at the four-sigma level of performance, as indicated by the process capability ratio:

$$C_p = \frac{30.0 - 20.0}{6(1.20)} = 1.39$$

However, the process capability index indicated additional problems to resolve:

$$C_{pk} = \text{Minimum of} \left[\frac{(26.1 - 20.0)}{3(1.20)}, \frac{(30.0 - 26.1)}{3(1.20)} \right] = 1.08$$

DECISION POINT

The lab process was still not at the level of four-sigma performance on turnaround time. The lab administrator searched for the causes of the off-center turnaround time distribution. She discovered periodic backlogs at a key piece of testing equipment. Acquiring a second machine provided the capacity to reduce the turnaround times to four-sigma capability.

International Quality Documentation Standards and Awards

Once a company has gone through the effort of making its processes capable, it must document its level of quality so as to better market its services or products. This documentation of quality is especially important in international trade. However, if each country had its own set of standards, companies selling in international markets would have difficulty complying with quality documentation standards in each country where they did business. To overcome this problem, the International Organization for Standardization devised a family of standards called ISO 9000 for companies doing business in the European Union.

The ISO 9001:2015 Documentation Standards

ISO 9001:2015

A set of standards governing documentation of a quality program.

ISO 9001:2015 is the latest update of the ISO 9000 standards governing documentation of a quality program. According to the International Organization for Standardization, the ISO 9001:2015 standards are similar in scope to the 2008 standards, but some core terms were modified to better integrate with other international management standards. The change makes the new standard less prescriptive and more focused on performance. It helps ensure that customers get reliable and desired quality of goods and services by specifying what the firm does to fulfill the customer's quality requirements and applicable regulatory requirements, while aiming to enhance customer satisfaction and achieve continual improvement of its performance in pursuit of these objectives. Companies become certified by proving to a qualified external examiner that they comply with all the requirements. Once certified, companies are listed in a directory so that potential customers can see which companies are certified and to what level. The certifications have to be renewed periodically. Compliance with ISO 9001:2015 standards, however, says *nothing* about the actual quality of a product. Rather, it indicates to customers that companies can provide documentation to support whatever claims they make about quality. As of 2014, more than 1.1 million organizations worldwide have been certified in the ISO 9000 family of documentation standards.

Completing the certification process can take as long as 18 months and involve many hours of management and employee time. The cost of certification can exceed $1 million for large companies. Despite the expense and commitment involved in ISO certification, it bestows significant external and internal benefits. The external benefits come from the potential sales advantage that companies in compliance have. Companies looking for a supplier will more likely select a company that has demonstrated compliance with ISO documentation standards, all other factors being equal. Consequently, more and more firms are seeking certification to gain a competitive advantage.

Internal benefits can be substantial. Registered companies report an average of 48 percent increased profitability and 76 percent improvement in marketing. The British Standards Institute, a leading third-party auditor, estimates that most ISO 9001–registered companies experience a 10 percent reduction in the cost of producing a product because of the quality improvements they make while striving to meet the documentation requirements. Certification in ISO 9001:2015 requires a company to analyze and document its procedures, which is necessary in any event for implementing continuous improvement, employee involvement, and similar programs. The guidelines and requirements of the ISO documentation standards provide companies with a jump-start in pursuing TQM programs.

Malcolm Baldrige Performance Excellence Program

Regardless of where a company does business, it is clear that all organizations have to produce high-quality products and services if they are to be competitive. To emphasize that point, in August 1987 the U.S. Congress signed into law the Malcolm Baldrige National Quality

Improvement Act, creating the Malcolm Baldrige National Quality Award, which is now called the **Baldrige Performance Excellence Program** (www.quality.nist.gov/baldrige). Named for the late secretary of commerce, who was a strong proponent of enhancing quality as a means of reducing the trade deficit, the award promotes, recognizes, and publicizes quality strategies and achievements.

Baldrige Performance Excellence Program

A program named for the late secretary of commerce Malcolm Baldrige, who was a strong proponent of enhancing quality as a means of reducing the trade deficit; organizations vie for an award that promotes, recognizes, and publicizes quality strategies and achievements.

The application and review process for the Baldrige award is rigorous. However, the act of preparing the application itself is often a major benefit to organizations because it helps firms define what *quality* means for them. According to the U.S. Commerce Department's National Institute of Standards and Technology (NIST), investing in quality principles and performance excellence pays off in increased productivity, satisfied employees and customers, and improved profitability, both for customers and investors. The seven major criteria for the award are leadership, strategic planning, customer focus, workforce focus, operations focus, measurement analysis, and results. Customer satisfaction underpins these seven criteria, with achievement of results being given the most weight in selecting winners. By 2016, 113 awards had been presented to over 106 organizations across the six award categories of manufacturing, service, small business, education, health care, and nonprofit.

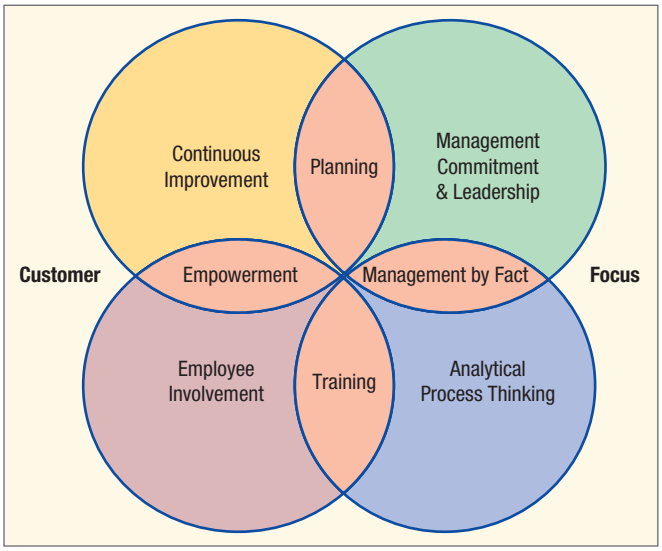
Systems Approach to Total Quality Management

Figure 3.15 integrates and summarizes the organizational components required to build an effective culture of quality that underpins the total quality management philosophy outlined earlier in Figure 3.1, the TQM wheel. The overall focus of TQM is always on the needs of the customer through a culture of continuous improvement and an active engagement and involvement of employees at all levels. Continuous improvement and employee involvement are two pillars for customer satisfaction. In this chapter we have shown that there are two other pillars as well: (1) management commitment and leadership driving a relentless focus on quality, and (2) analytical process thinking through the use of tools such as acceptance sampling, process control, and process capability.

The intersections between these four TQM pillars relate to cultural changes that are often the most difficult ones to establish. The Continuous Improvement and Employee Involvement intersection requires that the employees are actually empowered to do their jobs and given autonomy in decision making. The Employee Involvement and Analytical Process Thinking intersection requires a commitment to ongoing employee training in statistical tools and their usage. The intersection between Management Commitment/Leadership and Analytical Process Thinking requires management by fact, and not authority. Finally, the intersection between Continuous Improvement and Management Commitment/Leadership requires making quality an integral part of long-term planning.

Failure in managing the intersections is where most companies fall short in achieving their quality objectives. For instance, failing to plan for quality is not conducive to building a culture of continuous quality improvement. Likewise, firing trainers during times of economic stress in order to conserve financial resources compromises quality initiatives. Building a culture of long-term quality requires consistency of purpose, thinking, and action as outlined in this chapter.

▼ **FIGURE 3.15**
An integrative view of Total Quality Management



LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
3.1 Define the four major costs of quality, and their relationship to the role of ethics in determining the overall costs of delivering products and services.	See the section "Costs of Quality" and understand how deceptive business practices can affect a customer's experiences and why the costs of quality should be balanced with ethical considerations.	
3.2 Explain the basic principles of total quality management (TQM) and Six Sigma.	See the section "Total Quality Management and Six Sigma." Focus on the five customer definitions of quality, and the key Figures 3.1 and 3.2. Be sure to understand Figure 3.3, which shows the goals of Six Sigma.	
3.3 Understand how acceptance sampling and process performance approaches interface in a supply chain.	See the section "Acceptance Sampling." Figure 3.4 shows how TQM or Six Sigma works in a supply chain through the tactic of acceptance sampling.	**POM for Windows:** Acceptance Sampling **Supplement G:** Acceptance Sampling Plans

Learning Objective	Guidelines for Review	Online Resources
3.4 Describe how to construct process control charts and use them to determine whether a process is out of statistical control.	See the section "Statistical Process Control." Understanding Figures 3.5 and 3.6 is key to understanding the methods to follow. The subsections on "Control Charts," "Control Charts for Variables," and "Control Charts for Attributes" show you how to determine if a process is in statistical control. Study Examples 3.1 to 3.4 as well as Solved Problems 1 to 3.	**Active Model Exercises:** 3.1: *x*-Bar and *R*-Charts; 3.2: *p*-Charts **OM Explorer Solvers:** *R*-and *x*-Bar Charts; *c*-Charts; *p*-Charts **OM Explorer Tutors:** 3.1: *x*-Bar and *R*-Charts; 3.2: *p*-Charts; 3.3: c-Charts **POM for Windows:** *x*-Bar Charts; *p*-Charts; *c*-Charts
3.5 Explain how to determine whether a process is capable of producing a service or product to specifications.	The major takeaway in the chapter is found in the section "Process Capability". Be sure you understand Figures 3.13 and 3.14; study Example 3.5 and Solved Problem 4.	**Active Model Exercise:** 3.3: Process Capability **OM Explorer Solver:** Process Capability **OM Explorer Tutor:** 3.4: Process Capability **POM for Windows:** Process Capability
3.6 Describe International Quality Documentation Standards and the Baldrige Performance Excellence Program.	The section "International Quality Documentation Standards and Awards" reviews details of ISO quality standards and the Baldrige Award Program.	
3.7 Understand the systems approach to total quality management.	The section "Systems Approach to Total Quality Management" summarizes different pillars of the total quality management philosophy, and how managing the interaction between each pillar leads to higher quality.	

Key Equations

Statistical Process Control

1. Sample mean:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

2. Standard deviation of a sample:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \text{ or } \sigma = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \frac{(\Sigma x_i)^2}{n}}{n-1}}$$

3. Control limits for variable process control charts

a. *R*-chart, range of sample:

$$\text{Upper control limit} = \text{UCL}_R = D_4\bar{R}$$
$$\text{Lower control limit} = \text{LCL}_R = D_3\bar{R}$$

b. $\bar{x}$-chart, sample mean:

$$\text{Upper control limit} = \text{UCL}_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R}$$
$$\text{Lower control limit} = \text{LCL}_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R}$$

c. When the standard deviation of the process distribution, σ, is known:

$$\text{Upper control limit} = \text{UCL}_{\bar{x}} = \bar{\bar{x}} + z\sigma_{\bar{x}}$$
$$\text{Lower control limit} = \text{LCL}_{\bar{x}} = \bar{\bar{x}} + z\sigma_{\bar{x}}$$

where

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

4. Control limits for attribute process control charts
   a. *p*-chart, proportion defective:

$$\text{Upper control limit} = \text{UCL}_p = \bar{p} + z\sigma_p$$
$$\text{Lower control limit} = \text{LCL}_p = \bar{p} - z\sigma_p$$

where

$$\sigma_p = \sqrt{\bar{p}(1-\bar{p})/n}$$

   b. *c*-chart, number of defects:

$$\text{Upper control limit} = \text{UCL}_c = \bar{c} + z\sqrt{\bar{c}}$$
$$\text{Lower control limit} = \text{LCL}_c = \bar{c} - z\sqrt{\bar{c}}$$

Process Capability

5. Process capability index:

$$C_{pk} = \text{Minimum of}\left[\frac{\bar{\bar{x}} - \text{Lower specification}}{3\sigma}, \frac{\text{Upper specification} - \bar{\bar{x}}}{3\sigma}\right]$$

6. Process capability ratio:

$$C_p = \frac{\text{Upper specification} - \text{Lower specification}}{6\sigma}$$

Key Terms

acceptable quality level (AQL) 131
acceptance sampling 131
appraisal costs 126
assignable causes of variation 135
attributes 133
Baldrige Performance Excellence Program 147
c-chart 142
common causes of variation 135
continuous improvement 129
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Solved Problem 1

The Watson Electric Company produces incandescent lightbulbs. The following data on the number of lumens for 40-watt lightbulbs were collected when the process was in control.

	OBSERVATION			
Sample	**1**	**2**	**3**	**4**
1	604	612	588	600
2	597	601	607	603
3	581	570	585	592
4	620	605	595	588
5	590	614	608	604

a. Calculate control limits for an *R*-chart and an $\bar{x}$-chart.

b. Since these data were collected, some new employees were hired. A new sample obtained the following readings: 625, 592, 612, and 635. Is the process still in control?

SOLUTION

a. To calculate $\bar{x}$, compute the mean for each sample. To calculate R, subtract the lowest value in the sample from the highest value in the sample. For example, for sample 1,

$$\bar{x} = \frac{604 + 612 + 588 + 600}{4} = 601$$
$$R = 612 - 588 = 24$$

Sample	$\bar{x}$	R
1	601	24
2	602	10
3	582	22
4	602	32
5	604	24
Total	2,991	112
Average	$\bar{\bar{x}} = 598.2$	$\bar{R} = 22.4$

The R-chart control limits are

$$\text{UCL}_R = D_4\bar{R} = 2.282(22.4) = 51.12$$
$$\text{LCL}_R = D_3\bar{R} = 0(22.4) = 0$$

The $\bar{x}$-chart control limits are

$$\text{UCL}_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R} = 598.2 + 0.729(22.4) = 614.53$$
$$\text{LCL}_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R} = 598.2 - 0.729(22.4) = 581.87$$

b. First check to see whether the variability is still in control based on the new data. The range is 43 (or 635 − 592), which is inside the UCL and LCL for the R-chart. Since the process variability is in control, we test for the process average using the current estimate for $\bar{R}$. The average is 616 [or (625 + 592 + 612 + 635)/4], which is above the UCL for the $\bar{x}$-chart. Since the process average is out of control, a search for assignable causes inducing excessive average lumens must be conducted.

Solved Problem 2

The data processing department of the Arizona Bank has five data entry clerks. Each working day their supervisor verifies the accuracy of a random sample of 250 records. A record containing one or more errors is considered defective and must be redone. The results of the last 30 samples are shown in the table. All were checked to make sure that none was out of control.

Sample	Number of Defective Records	Sample	Number of Defective Records	Sample	Number of Defective Records	Sample	Number of Defective Records
1	7	9	6	17	12	24	7
2	5	10	13	18	4	25	13
3	19	11	18	19	6	26	10
4	10	12	5	20	11	27	14
5	11	13	16	21	17	28	6
6	8	14	4	22	12	29	11
7	12	15	11	23	6	30	9
8	9	16	8				
						Total	300

a. Based on these historical data, set up a p-chart using $z = 3$.

b. Samples for the next 4 days showed the following:

Sample	Number of Defective Records
Tues	17
Wed	15
Thurs	22
Fri	21

What is the supervisor's assessment of the data entry process likely to be?

SOLUTION

a. From the table, the supervisor knows that the total number of defective records is 300 out of a total sample of 7,500 [or 30(250)]. Therefore, the central line of the chart is

$$\bar{p} = \frac{300}{7{,}500} = 0.04$$

The control limits are

$$\text{UCL}_p = \bar{p} + z\sqrt{\frac{\bar{p}(1-\bar{p})}{n}} = 0.04 + 3\sqrt{\frac{0.04(0.96)}{250}} = 0.077$$

$$\text{LCL}_p = \bar{p} - z\sqrt{\frac{\bar{p}(1-\bar{p})}{n}} = 0.04 - 3\sqrt{\frac{0.04(0.96)}{250}} = 0.003$$

b. Samples for the next 4 days showed the following:

Sample	Number of Defective Records	Proportion
Tues	17	0.068
Wed	15	0.060
Thurs	22	0.088
Fri	21	0.084

Samples for Thursday and Friday are out of control. The supervisor should look for the problem and, upon identifying it, take corrective action.

Solved Problem 3

The Minnow County Highway Safety Department monitors accidents at the intersection of Routes 123 and 14. Accidents at the intersection have averaged three per month.

a. Which type of control chart should be used? Construct a control chart with three-sigma control limits.

b. Last month, seven accidents occurred at the intersection. Is this sufficient evidence to justify a claim that something has changed at the intersection?

SOLUTION

a. The safety department cannot determine the number of accidents that did *not* occur, so it has no way to compute a proportion defective at the intersection. Therefore, the administrators must use a c-chart for which

$$\text{UCL}_c = \bar{c} + z\sqrt{\bar{c}} = 3 + 3\sqrt{3} = 8.20$$

$$\text{LCL}_c = \bar{c} - z\sqrt{\bar{c}} = 3 - 3\sqrt{3} = -2.196, \text{ adjusted to } 0$$

There cannot be a negative number of accidents, so the LCL in this case is adjusted to zero.

b. The number of accidents last month falls within the UCL and LCL of the chart. We conclude that no assignable causes are present and that the increase in accidents was due to chance.

Solved Problem 4

Pioneer Chicken advertises "lite" chicken with 30 percent fewer calories. (The pieces are 33 percent smaller.) The process average distribution for "lite" chicken breasts is 420 calories, with a standard deviation of the population of 25 calories. Pioneer randomly takes samples of six chicken breasts to measure calorie content.

a. Design an $\bar{x}$-chart using the process standard deviation. Use three-sigma limits.

b. The product design calls for the average chicken breast to contain 400 $\pm$ 100 calories. Calculate the process capability index (target = 1.33) and the process capability ratio. Interpret the results.

SOLUTION

a. For the process standard deviation of 25 calories, the standard deviation of the sample mean is

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}} = \frac{25}{\sqrt{6}} = 10.2 \text{ calories}$$

$$\text{UCL}_{\bar{x}} = \bar{\bar{x}} + z\sigma_{\bar{x}} = 420 + 3(10.2) = 450.6 \text{ calories}$$

$$\text{LCL}_{\bar{x}} = \bar{\bar{x}} - z\sigma_{\bar{x}} = 420 - 3(10.2) = 389.4 \text{ calories}$$

b. The process capability index is

$$C_{pk} = \text{Minimum of}\left[\frac{\bar{\bar{x}} - \text{Lower specification}}{3\sigma}, \frac{\text{Upper specification} - \bar{\bar{x}}}{3\sigma}\right]$$

$$= \text{Minimum of}\left[\frac{420 - 300}{3(25)} = 1.60, \frac{500 - 420}{325} = 1.07\right] = 1.07$$

The process capability ratio is

$$C_p = \frac{\text{Upper specification} - \text{Lower specification}}{6\sigma} = \frac{500 \text{ calories} - 300 \text{ calories}}{6(25)} = 1.33$$

Because the process capability ratio is 1.33, the process should be able to produce the product reliably within specifications. However, the process capability index is 1.07, so the current process is not centered properly for four-sigma performance. The mean of the process distribution is too close to the upper specification.

Discussion Questions

1. Pano Lefkara is a village in Cyprus known for its lace and silver handicrafts. Their handmade embroidery design is used in tablecloths, curtain borders, and mats. However, the art is slowly dying as the village population is migrating to urban areas. Do you think it is a good idea to replace this handicraft with a machine? What would be the consequences?
2. Recently, the Polish General Corporation, well-known for manufacturing appliances and automobile parts, initiated a $13 billion project to produce automobiles. A great deal of learning on the part of management and employees was required. Even though pressure was mounting to get a new product to market in early 2012, the production manager of the newly formed automobile division insisted on almost a year of trial runs before sales started because workers have to do their jobs 60 to 100 times before they can memorize the right sequence. The launch date was set for early 2013. What are the consequences of using this approach to enter the market with a new product?
3. Explain how unethical business practices degrade the quality of the experience a customer has with a service or product. How is the International Organization for Standardization trying to encourage ethical business behavior?

Problems

The OM Explorer, POM for Windows, and Active Model software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software replaces entirely the manual calculations. The software also can be a valuable resource well after your course is completed.

Statistical Process Control

1. At Quick Car Wash, the wash process is advertised to take less than 7 minutes. Consequently, management has set a target average of 390 seconds for the wash process. Suppose the average range for a sample of 9 cars is 10 seconds. Use Table 3.1 to establish control limits for sample means and ranges for the car wash process.
2. At Isogen Pharmaceuticals, the filling process for its asthma inhaler is set to dispense 150 milliliters (ml) of steroid solution per container. The average range for a sample of 4 containers is 3 ml. Use Table 3.1 to establish control limits for sample means and ranges for the filling process.
3. The Canine Gourmet Company produces delicious dog treats for canines with discriminating tastes. Management wants the box-filling line to be set so that the process average weight per packet is 45 grams. To make sure that the process is in control, an inspector at the end of the filling line periodically selects a random box of 10 packets and weighs each packet. When the process is in control, the range in the weight of each sample has averaged 6 grams.
   a. Design an R- and an $\bar{x}$-chart for this process.
   b. The results from the last five samples of 10 packets are

Sample	$\bar{x}$	R
1	44	9
2	40	2
3	46	5
4	39	8
5	48	3

   Is the process in control? Explain.
4. Aspen Plastics produces plastic bottles to customer order. The quality inspector randomly selects four bottles from the bottle machine and measures the outside diameter of the bottle neck, a critical quality dimension that determines whether the bottle cap will fit properly. The dimensions (in inches) from the last six samples are

	BOTTLE			
Sample	1	2	3	4
1	0.594	0.622	0.598	0.590
2	0.587	0.611	0.597	0.613
3	0.571	0.580	0.595	0.602
4	0.610	0.615	0.585	0.578
5	0.580	0.624	0.618	0.614
6	0.585	0.593	0.607	0.569

   Assume that only these six samples are sufficient, and use the data to determine control limits for an R- and an $\bar{x}$-chart
5. In an attempt to judge and monitor the quality of instruction, the administration of Mega-Byte Academy devised an examination to test students on the basic concepts that all should have learned. Each year, a random sample of 10 graduating students is selected for the test. The average score is used to track the quality of the educational process. Test results for the past 10 years are shown in Table 3.2.

   Use these data to estimate the center and standard deviation for this distribution. Then, calculate the two-sigma control limits for the process average. What comments would you make to the administration of the Mega-Byte Academy?

TABLE 3.2 | TEST SCORES ON EXIT EXAM

	STUDENT										
Year	1	2	3	4	5	6	7	8	9	10	Average
1	63	57	92	87	70	61	75	58	63	71	69.7
2	90	77	59	88	48	83	63	94	72	70	74.4
3	67	81	93	55	71	71	86	98	60	90	77.2
4	62	67	78	61	89	93	71	59	93	84	75.7
5	85	88	77	69	58	90	97	72	64	60	76.0
6	60	57	79	83	64	94	86	64	92	74	75.3
7	94	85	56	77	89	72	71	61	92	97	79.4
8	97	86	83	88	65	87	76	84	81	71	81.8
9	94	90	76	88	65	93	86	87	94	63	83.6
10	88	91	71	89	97	79	93	87	69	85	84.9

6. The McGranger Mortgage Company is interested in monitoring the performance of the mortgage process. Fifteen samples of five completed mortgage transactions each were taken during a period when the process was believed to be in control. The times to complete the transactions were measured. The means and ranges of the mortgage process transaction times, measured in days, are as follows:

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mean	17	14	8	17	12	13	15	16	13	14	16	9	11	9	12
Range	6	11	4	8	9	14	12	15	10	10	11	6	9	11	13

   Subsequently, samples of size 5 were taken from the process every week for the next 10 weeks. The times were measured and the following results obtained:

Sample	16	17	18	19	20	21	22	23	24	25
Mean	11	14	9	15	17	19	13	22	20	18
Range	7	11	6	4	12	14	11	10	8	6

   a. Construct the control charts for the mean and the range, using the original 15 samples.
   b. On the control charts developed in part (a), plot the values from samples 16 through 25 and comment on whether the process is in control.

c. In part (b), if you concluded that the process was out of control, would you attribute it to a drift in the mean, an increase in the variability, or both? Explain your answer.

7. Webster Chemical Company produces mastics and caulking for the construction industry. The product is blended in large mixers and then pumped into tubes and capped. Management is concerned about whether the filling process for tubes of caulking is in statistical control. The process should be centered on 8 ounces per tube. Several samples of eight tubes were taken, each tube was weighed, and the weights in Table 3.3 were obtained.

a. Assume that only six samples are sufficient and develop the control charts for the mean and the range.

b. Plot the observations on the control chart and comment on your findings.

TABLE 3.3 | OUNCES OF CAULKING PER TUBE

	TUBE NUMBER							
Sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	7.98	8.34	8.02	7.94	8.44	7.68	7.81	8.11
2	8.33	8.22	8.08	8.51	8.41	8.28	8.09	8.16
3	7.89	7.77	7.91	8.04	8.00	7.89	7.93	8.09
4	8.24	8.18	7.83	8.05	7.90	8.16	7.97	8.07
5	7.87	8.13	7.92	7.99	8.10	7.81	8.14	7.88
6	8.13	8.14	8.11	8.13	8.14	8.12	8.13	8.14

8. The Digital Guardian Company issues policies that protect clients from downtime costs due to computer system failures. It is very important to process the policies quickly because long cycle times not only put the client at risk but could also lose business for Digital Guardian. Management is concerned that customer service is degrading because of long cycle times, measured in days. The following table contains the data from five samples, each sample consisting of eight random observations.

	OBSERVATION (DAYS)							
Sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	13	9	4	8	8	15	8	6
2	7	15	8	10	10	14	10	15
3	8	11	4	11	8	12	9	15
4	12	7	12	9	11	8	12	8
5	8	12	6	12	11	5	12	8

a. What is your estimate of the process average?

b. What is your estimate of the average range?

c. Construct an R-chart and an $\bar{x}$-chart for this process. Are assignable causes present?

9. The Precision Machining Company makes handheld tools on an assembly line that produces one product every minute. On one of the products, the critical quality dimension is the diameter (measured in thousandths of an inch) of a hole bored in one of the assemblies. Management wants to detect any shift in the process average diameter from 0.015 inch. Management considers the variance in the process to be in control. Historically, the average range has been 0.002 inch, regardless of the process average. Design an $\bar{x}$-chart to control this process, with a center line at 0.015 inch and the control limits set at three sigmas from the center line.

Management provided the results of 80 minutes of output from the production line, as shown in Table 3.4. During these 80 minutes, the process average changed once. All measurements are in thousandths of an inch.

a. Set up an $\bar{x}$-chart with $n = 4$. The frequency should be sample four and then skip four. Thus, your first sample would be for minutes 1–4, the second would be for minutes 9–12, and so on. When would you stop the process to check for a change in the process average?

b. Set up an $\bar{x}$-chart with $n = 8$. The frequency should be sample eight and then skip four. When would you stop the process now? What can you say about the desirability of large samples on a frequent sampling interval?

TABLE 3.4 | SAMPLE DATA FOR PRECISION MACHINING COMPANY

Minutes	Diameter (thousandths of an inch)											
1–12	15	16	18	14	16	17	15	14	14	13	16	17
13–24	15	16	17	16	14	14	13	14	15	16	15	17
25–36	14	13	15	17	18	15	16	15	14	15	16	17
37–48	18	16	15	16	16	14	17	18	19	15	16	15
49–60	12	17	16	14	15	17	14	16	15	17	18	14
61–72	15	16	17	18	13	15	14	14	16	15	17	18
73–80	16	16	17	18	16	15	14	17				

10. Using the data from Problem 9, continue your analysis of sample size and frequency by trying the following plans.

a. Using the $\bar{x}$-chart for $n = 4$, try the frequency sample four, then skip eight. When would you stop the process in this case?

b. Using the $\bar{x}$-chart for $n = 8$, try the frequency sample eight, then skip eight. When would you consider the process to be out of control?

c. Using your results from parts (a) and (b), determine what trade-offs you would consider in choosing between them.

11. Garcia's Garage desires to create some colorful charts and graphs to illustrate how reliably its mechanics "get under the hood and fix the problem." The historic average for the proportion of customers that return for the same repair within the 30-day warranty period is 0.10. Each month, Garcia tracks 100 customers to see whether they return for warranty repairs. The results are plotted as a proportion to report progress toward the goal. If the control limits are to be set at 2 standard deviations on either side of the goal, determine the control limits for this chart. In March, 8 of the 100 customers in the sample group returned for warranty repairs. Is the repair process in control?

12. As a hospital administrator of a large hospital, you are concerned with the absenteeism among nurses' aides. The issue has been raised by registered nurses, who feel they often have to perform work normally done by their aides. To get the facts, absenteeism data were gathered for the past 3 weeks, which is considered a representative period for future conditions. After taking random samples of 64 personnel files each day, the following data were produced:

Day	Aides Absent	Day	Aides Absent
1	4	9	7
2	3	10	2
3	2	11	3
4	4	12	2
5	2	13	1
6	5	14	3
7	3	15	4
8	4		

Because your assessment of absenteeism is likely to come under careful scrutiny, you would like a type I error of only 1 percent. You want to be sure to identify any instances of unusual absences. If some are present, you will have to explore them on behalf of the registered nurses.

a. Design a p-chart.

b. Based on your p-chart and the data from the past 3 weeks, what can you conclude about the absenteeism of nurses' aides?

13. The IRS is concerned with improving the accuracy of tax information given by its representatives over the telephone. Previous studies involved asking a set of 25 questions of a large number of IRS telephone representatives to determine the proportion of correct responses. Historically, the average proportion of correct responses has been 72 percent. Recently, IRS representatives have been receiving more training. On April 26, the set of 25 tax questions were again asked of 20 randomly selected IRS telephone representatives. The numbers of correct answers were 18, 16, 19, 21, 20, 16, 21, 16, 17, 10, 25, 18, 25, 16, 20, 15, 23, 19, 21, and 19.

a. What are the upper and lower control limits for the appropriate p-chart for the IRS? Use $z = 3$.

b. Is the tax information process in statistical control?

14. Management at Webster, in Problem 7, is now concerned as to whether caulking tubes are being properly capped. If a significant proportion of the tubes are not being sealed, Webster is placing its customers in a messy situation. Tubes are packaged in large boxes of 144. Several boxes are inspected, and the following numbers of leaking tubes are found:

Sample	Tubes	Sample	Tubes	Sample	Tubes
1	3	8	6	15	5
2	5	9	4	16	0
3	3	10	9	17	2
4	4	11	2	18	6
5	2	12	6	19	2
6	4	13	5	20	1
7	2	14	1	Total	72

Calculate p-chart three-sigma control limits to assess whether the capping process is in statistical control.

15. Janice Sanders, CEO of Pine Crest Medical Clinic, is concerned over the number of times patients must wait more than 30 minutes beyond their scheduled appointments. She asked her assistant to take random samples of 64 patients to see how many in each sample had to wait more than 30 minutes. Each instance is considered a defect in the clinic process. The table below contains the data for 15 samples.

Sample	Number of Defects
1	5
2	2
3	1
4	3
5	1
6	5
7	2
8	3
9	6
10	3
11	9
12	9
13	5
14	2
15	3

a. Assuming Janice Sanders is willing to use three-sigma control limits, construct a p-chart.

b. Based on your p-chart and the data in the table, what can you conclude about the waiting time of the patients?

16. A cake manufacturing business based in London has 120 branches spread all over the city. All cakes are customized as per the needs of the customers, including

type of cake and choice of toppings. For quality control and consistency, cakes are manufactured at a central location and distributed to the branches. Cakes are randomly inspected for errors such as the writing on the cake, toppings, delivery location, and type of cake. Even a single error makes a cake defective. The following data were collected over the last 30 days to see how many cakes turned out defective. Each sample has 200 randomly selected cakes.

Sample	Defects	Sample	Defects
1	20	16	20
2	14	17	12
3	8	18	11
4	14	19	15
5	15	20	15
6	11	21	20
7	13	22	8
8	18	23	9
9	14	24	11
10	12	25	11
11	9	26	14
12	17	27	8
13	13	28	10
14	15	29	11
15	14	30	9

a. What are the upper and lower control limits of a p-chart for the number of defective cakes? Use $z = 3$.

b. Is the process in statistical control?

17. The manager of the customer service department of Data Tech Credit Card Service Company is concerned about the number of defects produced by the billing process. Every day a random sample of 250 statements was inspected for errors regarding incorrect entries involving account numbers, transactions on the customer's account, interest charges, and penalty charges. Any statement with one or more of these errors was considered a defect. The study lasted 30 days and yielded the data in Table 3.5.

a. Construct a p-chart for the billing process.

b. Is there any nonrandom behavior in the billing process that would require management attention?

TABLE 3.5 | SAMPLE DATA FOR DATA TECH CREDIT CARD SERVICE

Samples	Number of Errors in Sample of 250									
1–10	3	8	5	11	7	1	12	9	0	8
11–20	3	5	7	9	11	3	2	9	13	4
21–30	12	10	6	2	1	7	10	5	8	4

18. Red Baron Airlines serves hundreds of cities each day, but competition is increasing from smaller companies affiliated with major carriers. One of the key competitive priorities is on-time arrivals and departures. Red Baron defines *on time* as any arrival or departure that takes place within 15 minutes of the scheduled time. To stay on top of the market, management set the high standard of 98 percent on-time performance. The operations department was put in charge of monitoring the performance of the airline. Each week, a random sample of 300 flight arrivals and departures was checked for schedule performance. Table 3.6 contains the numbers of arrivals and departures over the past 30 weeks that did not meet Red Baron's definition of on-time service. Using three-sigma control limits based on 98 percent on-time arrivals or departures, what can you tell the management about the quality of service? Can you identify any nonrandom behavior in the process? If so, what might cause the behavior?

TABLE 3.6 | SAMPLE DATA FOR RED BARON AIRLINES

Samples	Number of Late Planes in Sample of 300 Arrivals and Departures									
1–10	3	8	5	11	7	2	12	9	1	8
11–20	3	5	7	9	12	5	4	9	13	4
21–30	12	10	6	2	1	8	4	5	8	2

19. A textile manufacturer wants to set up a control chart for irregularities (e.g., oil stains, shop soil, loose threads, and tears) per 100 square yards of carpet. The following data were collected from a sample of twenty 100-square-yard pieces of carpet:

Sample	1	2	3	4	5	6	7	8	9	10
Irregularities	11	8	9	12	4	16	5	8	17	10
Sample	11	12	13	14	15	16	17	18	19	20
Irregularities	11	5	7	12	13	8	19	11	9	10

a. Using these data, set up a c-chart with $z = 3$.

b. Suppose that the next five samples had 15, 18, 12, 22, and 21 irregularities. What do you conclude?

20. A travel agency is concerned with the accuracy and appearance of itineraries prepared for its clients. Defects can include errors in times, airlines, flight numbers, prices, car rental information, lodging, charge card numbers, and reservation numbers, as well as typographical errors. As the possible number of errors is nearly infinite, the agency measures the number of errors that do occur. The current process results in an average of three errors per itinerary.

a. What are the two-sigma control limits for these defects?

b. A client scheduled a trip to Dallas. Her itinerary contained six errors. Interpret this information.

21. Furniture Mart makes bespoke and standard household furniture such as table, chairs, and cots using a variety of material such as wood, steel, and plastic. Due to rapid expansion and heavy workload, the quality department identified a number of defects. The

furniture could be flawed in various ways, including incorrect dimensions, uneven stitches in the upholstery, and surface not polished properly. A random examination of 10 products generated the following results:

Product	Number of Defects
1	7
2	5
3	8
4	0
5	5
6	12
7	6
8	9
9	2
10	5

a. Assuming that 10 observations are adequate for these purposes, determine the three-sigma control limits for defects per product.

b. Suppose that the next product has 13 defects. What can you say about the process now?

22. Matrix Enterprises manufactures molded plastic chairs of various sizes and colors using the blow molding process. However, due to improper maintenance, defects have been steadily increasing. The following results are obtained from a random examination of 10 samples:

Chair	Defects
1	8
2	4
3	6
4	0
5	8
6	10
7	9
8	3
9	7
10	5

a. Assuming 10 observations are adequate for this purpose, determine the three-sigma control limits for defects per chair.

b. What conclusions can be drawn about the process if the next output being examined has 15 defects?

23. Ferrous steel company manufactures steel plates for the construction industry. During fabrication, it faces various defects such as blisters, cracks, and porosity. Since there could be internal cracks, testing plates can be a challenge and hence it adopts nondestructive testing techniques through ultrasonic sounds. The following results are obtained from testing eight randomly selected samples:

Steel Plate Number	Defects	Steel Plate Number	Defects
1	5	5	3
2	6	6	0
3	9	7	9
4	4	8	19

Determine the c-chart two-sigma upper and lower control limits for this process. Is the process in statistical control?

Process Capability

24. The production manager at Sunny Soda, Inc., is interested in tracking the quality of the company's 12-ounce bottle filling line. The bottles must be filled within the tolerances set for this product because the dietary information on the label shows 12 ounces as the serving size. The design standard for the product calls for a fill level of 12.00 ± 0.10 ounces. The manager collected the following sample data (in fluid ounces per bottle) on the production process:

	OBSERVATION			
Sample	1	2	3	4
1	12.00	11.97	12.10	12.08
2	11.91	11.94	12.10	11.96
3	11.89	12.02	11.97	11.99
4	12.10	12.09	12.05	11.95
5	12.08	11.92	12.12	12.05
6	11.94	11.98	12.06	12.08
7	12.09	12.00	12.00	12.03
8	12.01	12.04	11.99	11.95
9	12.00	11.96	11.97	12.03
10	11.92	11.94	12.09	12.00
11	11.91	11.99	12.05	12.10
12	12.01	12.00	12.06	11.97
13	11.98	11.99	12.06	12.03
14	12.02	12.00	12.05	11.95
15	12.00	12.05	12.01	11.97

a. Are the process average and range in statistical control?

b. Is the process capable of meeting the design standard at four-sigma quality? Explain.

25. The McGranger Mortgage Company of Problem 6 made some changes to the process and undertook a process capability study. The following data were obtained for 15 samples of size 5. On the basis of individual observations, management estimated the process standard deviation to be 4.21 (days) for use in the process capability analysis. The lower and upper specification limits (in days) for the mortgage process times were 5 and 25.

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mean	11	12	8	16	13	12	17	16	13	14	17	9	15	14	9
Range	9	13	4	11	10	9	8	15	14	11	6	6	12	10	11

a. Calculate the process capability index and the process capability ratio values.

b. Suppose management would be happy with three-sigma performance. What conclusions is management likely to draw from the capability analysis? Can valid conclusions about the process be drawn from the analysis?

c. What remedial actions, if any, do you suggest that management take?

26. A manufacturer of glass panes received a new order from a customer to supply 18 millimeters thick glass planes with a tolerance of +/−2 millimeters. The manufacturer is concerned about the capability of the process to produce this glass. The following data were randomly collected during five shifts of the production process:

	OBSERVATION (Thickness of Glass Panes in Millimeters)							
Shift	1	2	3	4	5	6	7	8
1	18.05	17.76	18.10	19.50	16.50	16.00	15.80	18.20
2	17.90	19.70	18.50	18.30	19.20	16.50	16.00	19.00
3	17.80	16.70	19.20	18.42	17.76	16.60	18.30	17.50
4	16.34	17.83	16.00	15.90	17.80	18.80	19.20	19.50
5	19.55	19.78	18.75	19.45	17.87	16.65	17.32	18.45

Assume that the process is in statistical control. Is the process capable of achieving six-sigma quality levels with regard to the thickness of the glass panes? Explain.

27. A critical dimension of the service quality of a call center is the wait time of a caller to get to a sales representative. Periodically, random samples of three customer calls are measured for time. The results of the last four samples are in the following table:

Sample	Time (Sec)		
1	495	501	498
2	512	508	504
3	505	497	501
4	496	503	492

a. Assuming that management is willing to use three-sigma control limits, and using only the historical information contained in the four samples, show that the call center access time is in statistical control.

b. Suppose that the standard deviation of the process distribution is 5.77. If the specifications for the access time are 500 ± 18 seconds, is the process capable? Why or why not? Assume three-sigma performance is desired.

28. An automatic lathe produces rollers for roller bearings, and statistical process control charts are used to monitor the process. The central line of the chart for the sample means is set at 8.50 and for the range at 0.31 mm. The process is in control, as established by samples of size 5. The upper and lower specifications for the diameter of the rollers are (8.50 + 0.25) and (8.50 − 0.25) mm, respectively.

a. Calculate the control limits for the mean and range charts.

b. If the standard deviation of the process distribution is estimated to be 0.13 mm, is the process capable of meeting specifications? Assume four-sigma performance is desired.

c. If the process is not capable, what percent of the output will fall outside the specification limits? (*Hint*: Use the normal distribution.)

29. Canine Gourmet Super Breath dog treats are sold in boxes labeled with a net weight of 12 ounces (340 grams) per box. Each box contains 8 individual 1.5-ounce packets. To reduce the chances of shorting the customer, product design specifications call for the packet-filling process average to be set at 43.5 grams so that the average net weight per box of 8 packets will be 348 grams. Tolerances are set for the box to weigh 348 ± 12 grams. The standard deviation for the *packet-filling* process is 1.01 grams. The target process capability ratio is 1.33. One day, the packet-filling process average weight drifts down to 43.0 grams. Is the packaging process capable? Is an adjustment needed?

30. Return to Problem 4 relating to Aspen Plastics producing plastic bottles to customer order. Suppose that the specification for the bottleneck diameter is 0.600 ± 0.050 and the population standard deviation is 0.013 inch.

a. What is the process capability index?

b. What is the process capability ratio?

c. If the firm is seeking four-sigma performance, is the process capable of producing the bottle?

31. Marodin Brothers, Inc., is conducting a study to assess the capability of its 150-gram bar soap production line. A critical quality measure is the weight of the soap bars after stamping. The lower and upper specification limits are 162 and 170 grams, respectively. As a part of an initial capability study, 25 samples of size 5 were collected by the quality assurance group and the observations in Table 3.7 were recorded.

After analyzing the data by using statistical control charts, the quality assurance group calculated the process capability ratio, C_p, and the process capability index, C_{pk}. It then decided to improve the stamping process, especially the feeder mechanism. After making all the changes that were

TABLE 3.7 | SAMPLE DATA FOR MARODIN BROTHERS, INC.

Sample	OBS.1	OBS.2	OBS.3	OBS.4	OBS.5
1	167.0	159.6	161.6	164.0	165.3
2	156.2	159.5	161.7	164.0	165.3
3	167.0	162.9	162.9	164.0	165.4
4	167.0	159.6	163.7	164.1	165.4
5	156.3	160.0	162.9	164.1	165.5
6	164.0	164.2	163.0	164.2	163.9
7	161.3	163.0	164.2	157.0	160.6
8	163.1	164.2	156.9	160.1	163.1
9	164.3	157.0	161.2	163.2	164.4
10	156.9	161.0	163.2	164.3	157.3
11	161.0	163.3	164.4	157.6	160.6
12	163.3	164.5	158.4	160.1	163.3
13	158.2	161.3	163.5	164.6	158.7
14	161.5	163.5	164.7	158.6	162.5
15	163.6	164.8	158.0	162.4	163.6
16	164.5	158.5	160.3	163.4	164.6
17	164.9	157.9	162.3	163.7	165.1
18	155.0	162.2	163.7	164.8	159.6
19	162.1	163.9	165.1	159.3	162.0
20	165.2	159.1	161.6	163.9	165.2
21	164.9	165.1	159.9	162.0	163.7
22	167.6	165.6	165.6	156.7	165.7
23	167.7	165.8	165.9	156.9	165.9
24	166.0	166.0	165.6	165.6	165.5
25	163.7	163.7	165.6	165.6	166.2

deemed necessary, 18 additional samples were collected. The summary data FOR these samples are

$$\bar{\bar{x}} = 163 \text{ grams}$$

$$\bar{R} = 2.326 \text{ grams}$$

$$\sigma = 1 \text{ gram}$$

All sample observations were within the control chart limits. With the new data, the quality assurance group recalculated the process capability measures. It was pleased with the improved C_p but felt that the process should be centered at 166 grams to ensure that everything was in order. Its decision concluded the study.

a. Draw the control charts for the data obtained in the initial study and verify that the process was in statistical control.

b. What were the values obtained by the group for C_p and C_{pk} for the initial capability study? Comment on your findings and explain why further improvements were necessary.

c. What are the C_p and C_{pk} after the improvements? Comment on your findings, indicating why the group decided to change the centering of the process.

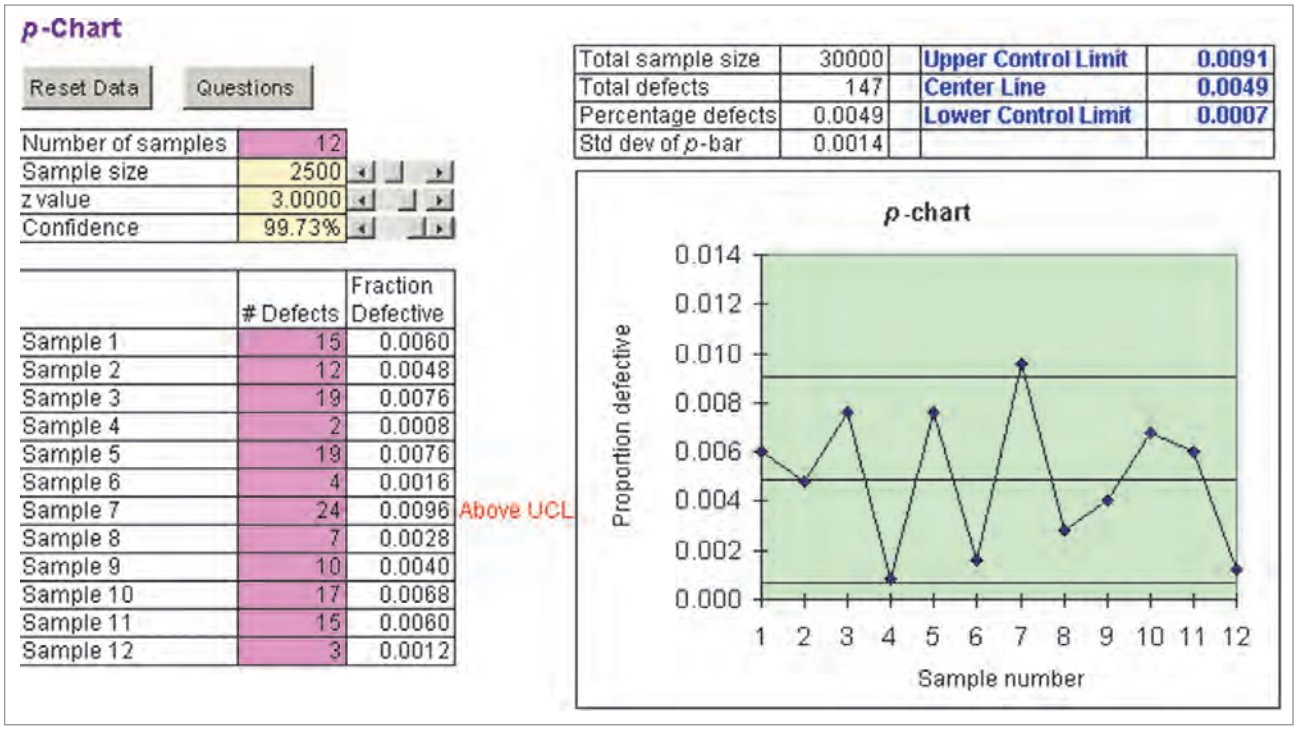
d. What are the C_p and C_{pk} if the process were centered at 166? Comment on your findings.

Active Model Exercise

This Active Model is available online. It allows you to see the effects of sample size and *z*-values on control charts.

QUESTIONS

1. Has the booking process been in statistical control?
2. Suppose we use a 95 percent *p*-chart. How do the upper and lower control limits change? What are your conclusions about the booking process?
3. Suppose that the sample size is reduced to 2,000 instead of 2,500. How does this affect the chart?
4. What happens to the chart as we reduce the *z*-value?
5. What happens to the chart as we reduce the confidence level?



p-Chart Using Data from Example 3.3

EXPERIENTIAL LEARNING 3.1 Statistical Process Control with a Coin Catapult

Exercise A: Control Charts for Variables

Materials

1 ruler
1 pen or pencil
1 coin (a quarter will do nicely)
1 yardstick
An exercise worksheet
Access to a calculator

Tasks

Divide into teams of two to four. If four people are on a team, one person holds the yardstick and observes the action, one person adjusts the catapult and launches the coin, one person observes the maximum height for each trial, and one person records the results.

If teams of fewer than four are formed, provide a support for the yardstick and combine the other tasks as appropriate.

Practice

To catapult the coin, put a pen or pencil under the 6-inch mark of the ruler. Put the coin over the 11-inch mark. Press both ends of the ruler down as far as they will go. Let the end that holds the coin snap up, catapulting the coin into the air. The person holding the yardstick should place the stick so that it is adjacent to, but does not interfere with, the trajectory of the coin. To observe the maximum height reached by the coin, the observer should stand back with his or her eye at about the same level as the top of the coin's trajectory. Practice until each person is comfortable with his or her role. The person operating the catapult should be sure that the pen or pencil fulcrum has not moved between shots and that the launch is done as consistently as possible.

Step 1. *Gather data.* Take four samples of five observations (launches) each. Record the maximum height reached by the coin in the first

data table on the worksheet. When you have finished, determine the mean and range for each sample, and compute the mean of the means $\bar{\bar{x}}$ and the mean of the ranges $\bar{R}$.

Step 2. *Develop an R-chart.* Using the data gathered and the appropriate D_3 and D_4 values, compute the upper and lower three-sigma control limits for the range. Enter these values and plot the range for each of the four samples on the range chart on the worksheet. Be sure to indicate an appropriate scale for range on the *y*-axis.

Step 3. *Develop an $\bar{x}$-chart.* Now, using the data gathered and the appropriate value for A_2, compute the upper and lower three-sigma control limits for the sample means. Enter these values and plot the mean for each of the four samples on the *$\bar{x}$-chart* on the worksheet. Again, indicate an appropriate scale for the *y*-axis.

Step 4. *Observe the process.* Once a control chart has been established for a process, it is used to monitor the process and to identify when it is not running normally. Collect two more samples of five trials each, as you did to collect the first set of data. Plot the range and the sample mean on the charts you constructed on the worksheet each time you collect a sample. What have you observed that affects the process? Does the chart indicate that the process is operating the way it did when you first collected data?

Step 5. *Observe a changed process.* Now change something (for instance, move the pencil out to the 8-inch mark). Collect data for samples 7 and 8. Plot the range and the sample mean on the charts you constructed on the worksheet as you complete each sample. Can you detect a change in the process from your control chart? If the process has changed, how sure are you that this change is real and not just due to the particular sample you chose?

Exercise B: Control Charts for Attributes

Materials

1 ruler
1 pen or pencil
1 coin (a quarter will do nicely)
1 paper or plastic cup (with a 4-inch mouth)
An exercise worksheet
Access to a calculator

Tasks

Divide into teams of two or three. If three people are on a team,
one person adjusts the catapult and launches the coin,
one person observes the results and fetches the coin, and
one person records the results.
If teams of two are formed, combine the tasks as appropriate.

Practice

The object is to flip a coin into a cup using a ruler. To catapult the coin, put a pen or pencil under the 6-inch mark of the ruler.

Put a coin over the 11-inch mark and let its weight hold that end of the ruler on the tabletop. Strike the raised end of the ruler with your hand to flip the coin into the air. Position a cup at the place where the coin lands so that on the next flip, the coin will land inside. You will have to practice several times until you find out how hard to hit the ruler and the best position for the cup. Be sure that the pen or pencil fulcrum has not moved between shots and that the launch is done as consistently as possible.

Step 1. *Gather data.* Try to catapult the coin into the cup 10 times for each sample. Record each trial in the data table on the worksheet as a hit (H) when the coin lands inside or a miss (M) when it does not. The proportion of misses will be the number of misses divided by the sample size, *n*, in this case 10. A miss is a "defect," so the proportion of misses is the proportion defective, *p*.

Step 2. *Develop a p-chart.* Compute the upper and lower three-sigma control limits for the average fraction defective. Plot these values and the mean for each of the four samples on the *p*-chart on the worksheet.

Step 3. *Observe the process.* Once a chart has been established for a process, it is used to monitor the process and to identify abnormal behavior. Exchange tasks so that someone else is catapulting the coin. After several practice launches, take four more samples of 10. Plot the proportion defective for this person's output. Is the process still in control? If it is not, how sure are you that it is out of control? Can you determine the control limits for a 95 percent confidence level? With these limits, was your revised process still in control?[4]

[4] *Source:* The basis for Exercise A was written by J. Christopher Sandvig, Western Washington University, as a variation of the "Catapulting Coins" exercise from *Games and Exercises for Operations Management* by Janelle Heinke and Larry Meile (Prentice Hall, 1995). Given these foundations, Larry Meile of Boston College wrote Exercise A. He also wrote Exercise B as a new extension. Reprinted by permission of Larry Meile.

VIDEO CASE Quality at Axon

Protect life. Protect truth. That's the mission of Axon, the company that produces public safety technologies such as Taser electrical smart weapons and body cameras for law enforcement around the globe. In business since 1993, the company manufactures three weapons lines inside its high-tech headquarters in Scottsdale, Arizona. Ninety-nine percent of its customers are in law enforcement, military, correctional, and professional security organizations.

Designing and manufacturing smart weapons technologies requires precise engineering and production processes that can ensure both accuracy and operational safety for its organizational customers and personal protection buyers. This attention to detail is evidenced in the company's commitment to quality, and can be seen in the way the manufacturing operation is organized. Axon's manufacturing operations are ISO 9001:2008 certified.

All finished goods are produced to stock, so that the company can be responsive when an order is received. Sales history data help dictate which items to make to stock, and which could sit in inventory between 6 and 12 weeks before being sold. Most employees have undergone voluntary exposure to the weapons, including the founders.

Axon's work cells are arranged by product. At the start of the week, each cell is given a "production order" document that lists the bill of materials for the finished goods that cell must produce during the week. The production order is released by Axon's Enterprise Resource Planning (ERP) system, with raw materials required for assembly pulled and staged at each cell weekly. In addition to supporting the informational needs of all the functional areas of a firm, ERP systems support the manufacture of a firm's products by scheduling the fabrication of components and the arrival of purchased materials in support of the overall production plan.

Axon's attention to quality is embedded throughout its manufacturing processes. Raw materials are tested and inspected for quality conformance at the supplier to be certain no faulty components are shipped. Circuit boards, which are assembled domestically, are each tested prior to shipment, and then acceptance sampling at Axon's receiving dock confirms shipment conformance. The same process occurs for the supplier of injection molded components, such as weapons casings. Testing includes functionality checks, drop tests to ensure the product can withstand being dropped, and temperature checks to make sure the weapons will work between a temperature range of −20 degrees Celsius and +50 degrees Celsius. When finished goods are ready, Axon performs a final quality assurance check on 100% of goods to ensure everything functions properly prior to shipping to the customer. All goods come with a 1-year warranty.

In 2009, 25 company managers from engineering, manufacturing, R&D, and quality assurance enrolled in a Six Sigma Green Belt training program offered at a nearby university. While the coursework was meaningful, Axon faced intense pressure to bring new products to market, due to which management focus on implementing Six Sigma principles waned. It wasn't until 2011 that Axon would again revisit its Six Sigma journey with renewed interest. Management broadened the employee base to be trained, including customer service and marketing divisions, and chose to incorporate more stringent Six Sigma methodologies into its training. Six Black Belts emerged with projects targeted to strengthen operations at the company. One such project, initiated by Vice President of Manufacturing Bill Denzer, took aim at the softer side of production: its employees. Bill saw a need to empower manufacturing line employees with data so that they could take greater ownership of what was occurring within their environments. Although Axon collected manufacturing data daily for continuous improvement purposes prior to 2011, line level employees weren't involved in the analysis and problem solving required to rapidly change or fix issues. The manufacturing engineering group reviewed the data only after problems emerged, taking some time to investigate and resolve even as production tried to continue.

Bill's project sought to engage manufacturing engineering in the automation of test data collection to develop baselines for processes and establish upper and lower control limits. Line workers were given explicit parameters for processes, and they immediately took ownership of those processes. As a result, it quickly became evident when something in the work cell was trending out of control so the issue could be resolved within hours. A formal escalation process further ensured that the right individuals were notified to get action.

In 2013, Axon installed computer monitors above each work cell so that all manufacturing employees could see the data related to how they were doing. The data include scrap dollars as a percentage of total production, process yield (units produced), average labor cost per unit compared to expected labor cost, average material costs per unit compared to expected material costs, daily/monthly/quarterly production output compared to planned output, throughput times compared to standards, and more.



ATHENA PICTURE AGENCY LTD/Alamy Stock Photo

The AXON bodycams on their charge and download cradle. Body worn video cameras are being introduced into the South Wales Police force as part of operational equipment and will be rolled out over the next few months.

To close the loop on data collection and performance analysis, Axon holds daily meetings at the start of each shift to review the metrics. In addition, the Axon Continuing Improvement program, or TCI, was created. This program generates over 15 suggestions weekly from employees across all areas of the manufacturing process. Bulletin boards in each work cell make it easy to write up issues, and the visibility of the suggestions gets immediate attention. Further, anyone can stop production if a problem is detected, and issues get resolved within hours instead of days or weeks, leading to reduced downtime and quality problems.

QUESTIONS

1. Implementing Six Sigma programs takes considerable time and commitment from an organization. Evaluate Axon's efforts with regard to management commitment, measurement systems to track progress, tough goal setting, education, communication, and customer priorities.
2. How might Axon's commitment to employee engagement help the company avoid the four costs of poor process performance and quality (prevention, appraisal, internal failure, external failure)?
3. Describe Axon's total quality management approach as it relates to customer satisfaction, employee involvement, and continuous improvement.

LEAN SYSTEMS

4

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

4.1 Describe how lean systems can facilitate the continuous improvement of processes.

4.2 Identify the strategic supply chain and process characteristics of lean systems.

4.3 Explain the differences between one-worker, multiple-machine (OWMM) and group technology (GT) approaches to lean system layouts.

4.4 Understand Kanban systems for creating a production schedule in a lean system.

4.5 Understand value stream mapping and its role in waste reduction.

4.6 Explain the implementation issues associated with the application of lean systems.

Nike, Inc.



rblfmr/Shutterstock

Shoppers and visitors outside the Nike House of Innovation flagship store on Fifth avenue in New York, USA-December 19, 2019. Nike is an American Company that designs, manufactures, markets, and sells athletic shoes and apparel.

Nike, Inc., is a global designer, manufacturer, and distributor of athletic apparel, footwear, and sports equipment with sales in excess of $36 billion in 2018. Named after the Greek goddess of victory, Nike is one of the most

valuable brands, with well-recognized trademarks and logos such as "Just Do It" and "Swoosh." While very successful now, Nike had a major image problem and falling customer demand in the 1990s centered on poor wages, forced overtime, and dismal working conditions in its factories. Over a two-decade journey, Nike engineered its turnaround by dramatically transforming its contract factories into following the lean principles and using them to affirm its commitment to corporate social responsibility.

Nike started by streamlining its supply chain and reducing the number of contract factories located across India, Philippines, Vietnam, and South America, from 910 to 785. Employing over one million people and manufacturing half a million unique products, Nike built a culture of empowerment in these factories that revolved around continuous improvement and respect for people. Managers responsible for lean transformation were sent to Nike's training facility in Sri Lanka. Workers were increasingly seen as a key source of innovation and improvement, and were encouraged to shift to higher and diverse sets of skills while adopting newer tools and techniques. To deliver high-quality products at low cost, Nike had to not only improve the working conditions but also reduce waste and promote more efficient use of water. Several factories also had to change the physical layout of their shop floor.

To ensure compliance and attainment of uniformly high standards, Nike developed a sourcing and manufacturing sustainability index for its contract manufacturers. This manufacturing index can be used to assess each factory in terms of its lean capabilities, including quality, just in time, operational stability, and culture of empowerment. Other parts of the Manufacturing Index are Labor and Human Resource Management, Health and Safety practices, Energy and Carbon usage, and Environmental Sustainability. World-class factories are rated as gold, while bronze level reflects compliance with the standards that Nike expects from all its factories. By the end of 2015, 85% of the Nike factories had attained the bronze standard. This change was also associated with a 15% reduction in noncompliance, with labor standards measured by wages, benefits, and time off.

The benefits of a leaner supply chain resulted in lower overtime, elimination of late orders and sudden changes in material requirements, improvement in productivity by 10 to 20 percent, lowering of defect rates by 50 percent, and reduction of delivery times by 20 to 40 percent. Nike is now rated as one of the most lean manufacturers in the world. By pursuing systematic change through lean transformation, Nike turned its public relations woes into higher brand value, while at the same time also becoming an industry leader in sustainability and corporate social responsibility.[1]

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[1] *Sources:* Lorenzo Del Malmor, "From Child Labor to Social Responsible Lean Innovation," Lean Six Sigma Belgium, https://leansixsigmabelgium.com/blog/lean-innovation-nike/ (July 28, 2020); "Nike Gears up for a Manufacturing Revolution," *Manufacturing*, https://www.manufacturingglobal.com/lean-manufacturing/nike-gears-manufacturing-revolution (June 10, 2020); https://theleadershipnetwork.com/article/how-nike-used-lean-manufacturing (October 31, 2016); https://en.wikipedia.org/wiki/Nike,_Inc. (July 28, 2020).

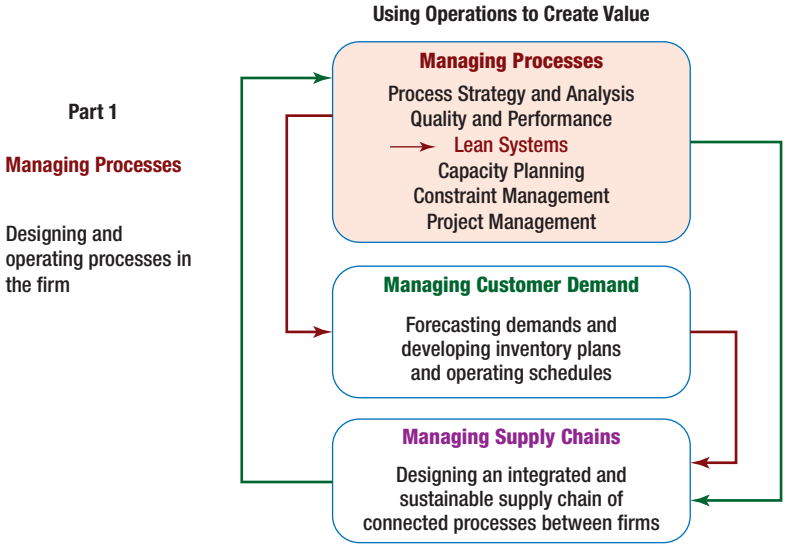
Nike, Inc., is a learning organization and an excellent example of an approach for designing manufacturing and supply chains known as lean systems, which allow organizations to continuously improve their operations and spread the lessons learned across the entire corporation. **Lean systems** are operations systems that maximize the value added by each of a company's activities by removing waste and delays from them. They encompass the company's operations strategy, process design, quality management, constraint management, layout design, supply chain design, and technology and inventory management and can be used by both service and manufacturing firms. Like a manufacturer, each service business takes an order from a customer, delivers the service, and then collects revenue. Each service business purchases services or items, receives and pays for them, and hires and pays employees. Each of these activities bears considerable similarity to those in manufacturing firms. They also typically contain huge amounts of waste.

lean systems

Operations systems that maximize the value added by each of a company's activities by removing waste and delays from them.

Lean systems affect a firm's internal linkages between its core and supporting processes and its external linkages with its customers and suppliers. The design of supply chains using the lean systems approach is important to various departments and functional areas across the organization. Marketing relies on lean systems to deliver high-quality services or products on time and at reasonable prices. Human resources must put in place the right incentive systems that reward teamwork and also recruit, train, and evaluate the employees needed to create a flexible workforce that can successfully operate a lean system. Engineering must design products that use more common parts, so that fewer setups are required and focused factories can be used. Operations is responsible for maintaining close ties with suppliers, designing the lean system, and using it in the production of services or goods. Accounting must adjust its billing and cost accounting practices to provide the support needed to manage lean systems. Finally, top management must embrace the lean philosophy and make it a part of organizational culture and learning, as is done by Nike and also by Aldi, a discount supermarket chain with headquarters in Germany and over 10,000 stores worldwide in 20 countries, including Australia, Europe, Great Britain, Ireland, and the United States. Its emphasis on core values of simplicity, consistency, and corporate responsibility are closely tied to the principles of lean production, which Aldi uses to keep costs down in all areas, provide customers more value for their money, and remain more competitive in a business with razor-thin margins. Aldi's lean philosophy extends into the supply chain as well. Up to 60 percent of its fruits and vegetables are sourced locally to save on transportation costs and time. As part of its inventory reduction policies, suppliers are not allowed to hold more than 1 month of normal orders and requirements of Aldi's private label products in inventory at any given point of time, unless Aldi submits a written authorization for a temporary or permanent change in suppliers' inventory levels. Consequently, Aldi's products can be as much as 30 percent cheaper than its competitors in some cases. Due to its relentless focus on lean principles, it is no wonder that Aldi is a clear leader in prices among leading grocery brands.

Thus far in the text, we have discussed many ways to improve manufacturing and service processes. We take that further in this chapter by showing how process improvement techniques can be used to make a firm lean by first discussing the continuous improvement aspect of lean systems, followed by a discussion of the characteristics of lean systems, and the design of layouts needed to achieve these characteristics. We also address different types of lean systems used in practice and some of the implementation issues that companies face.





Joe Seer/Shutterstock

Aldi Store grand opening on June 16, 2016 in Simi Valley, California. Aldi is a low price grocery outlet that is rapidly expanding in the USA.

Continuous Improvement Using a Lean Systems Approach

just-in-time (JIT) system

The JIT system is a key foundation of a lean system, and represents a collection of practices that eliminate waste, or *muda*, by cutting excess capacity or inventory and removing nonvalue-added activities.

One of the most popular systems that incorporate the generic elements of lean systems is the just-in-time (JIT) system. According to Taiichi Ohno, one of the earlier pioneers at Toyota Corporation, the **just-in-time (JIT) system** is a key foundation of lean systems, and represents a collection of practices that eliminate waste, or *muda*, by cutting excess capacity or inventory and removing nonvalue-added activities. Even though traditionally only seven types of waste have been discussed in the literature,[2] based on current management thinking we have added an eighth type that focuses on underutilization of employees. Table 4.1 shows the eight types of waste that often occur in firms in an interrelated fashion and that must be significantly reduced or eliminated in implementing lean systems.

TABLE 4.1 | THE EIGHT TYPES OF WASTE, OR *MUDA*

Waste	Definition
1. Overproduction	Manufacturing an item before it is needed, making it difficult to detect defects and creating excessive lead times and inventory.
2. Inappropriate Processing	Using expensive high-precision equipment when simpler machines would suffice. It leads to overutilization of expensive capital assets. Investment in smaller flexible equipment, immaculately maintained older machines, and combining process steps where appropriate reduce the waste associated with inappropriate processing.
3. Waiting	Unbalanced workstations make operators lose time, because if a process step takes longer than the next, then the operators will either stand idly waiting, or they will be performing their tasks at a speed that makes it appear that they have work to complete. Operators can also be waiting when a previous process step breaks down, has quality issues, lacks certain parts or information, or has a long changeover.
4. Transportation	Excessive movement and material handling of product between processes, which can cause damage and deterioration of product quality without adding any significant customer value.
5. Motion	Unnecessary effort related to the ergonomics of bending, stretching, reaching, lifting, and walking. Jobs with excessive motion should be redesigned.
6. Inventory	Excess inventory hides problems on the shop floor, consumes space, increases lead times, and inhibits communication. Work-in-process inventory is a direct result of overproduction and waiting.
7. Defects	Quality defects result in rework and scrap and add wasteful costs to the system in the form of lost capacity, rescheduling effort, increased inspection, and loss of customer goodwill.
8. Underutilization of Employees	Failure of the firm to learn from and capitalize on its employees' knowledge and creativity impedes long-term efforts to eliminate waste.

The goals of a lean system are thus to eliminate these eight types of waste, produce services and products only as needed, and to continuously improve the value-added benefits of operations. Identifying and removing waste can help an organization in multiple ways, while an inability to do so can hurt its financial performance, as illustrated by the following Managerial Challenge in a health care setting.

MANAGERIAL CHALLENGE Finance

Oak Grove Health is a major hospital system with a level 1 trauma center that provides the highest level of trauma care to critically ill or injured patients. In an ever changing health care landscape following the passage of the Affordable Care Act in March 2010, there has been a renewed focus on patient care and satisfaction coupled with a focus on cost reduction and efficiencies. In a recent upper management meeting, CEO Don Ramsey discussed Oak Grove's financial performance and noted that while patient care metrics were holding steady, cost per patient was rising far faster than at similar benchmark hospitals. In addition, revenues had declined in spite of high patient demand and backlogs. He charged Susan Richardson, the VP of finance, to take a closer look at this issue and identify specific opportunities where cost savings can be achieved without compromising patient care or investments in new technologies and nurses' training, both of which are considered essential for Oak Grove to remain competitive.

[2]David McBride, "The Seven Manufacturing Wastes," August 29, 2003, http://www.emsstrategies.com/dm090203article2.html.

Susan formed three task forces to better understand and eliminate waste from staffing, hospital operations, and administrative services, respectively. Albert Pinto had the most complex assignment as the leader of the hospital operations task force. He decided to focus initially on the surgical unit, hoping to apply the lessons learned there to other major units within hospital operations. He tracked patient flows through the different stages: the patient being registered and scheduled at the front desk, pre-operative care, the actual surgery itself, recovery in an intensive care unit (ICU), further stay in a general medical unit, and discharge. Variability in the arrival rates of patients and uneven utilization of facilities in each of these stages resulted in longer wait times, which in turn drove higher operating costs because reimbursements were based on curing the specific patient condition and not on patient length of stay. After collecting additional data, he also found that due to the limited number of beds in the ICU and the shortage of nurses, patients could not be moved out as quickly, and this backed up the operating rooms. As a result, surgeons sat idle and performed a lower number of procedures in a given month than the actual demand, leading to loss of both revenue and patient experience.

Four years ago, Oak Grove had acquired Piedmont Hospital located 3 miles away, and had already completed the operational integration. Yet, Albert learned that the automated carousel system used for storing and dispensing expensive surgery and anesthesia-related drugs operated independently at each hospital instead of working in a coordinated fashion. This resulted in large financially wasteful investments at both hospitals, when the drugs could be more readily shared between them, given the locational proximity. Depending upon the patient mix and caseload, independent procurement and storage of drugs at each location led to shortages at one hospital and excess availability at the other. Unfortunately, further analysis showed that this problem extended to other units such as cardiology, neurology, pediatrics, and oncology as well, leading Albert to wonder if there were interconnected systems of wasteful practices across multiple units. He clearly needed to drill deeper to learn the root causes behind different types of wastes that were occurring in Oak Grove's hospital operations, and how to identify and eliminate them. Concepts and techniques illustrated in the rest of this chapter can help Albert drive the kind of financial savings that Susan had requested him to find and implement.

By spotlighting areas that need improvement, lean systems lead to continuous improvement in quality and productivity. The Japanese term for this approach to process improvement is *kaizen*. The key to kaizen is the understanding that excess capacity or inventory hides underlying problems with the processes that produce a service or product. Lean systems provide the mechanism for management to reveal the problems by systematically lowering capacities or inventories until the problems are exposed. For example, Figure 4.1 characterizes the philosophy behind continuous improvement with lean systems. In services, the water surface represents service system capacity, such as staff levels. In manufacturing, the water surface represents product and component inventory levels. The rocks represent problems encountered in the fulfillment of services or products. When the water surface is high enough, the boat passes over the rocks because the high level of capacity or inventory covers up problems. As capacity or inventory shrinks, rocks are exposed. Ultimately, the boat will hit a rock if the water surface falls far enough. Through lean systems, workers, supervisors, engineers, and analysts apply methods for continuous improvement to demolish the exposed rock. The coordination required to achieve smooth material flows in lean systems identifies problems in time for corrective action to be taken.



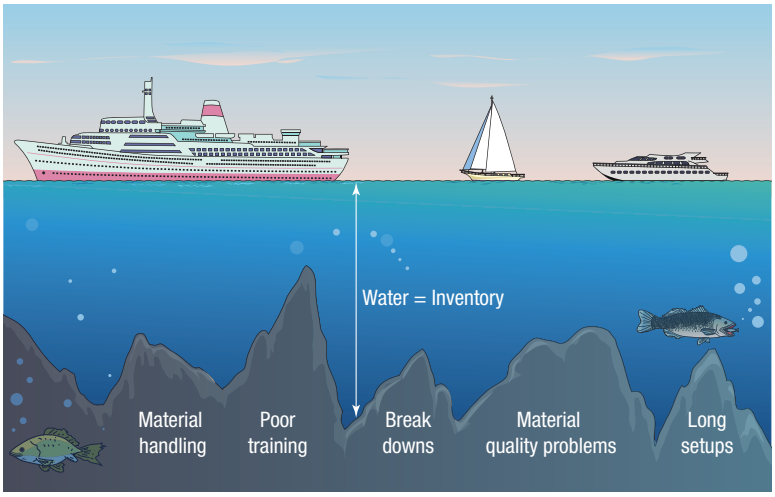
Jon G. Fuller, Jr./Jon G. Fuller/VWPics/Newscom

Workers sewing and assembling soft guitar cases at the Taylor Guitar factory in Tecate, Baja California, Mexico.

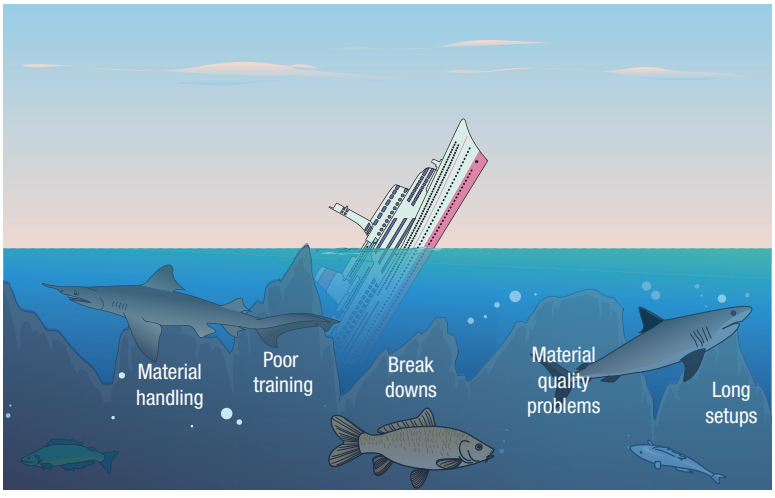
Maintaining low inventories, periodically stressing the system to identify problems, and focusing on the elements of the lean system lie at the heart of continuous improvement. For example, the plant may periodically cut its safety stocks almost to zero. The problems at the plant are exposed, recorded, and later assigned to employees as improvement projects. After improvements are made, inventories are permanently cut to the new level. Many firms use this trial-and-error process to develop more efficient manufacturing operations. In addition, workers using special presses often fabricate parts on the assembly line in exactly the quantities

The role of inventory in Traditional and JIT systems: The water and the rocks metaphor

Traditional systems use inventory (water) to buffer the process from problems (rocks) that cause disruption.



JIT systems view inventory as waste and work to lower inventory levels to expose and correct the problems (rocks) that cause disruption. However, the problems that arise must be corrected quickly. Otherwise, without the decoupling inventory, the process will flounder.



▲ **FIGURE 4.1**
Continuous Improvement with Lean Systems

needed. Service processes, such as scheduling, billing, order taking, accounting, and financial planning, can be improved with lean systems, too. In service operations, a common approach used by managers is to place stress on the system by reducing the number of employees doing a particular activity or series of activities until the process begins to slow or come to a halt. The problems can be identified, and ways for overcoming them explored. Other kaizen tactics can be used as well. Eliminating the problem of too much scrap might require improving the firm's work processes, providing employees with additional training, or finding higher quality suppliers. Eliminating capacity imbalances might involve revising the firm's master production schedule and improving the flexibility of its workforce. Irrespective of which problem is solved, there are always new ones that can be addressed to enhance system performance.

Often, continuous improvement occurs with the ongoing involvement and input of new ideas from employees, who play an important role in implementing the JIT philosophy. In one year alone, about 740,000 corporate-wide improvement suggestions were received at Toyota. A large majority of them got implemented, and employees making those suggestions received rewards ranging from 500 yen (about $5) to upwards of 50,000 yen (about $500) depending upon their bottom-line impact.

Strategic Characteristics of Lean Systems

The philosophy of lean systems, applicable at the process level, is also applicable at the supply chain level. Factors, both within and outside the firm, arising from supply chain and process considerations that have an important impact in creating and implementing lean systems, are discussed next in this section.

Supply Chain Considerations in Lean Systems

In this section, we discuss the two salient characteristics of lean systems that are related to creating and managing material flows in a supply chain: close supplier ties and small lot sizes.

Close Supplier Ties Because lean systems operate with low levels of capacity slack or inventory, firms that use them need to have a close relationship with their suppliers. Supplies must be shipped frequently, have short lead times, arrive on schedule, and be of high quality. A contract might even require a supplier to deliver goods to a facility as often as several times per day.

The lean system philosophy is to look for ways to improve efficiency and reduce inventories throughout the supply chain. Close cooperation between companies and their suppliers can be a win–win situation for everyone. Better communication of component requirements, for example, enables more efficient inventory planning and delivery scheduling by suppliers, thereby improving supplier profit margins. Customers can then negotiate lower component prices. Close supplier relations cannot be established and maintained if companies view their suppliers as adversaries whenever contracts are negotiated. Rather, they should consider suppliers to be partners in a venture, wherein both parties have an interest in maintaining a long-term, profitable relationship. Consequently, one of the first actions undertaken when a lean system is implemented is to pare down the number of suppliers, and make sure they are located in close geographic proximity to promote strong partnerships and better synchronize product flows.

A particularly close form of supplier partnerships through lean systems is the JIT II system, which was conceived and implemented by Bose Corporation, a producer of high-quality professional sound and speaker systems. In a JIT II system, also called *vendor-managed inventories*, the supplier is brought into the plant to be an active member of the purchasing office of the customer. The in-plant representative is onsite full time at the supplier's expense and is empowered to plan and schedule the replenishment of materials from the supplier. Thus, JIT II fosters extremely close interaction with suppliers. The qualifications for a supplier to be included in the program are stringent.

In general, JIT II can offer benefits to both buyers and suppliers because it provides the organizational structure needed to improve supplier coordination by integrating the logistics, production, and purchasing processes together. We have more to say about supplier relationships and vendor-managed inventories in Chapter 14, "Supply Chain Integration."

Small Lot Sizes Lean systems use lot sizes that are as small as possible. A **lot** is a quantity of items that are processed together. Small lots have the advantage of reducing the average level of inventory relative to large lots. Small lots pass through the system faster than large lots, since they do not keep materials waiting. In addition, if any defective items are discovered, large lots cause longer delays because the entire lot must be examined to find all the items that need rework. Finally, small lots help achieve a uniform workload on the system and prevent overproduction. Large lots consume large chunks of capacity at workstations and, therefore, complicate scheduling. Small lots can be juggled more effectively, enabling schedulers to efficiently utilize capacities.

lot
A quantity of items that are processed together.

Although small lots are beneficial to operations, they have the disadvantage of increased setup frequency. A setup is the group of activities needed to change or readjust a process between successive lots of items, sometimes referred to as a changeover. This changeover in itself is a process that can be made more efficient. Setups involve trial runs, and the material waste can be substantial as the machines are fine-tuned for the new parts. Typically, a setup takes the same time regardless of the size of the lot. Consequently, many small lots, in lieu of several large lots, may result in waste in the form of idle employees, equipment, and materials. Setup times must be brief to realize the benefits of small-lot production.

Achieving brief setup times often requires close cooperation among engineering, management, and labor. For example, changing dies on large presses to form automobile parts from sheet metal can take 3 to 4 hours. At Honda's Marysville, Ohio, plant—where four stamping lines stamp all the exterior and major interior body panels for Accord production—teams worked on ways to reduce the changeover time for the massive dies. As a result, a complete change of dies for a giant 2,400-ton press now takes less than 8 minutes. The goal of **single-digit setup** means having setup times of less than 10 minutes. Some techniques used to reduce setup times at the Marysville plant include using conveyors for die storage, moving large dies with cranes, simplifying dies, enacting machine controls, using microcomputers to automatically feed and position work, and preparing for changeovers while a job currently in production is still being processed.

single-digit setup
The goal of having a setup time of less than 10 minutes.

pull method
A method in which customer demand activates production of the service or item.

push method
A method in which production of the item begins in advance of customer needs.

Process Considerations in Lean Systems

In this section, we discuss the following characteristics of lean systems: pull method of workflow, quality at the source, uniform workstation loads, standardized components and work methods, flexible workforce, automation, Five S (5S) practices, and total productive (or preventive) maintenance (TPM).

Pull Method of Workflow Managers have a choice as to the nature of the material flows in a process or supply chain. Most firms using lean operations use the **pull method**, in which customer demand activates the production of a good or service. In contrast, a method often used in conventional systems that do not emphasize lean systems is the **push method**, which involves using forecasts of demand and producing the item before the customer orders it. To differentiate between these two methods, let us use a service example that involves a favorite pastime, eating.



Paula Solloway/Alamy Stock Photo

A diner at a Chinese restaurant buffet. Because the food items must be prepared in advance, the restaurant uses a push method of workflow.

For an illustration of the pull method, consider a five-star restaurant in which you are seated at a table and offered a menu of exquisite dishes, appetizers, soups, salads, and desserts. You can choose from filet mignon, porterhouse steak, yellow fin tuna, eggplant parmesan, grouper, and lamb chops. Your choice of several salads is prepared at your table. Although some appetizers, soups, and desserts can be prepared in advance and brought to temperature just before serving, the main course and salads cannot. Your order for the salad and the main course signals the chef to begin preparing your specific requests. For these items, the restaurant is using the pull method. Firms using the pull method must be able to fulfill the customer's demands within an acceptable amount of time.

For an understanding of the push method, consider a cafeteria on a busy downtown corner. During the busy periods around 12 P.M. and 5 P.M. lines develop, with hungry patrons eager to eat and then move on to other activities. The cafeteria offers choices of chicken (roasted or deep fried), roast beef, pork chops, hamburgers, hot dogs, salad, soup (chicken, pea, and clam chowder), bread (three types), beverages, and desserts (pies, ice cream, and cookies). Close coordination is required between the cafeteria's "front office," where its employees interface with customers, and its "back office," the kitchen, where the food is prepared and then placed along the cafeteria's buffet line. Because it takes substantial time to cook some of the food items, the cafeteria uses a push method. The cafeteria would have a difficult time using the pull method because it could not wait until a customer asked for an item before asking the kitchen to begin processing it. After all, shortages in food could cause riotous conditions (recall that customers are hungry), whereas preparing an excess amount of food will be wasteful because it will go uneaten. To make sure that neither of these conditions occurs, the cafeteria must accurately forecast the number of customers it expects to serve. A Chinese restaurant buffet (as shown on the previous page) would similarly follow a push method for serving its customers.

The choice between the push and pull methods is often situational. Firms using an assemble-to-order strategy sometimes use both methods: the push method to produce the standardized components, and the pull method to fulfill the customer's request for a particular combination of the components.

Quality at the Source Consistently meeting the customer's expectations is an important characteristic of lean systems. One way to achieve this goal is by adhering to a practice called quality at the source, which is a philosophy whereby defects are caught and corrected where they are created. The goal for workers is to act as their own quality inspectors and never pass on defective units to the next process. Automatically stopping the process when something is wrong and then fixing the problems on the line itself as they occur is also known as **jidoka**. Jidoka tends to separate worker and machine activities by freeing workers from tending to machines all the time, thus allowing them to staff multiple operations simultaneously. Jidoka represents a visual management system whereby status of the system in terms of safety, quality, delivery, and cost performance relative to the goals for a given fabrication cell or workstation in an assembly line is clearly visible to workers on the floor at all times.

jidoka
Automatically stopping the process when something is wrong and then fixing the problems on the line itself as they occur.

poka-yoke
Mistake-proofing methods aimed at designing fail-safe systems that minimize human error.

An alternative to jidoka or quality at the source is the traditional practice of pushing problems down the line to be resolved later. This approach is often ineffective. For example, a soldering operation at the Texas Instruments antenna department had a defect rate that varied from 0 to 50 percent on a daily basis, averaging about 20 percent. To compensate, production planners increased the lot sizes, which only increased inventory levels and did nothing to reduce the number of defective items. The company's engineers then discovered through experimentation that gas temperature was a critical variable in producing defect-free items. They subsequently devised statistical control charts for the firm's equipment operators to use to monitor the temperature and adjust it themselves. Process yields immediately improved and stabilized at 95 percent, and Texas Instruments was eventually able to implement a lean system.



Tropper2000/Shutterstock

An example of poka-yoke is the design of new fuel doors in automobiles. They are mistake-proof, since the filling pipe insert keeps larger, leaded-fuel nozzles from being inserted. In addition, a gas cap tether does not allow the motorist to drive off without the cap, and is also fitted with a ratchet to signal proper tightness and prevent over-tightening.

One successful approach for implementing quality at the source is to use **poka-yoke**, or mistake-proofing methods aimed at designing fail-safe systems that attack and minimize human error. Poka-yoke systems work well in practice. Consider, for instance, a company that makes modular products. The company could use the poka-yoke method by making different parts of the modular product in such a way that allows them to be assembled in only one way—the correct way. Similarly, a company's shipping boxes could be designed to be packed only in a certain way to minimize damage and eliminate

all chances of mistakes. At Toyota plants, every vehicle being assembled is accompanied by an RFID chip containing information on how many nuts and bolts need to be tightened on that vehicle for an operation at a given workstation. A green light comes on when the right numbers of nuts have been tightened. Only then does the vehicle move forward on the assembly line.

Another tool for implementing quality at the source is *andon*, which is a system that gives machines and machine operators the ability to signal the occurrence of any abnormal condition, such as tool malfunction, shortage of parts, or the product being made outside the desired specifications. It can take the form of audio alarms, blinking lights, LCD text displays, or cords that can be pulled by workers to ask for help or stop the production line if needed. Stopping a production line can, however, cost a company thousands of dollars each minute production is halted. Management must realize the enormous responsibility this method puts on employees and must prepare them properly.

Building quality at the source and eliminating waste resulting from poor quality also requires the application of several quality tools, as discussed in Chapter 3. Alcoa in Managerial Practice 4.1 illustrates how it achieved leaner systems by utilizing process improvement tools and continuous improvement to build quality at the source.

MANAGERIAL PRACTICE 4.1 Alcoa

Alcoa is the world's eighth largest aluminum company by revenue, with operations in 10 countries and 13,800 employees globally. It was founded in 1888 by Charles Martin, who discovered a way to produce aluminum through electrolysis that drastically reduced production cost. Alcoa has operated for over 132 years as a vertically integrated company that is engaged in mining businesses as well as in fabricating a diverse set of products ranging from aluminum foils to aerospace alloys. In 2016, Alcoa separated its mining/refining/smelting and power businesses (retaining the name Alcoa) from its fabrication businesses (which are now known as Arconic).

In 2011, management identified that the current production processes were yielding significant amounts of scrap and rework due to product defects. From a lean systems perspective, defects are a form of *muda*, or waste, which represents a deviation from the optimal allocation of resources. Defects in processes in turn led to high levels of customer complaints and poor delivery performance. To identify the root cause, Alcoa formed a process improvement team, which included engineering process owners, business unit and site managers, operations personnel, and quality staff. In addition, Alcoa involved the business unit's customers as external stakeholders to incorporate the voice of customers in the processes' improvement project. The goal of the project was to build quality at the source, and develop a sustainable method to gradually reduce defects by 10 percent over a 3-year period.

Using various tools such as Pareto charts, cause-and-effect diagrams, and data analysis, the process improvement team was able to narrow the scope of the project to focus on wax, shell, and cast manufacturing operations at nine selected locations. The team developed a three-staged approach to replace the previous processes. First, a new process was developed and implemented in a small number of pilot plants. Next, the process was transferred to fast-follower plants that were already well positioned for making changes, and finally, the new process was shared at the broad business unit level. There were significant benefits to implementing the new process using a staged diffusion approach. For example, one of the pilot stage plants implemented a new casting/mold wrap process and demonstrated a 30 percent reduction in related scrap in 3 months. In the subsequent fast-follower plants, this process was implemented to yield the same benefits. However, the implementation time was significantly reduced to 30 days. To overcome employee resistance to process change, the company conducted routine team-building meetings and shared monthly process audit information. Involving employees at the plant floor level in the process improvement project also helped them to prioritize activities, and to participate in several *kaizen* (continuous improvement) events.



Sean Gallup/Getty Images

Workers walk by finished forged aluminum truck wheels at the Alcoa aluminum factory October 24, 2006 in Szekesefehervar, Hungary. Alcoa bought the factory, once one of the main suppliers of semi-finished aluminum in the former East Bloc, in 1993.

Alcoa experienced drastic benefits from cost savings due to the lean process implementation project. For example, one of the plants was able to reduce 77 percent of the wax expenses, which resulted in annual savings of $38,000. In another plant, improvement in the shell weight control process yielded an annual savings of $400,000. The new lean process lowered scrap rates, reduced rework activities that are another form of *muda*, and reduced customer returns. This improvement led to more on-time deliveries and higher customer satisfaction. Another side benefit from the project was the accumulation of workers' organizational knowledge, which strengthened their belief that preventive and proactive improvements on a regular basis minimize the time spent managing problems and fighting fires.[3]

[3] *Sources:* J. Jacobsen, "Process Management Approach Reduces Scrap, Saves Alcoa Millions." http://asq.org/2016/05/process-management/approach-reduces-scrap-saves-alcoa-millions.pdf (May 2016); History of Alcoa. https://www.alcoa.com/global/en/who-we-are/history (July 27, 2020); https://en.wikipedia.org/wiki/Alcoa (July 27, 2020); https://investors.alcoa.com/~/media/Files/A/Alcoa-IR/documents/annual-reports-and-proxy-information/alcoa-annual-report-2019.pdf (July 29, 2020).

Uniform Workstation Loads A lean system works best if the daily load on individual workstations is relatively uniform. Service processes can achieve uniform workstation loads by using reservation systems. For example, hospitals schedule surgeries in advance of the actual service so that the facilities and facilitating goods can be ready when the time comes. The load on the surgery rooms and surgeons can be evened out to make the best use of these resources. Another approach is to use differential pricing of the service to manage the demand for it. Uniform loads are the rationale behind airlines promoting weekend travel or red-eye flights that begin late in the day and end in the early morning. Efficiencies can be realized when the load on the firm's resources can be managed.

For manufacturing processes, uniform loads can be achieved by assembling the same type and number of units each day, thus creating a uniform daily demand at all workstations. Capacity planning, which recognizes capacity constraints at critical workstations, and line balancing are used to develop the master production schedule. For example, at Toyota's plant the production plan may call for 4,500 vehicles per week for the next month. That requires two full shifts, 5 days per week, producing 900 vehicles each day, or 450 per shift. Three models are produced: Camry (C), Avalon (A), and Highlander (H). Suppose that Toyota needs 200 Camrys, 150 Avalons, and 100 Highlanders per shift to satisfy market demand. To produce 450 units in one shift of 480 minutes, the line must roll out a vehicle every 480/450 = 1.067 minutes. The 1.067 minutes, or 64 seconds, represents the **takt time** of the process, defined as the cycle time needed to match the rate of production to the rate of sales or consumption.

takt time
Cycle time needed to match the rate of production to the rate of sales or consumption.

With traditional big-lot production, all daily requirements of a model are produced in one batch before another model is started. The sequence of 200 Cs, 150 As, and 100 Hs would be repeated once per shift. Not only would these big lots increase the average inventory level, but they also would cause lumpy requirements on all the workstations feeding the assembly line.

But there are two other options for devising a production schedule for the vehicles. These options are based on the Japanese concept of **heijunka**, which is the leveling of production load by both volume and product mix. It does not build products according to the actual flow of customer orders but levels out the total volume of orders in a period so that the same amount and mix are being made each day.[4]

heijunka
The leveling of production load by both volume and product mix.

Let us explore two possible heijunka options. The first option uses leveled **mixed-model assembly**, producing a mix of models in smaller lots. Note that the production requirements at Toyota are in the ratio of 4 Cs to 3 As to 2 Hs, found by dividing the model's production requirements by the greatest common divisor, or 50. Thus, the Toyota planner could develop a production cycle consisting of 9 units: 4 Cs, 3 As, and 2 Hs. The cycle would repeat in 9(1.067) = 9.60 minutes, for a total of 50 times per shift (480 min/9.60 min = 50).

mixed-model assembly
A type of assembly that produces a mix of models in smaller lots.

The second heijunka option uses a lot size of one, such as the production sequence of C–H–C–A–C–A–C–H–A repeated 50 times per shift. The sequence would achieve the same total output as the other options; however, it is feasible only if the setup times are brief. The sequence generates a steady rate of component requirements for the various models and allows the use of small lot sizes at the feeder workstations. Consequently, the capacity requirements at those stations are greatly smoothed. These requirements can be compared to actual capacities during the planning phase, and modifications to the production cycle, production requirements, or capacities can be made as necessary.

Standardized Components and Work Methods In highly repetitive service operations, analyzing work methods and documenting the improvements to use can gain great efficiencies. For example, UPS consistently monitors its work methods, from sorting packages to delivering them, and revises them as necessary to improve service. In manufacturing, the standardization of components increases the total quantity that must be produced for that component. For example, a firm producing 10 products from 1,000 different components could redesign its products so that they consist of only 100 different components with larger daily requirements. Because the requirements per component increase, each worker performs a standardized task or work method more often each day. Productivity tends to increase because workers learn to do their tasks more efficiently with increased repetition. Standardizing components and work methods help a firm achieve the high-productivity, low-inventory objectives of a lean system.

Flexible Workforce The role of workers is elevated in lean systems. Workers in flexible workforces can be trained to perform more than one job. A benefit of flexibility is the ability to shift workers among workstations to help relieve bottlenecks as they arise without the need for inventory buffers—an important aspect of the uniform flow of lean systems. Also, workers can step in and do the job for those who are on vacation or who are out sick. Although assigning workers to tasks they do not usually perform can temporarily reduce their efficiency, some job rotation tends to relieve boredom and refreshes workers. At some firms that have implemented lean systems, cross-trained workers may switch jobs every 2 hours.

The more customized the service or product is, the greater the firm's need for a multiskilled workforce. For example, stereo repair shops require broadly trained personnel who can identify a wide

[4]David McBride, "Heijunka, Leveling the Load" (September 1, 2004), a www.emsstrategies.com.

variety of component problems when the customer brings the defective unit into the shop and who then can repair the unit. Alternatively, back-office designs, such as the mail-processing operations at a large post office, have employees with more narrowly defined jobs because of the repetitive nature of the tasks they must perform. These employees do not have to acquire as many alternative skills. In some situations, shifting workers to other jobs may require them to undergo extensive, costly training.



Hagai Nativ/Alamy Stock Photo

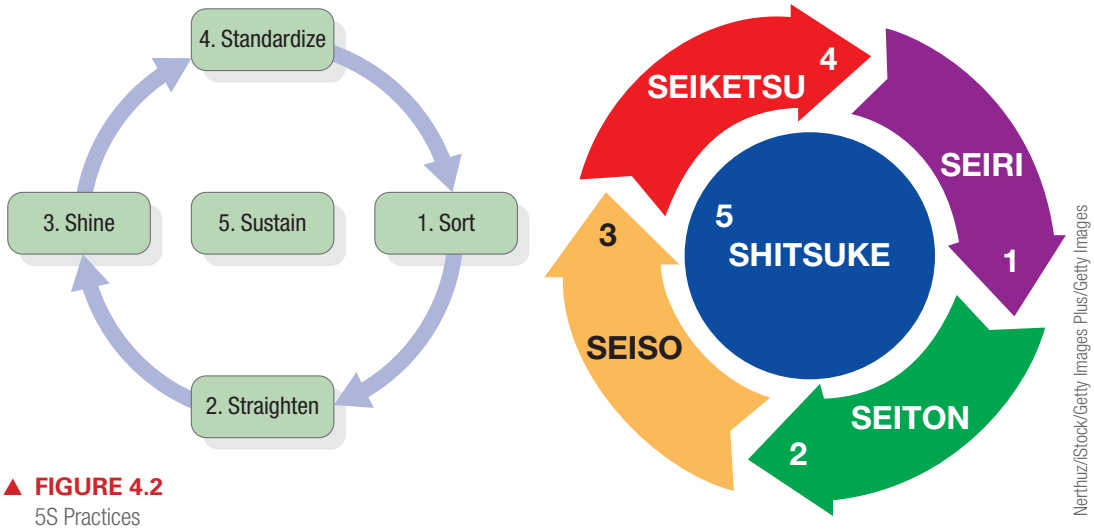
Computerized Avocado sorting and packing plant in Israel shows that automation can occur in many different settings.

Automation Automation plays a big role in lean systems and is a key to low-cost operations. Money freed up because of inventory reductions or other efficiencies can be invested in automation to reduce costs. The benefits, of course, are greater profits, greater market share (because prices can be cut), or both. Automation can play a big role when it comes to providing lean services. For example, banks offer ATMs that provide various bank services on demand 24 hours a day. Automation should be planned carefully, however. Many managers believe that if some automation is good, more is better, which is not always the case. At times, humans can do jobs better than robots and automated assembly systems. In other instances, especially when production volumes are high, automation can result in higher quality, precision, and productivity.

Five S Practices **Five S (5S)** is a methodology for organizing, cleaning, developing, and sustaining a productive work environment. It represents five related terms, each beginning with an S, that describe workplace practices conducive to visual controls and lean production. As shown in Figure 4.2, these five practices of sort, straighten, shine, standardize, and sustain build upon one another and are done systematically to achieve lean systems. These practices are interconnected and are not something that can be done as a stand-alone program. As such, they serve as an enabler and an essential foundation of lean systems. Table 4.2 shows the terms that represent the 5S and what they imply.

Five S (5S)
A methodology consisting of five workplace practices—sorting, straightening, shining, standardizing, and sustaining—that are conducive to visual controls and lean production.

It is commonly accepted that 5S forms an important cornerstone of waste reduction and removal of unneeded tasks, activities, and materials. 5S practices can enable workers to visually see everything differently, prioritize tasks, and achieve a greater degree of focus. They can also be applied to a diverse range of manufacturing and service settings, including organizing work spaces, offices, tool rooms, shop floors, and the like. Implementation of 5S practices has been shown to lead to lowered costs, improved on-time delivery and productivity, higher product quality, better use of floor space, and a safe working environment. It also builds the discipline needed to make the lean systems work well.



Nerthuz/iStock/Getty Images Plus/Getty Images

▲ **FIGURE 4.2**
5S Practices

Total Productive Maintenance Because lean systems emphasize finely tuned flows of work and little capacity slack or buffer inventory between workstations, unplanned machine downtime can be disruptive. Total productive maintenance (TPM), which is also sometimes referred to as total *preventive* maintenance, can reduce the frequency and duration of machine downtime. After performing

TABLE 4.2 | 5S DEFINED

5S Term	Definition
1. Sort	Separate needed items from unneeded items (including tools, parts, materials, and paperwork) and discard the unneeded.
2. Straighten	Neatly arrange what is left, with a place for everything and everything in its place. Organize the work area so that it is easy to find what is needed.
3. Shine	Clean and wash the work area and make it shine.
4. Standardize	Establish schedules and methods of performing the cleaning and sorting. Formalize the cleanliness that results from regularly doing the first three S practices so that perpetual cleanliness and a state of readiness are maintained.
5. Sustain	Create discipline to perform the first four S practices, whereby everyone understands, obeys, and practices the rules when in the plant. Implement mechanisms to sustain the gains by involving people and recognizing them through a performance measurement system.

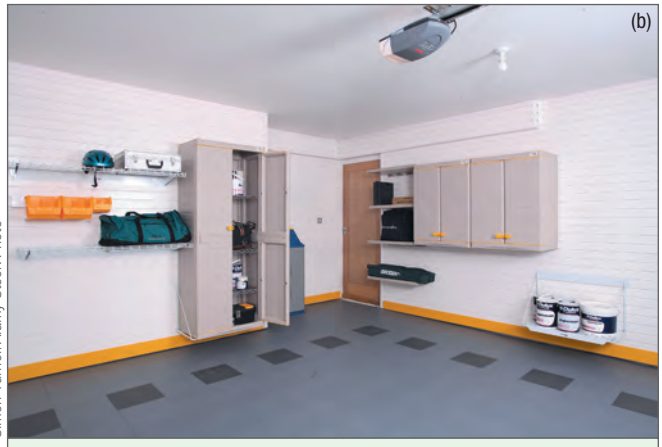
their routine maintenance activities, technicians can test other machine parts that might need to be replaced. Replacing parts during regularly scheduled maintenance periods is easier and quicker than dealing with machine failures during production. Maintenance is done on a schedule that balances the cost of the preventive maintenance program against the risks and costs of machine failure. Routine preventive maintenance is important for service businesses that rely heavily on machinery, such as the rides at Walt Disney World or Universal Studios.

Another tactic is to make workers responsible for routinely maintaining their own equipment, which will develop employee pride in keeping the machines in top condition. This tactic, however, typically is limited to general housekeeping chores, minor lubrication, and adjustments. Maintaining high-tech machines requires trained specialists. Nonetheless, performing even simple maintenance tasks goes a long way toward improving the performance of machines.

For long-term improvements, data can be collected for establishing trends in the failure pattern of machines, which can subsequently be analyzed to establish better standards and procedures for preventive maintenance. The data can also provide failure history and costs incurred to maintain the systems.



Tetra Images, LLC/Alamy Stock Photo



Simon Turner/Alamy Stock Photo

(a) Messy garage filled with toys and sporting equipment, before 5S is applied and new storage is placed. (b) A domestic double garage after the 5S process and fitted out with system-based storage – incorporating shelving, cupboards, work bench and racking.

Toyota Production System

If you were to select one company that regularly invokes the abovementioned features of lean systems and also exemplifies excellence in automobile manufacturing, it would probably be Toyota. Despite its problems with quality and product recalls in 2014, as well as component shortages and delayed new model launches caused by the Great East Japan Earthquake in March 2011, Toyota has become one of the largest car manufacturers in the world, with 11 manufacturing plants in North America alone. Much of this success is attributed to the famed Toyota Production System (TPS), which is one of the most admired lean manufacturing systems in existence. Replicating the system, however, is fraught with difficulties. What makes the system tick, and why has Toyota been able to use it so successfully in many different plants?

Most outsiders see the TPS as a set of tools and procedures that are readily visible during a plant tour. Even though they are important for the success of the TPS, they are not the key. What most people overlook is that through the process of continuous improvement, Toyota built a learning organization over the course of 50 years. Lean systems require constant improvements to increase efficiency and reduce waste. Toyota's system stimulates employees to experiment to find better ways to do their jobs. In fact, Toyota sets up all of its operations as "experiments" and teaches employees at all levels how to use the scientific method of problem solving.

Four principles form the basis of the TPS. First, all work must be completely specified as to content, sequence, timing,

and outcome. Detail is important; otherwise, a foundation for improvements is missing. Second, every customer–supplier connection must be direct, unambiguously specifying the people involved, the form and quantity of the services or goods to be provided, the way the requests are made by each customer, and the expected time in which the requests will be met. Customer–supplier connections can be internal (employee to employee) or external (company to company). Third, the pathway for every service and product must be simple and direct. That is, services and goods do not flow to the next available person or machine but to a specific person or machine. With this principle, employees can determine, for example, whether a capacity problem exists at a particular workstation and then analyze ways to solve it.

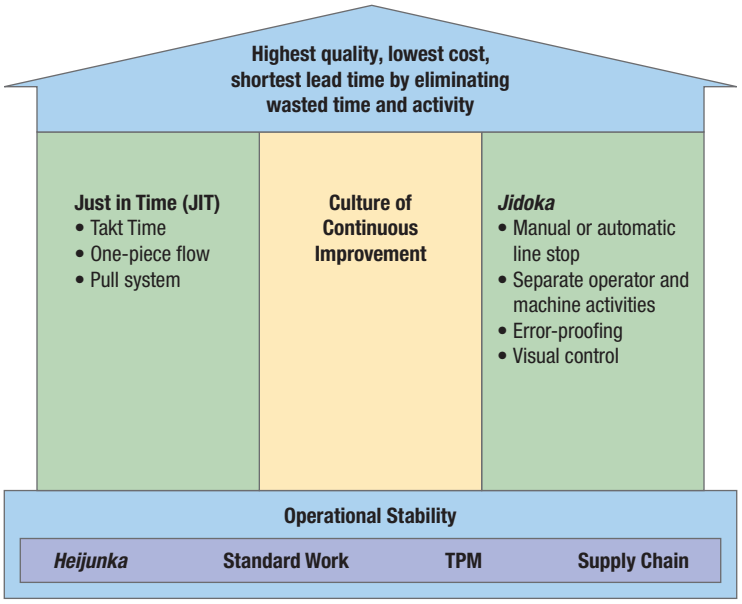


ITAR-TASS Photo Agency/Alamy Stock Photo

Workers on a Toyota Camry assembly line in a Toyota car factory in St. Petersburg, Russia.

The first three principles define the system in detail by specifying how employees do work and interact with each other and how the workflows are designed. However, these specifications actually are "hypotheses" about the way the system should work. For example, if something goes wrong at a workstation enough times, the hypothesis about the methods the employee uses to do work is rejected. The fourth principle, then, is that any improvement to the system must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible organizational level. These four principles are deceptively simple. However, they are difficult but not impossible to replicate. Those organizations that successfully implement them enjoy the benefits of a lean system that adapts to change. Toyota's lean system made it an innovative leader in the auto industry and served as an important cornerstone of its success.

House of Toyota Taiichi Ohno and Eiji Toyoda created a graphic representation (Figure 4.3) to define the TPS to its employees and suppliers, and which is now known as the House of Toyota. It captures the four principles of TPS described earlier, and represents all the essential elements of lean systems that make the TPS work well. The house conveys stability. The twin pillars of JIT and jidoka support the roof, representing the primary goals of high quality, low cost, waste elimination, and short lead times. Within JIT, TPS uses a pull system that focuses on one-piece workflow methods that can change and match the takt time of the process to the actual market demand, because setup reductions and small changeover times are facilitated by cross-trained workers in cellular layouts. Implementing various tools of jidoka ensures that quality is built into the product rather than merely inspected at the end. Finally, within an environment of continuous improvement, operational stability to the House of Toyota is provided at the base by leveraging other lean concepts such as heijunka, standard work methods, 5S practices, total preventive maintenance, and elimination of waste throughout the supply chain within which the Toyota products flow to reach their eventual customers.



▲ **FIGURE 4.3**
House of Toyota

Designing Lean System Layouts

Line flows are recommended in designing lean system layouts because they eliminate waste by reducing the frequency of setups. If volumes of specific products are large enough, groups of machines and workers can be organized into a line-flow layout to eliminate setups entirely. In a service setting, managers of back-office service processes can similarly organize their employees and equipment to provide uniform workflows through the process and, thereby, eliminate wasted employee time. Banks use this strategy in their check-processing operations, as does UPS in its parcel-sorting process.

When volumes are not high enough to justify dedicating a single line of multiple workers to a single customer type or product, managers still may be able to derive the benefits of line-flow layout—simpler materials handling, low setups, and reduced labor costs—by creating line-flow layouts in some portions of the facility. Two techniques for creating such layouts are one-worker, multiple-machines (OWMM) cells and group technology (GT) cells.

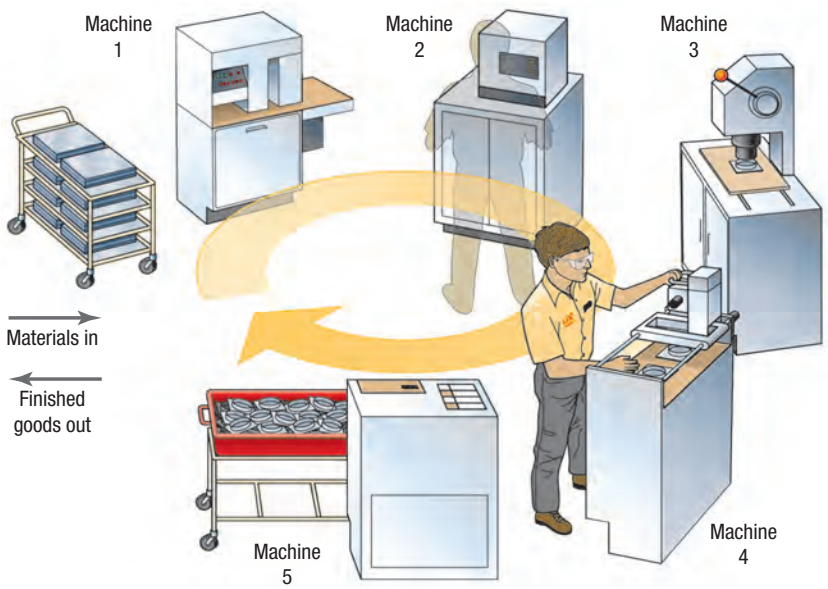
One Worker, Multiple Machines

one-worker, multiple-machines (OWMM) cell

A one-person cell in which a worker operates several different machines simultaneously to achieve a line flow.

If volumes are not sufficient to keep several workers busy on one production line, the manager might set up a line small enough to keep one worker busy. The **one-worker, multiple-machines (OWMM) cell** is a workstation in which a worker operates several different machines simultaneously to achieve a line flow. Having one worker operate several identical machines is not unusual. However, with an OWMM cell, several different machines are in the line.

Figure 4.4 illustrates a five-machine OWMM cell that is being used to produce a flanged metal part, with the machines encircling one operator in the center. (A U shape also is common.) The operator moves around the circle, performing tasks (typically loading and unloading) that have not been automated. Different products or parts can be produced in an OWMM cell by changing the machine setups. If the setup on one machine is especially time consuming for a particular part, management can add a duplicate machine to the cell for use whenever that part is being produced.



▲ **FIGURE 4.4**
One-Worker, Multiple-Machines (OWMM) Cell

An OWMM arrangement reduces both inventory and labor requirements. Inventory is cut because, rather than piling up in queues waiting for transportation to another part of the plant, materials move directly into the next operation. Labor is cut because more work is automated. The addition of several low-cost automated devices can maximize the number of machines included in an OWMM arrangement: automatic tool changers, loaders and unloaders, start and stop devices, and fail-safe devices that detect defective parts or products. Manufacturers are applying the OWMM concept widely because of their desire to achieve low inventories.

Group Technology

group technology (GT)

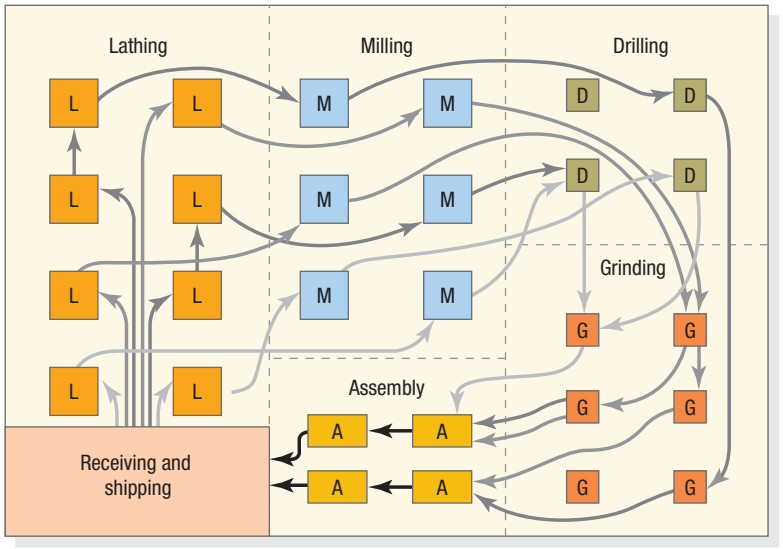
An option for achieving line-flow layouts with low volume processes; this technique creates cells not limited to just one worker and has a unique way of selecting work to be done by the cell.

A second option for achieving line-flow layouts with low volume processes is **group technology (GT)**. This manufacturing technique creates cells not limited to just one worker and has a unique way to selecting work to be done by the cell. The GT method groups parts or products with similar characteristics into families and sets aside groups of machines for their production. Families may be based on size, shape, manufacturing or routing requirements, or demand. The goal is to identify a set of products with similar processing requirements and minimize machine changeover or setup. For example, all bolts might be assigned to the same family because they all require the same basic processing steps regardless of size or shape.

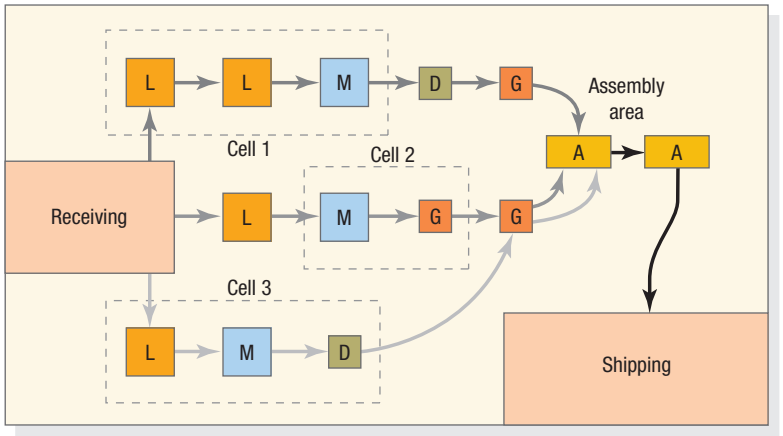
Once parts have been grouped into families, the next step is to organize the machine tools needed to perform the basic processes on these parts into separate cells. The machines in each cell require only minor adjustments to accommodate product changeovers from one part to the next in the same family. By simplifying product routings, GT cells reduce the time a job is in the shop. Queues of materials waiting to be worked on are shortened or eliminated. Frequently, materials handling is automated so that, after loading raw materials into the cell, a worker does not handle machined parts until the job has been completed.

Figure 4.5 compares process flows before and after creation of GT cells. Figure 4.5(a) shows a shop floor where machines are grouped according to function: lathing, milling, drilling, grinding, and assembly. After lathing, a part is moved to one of the milling machines, where it waits in line until it has a higher priority than any other job competing for the machine's capacity. When the milling operation on the part has been finished, the part is moved to a drilling machine, and so on. The queues can be long, creating significant time delays. Flows of materials are jumbled because the parts being processed in any one area of the shop have so many different routings.

By contrast, the manager of the shop shown in Figure 4.5(b) identified three product families that account for a majority of the firm's production. One family always requires two lathing operations followed by one operation at the milling machines. The second family always requires a milling operation followed by a grinding operation. The third family requires the use of a lathe, a milling machine, and a drill press. For simplicity, only the flows of parts assigned to these three families are shown. The remaining parts are produced at machines outside the cells and still have jumbled routings. Some equipment might have to be duplicated, as when a machine is required for one or more cells and for operations outside the cells. However, by creating three GT cells, the manager has definitely created more line flows and simplified routings.



(a) Jumbled flows in a job shop without GT cells



(b) Line flows in a job shop with three GT cells

▲ **FIGURE 4.5**
Process Flows Before and After the Use of GT Cells

Source: GROOVER, AUTOMATION, PRODUCTION SYSTEMS & COMPUTER-AIDED MANUFACTURING, 1st Ed., © 1980. Reprinted and Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.

The Kanban System

One of the most publicized aspects of lean systems, and the TPS in particular, is the Kanban system developed by Toyota. **Kanban**, meaning "card" or "visible record" in Japanese, refers to cards used to control the flow of production through a factory. The goal of a Kanban system is to make sure that the company has the minimum amount of inventory that is just enough to keep production running, and that production is being pulled by customer demand. In the most basic Kanban system, a card is attached to each container of items produced. The container holds a given percent of the daily production requirements for an item. When the user of the parts empties a container, the card is removed from the container and put on a receiving post. The empty container is then taken to the storage area, and the card signals the need to produce another container of the part. When the container has been refilled, the card is put back on the container, which is then returned to a storage area. The cycle begins again when the user of the parts retrieves the container with the card attached.

Kanban
A Japanese word meaning "card" or "visible record" that refers to cards used to control the flow of production through a factory.

Figure 4.6 shows how such a Kanban system works when it is managing inventory between a preceding process and a following process. The following steps, labeled from Figure 4.6(a) to Figure 4.6(e), are followed in a sequence that pulls products through the manufacturing system.

(a) The process starts with two containers full of parts A and B and one Kanban card in each container.

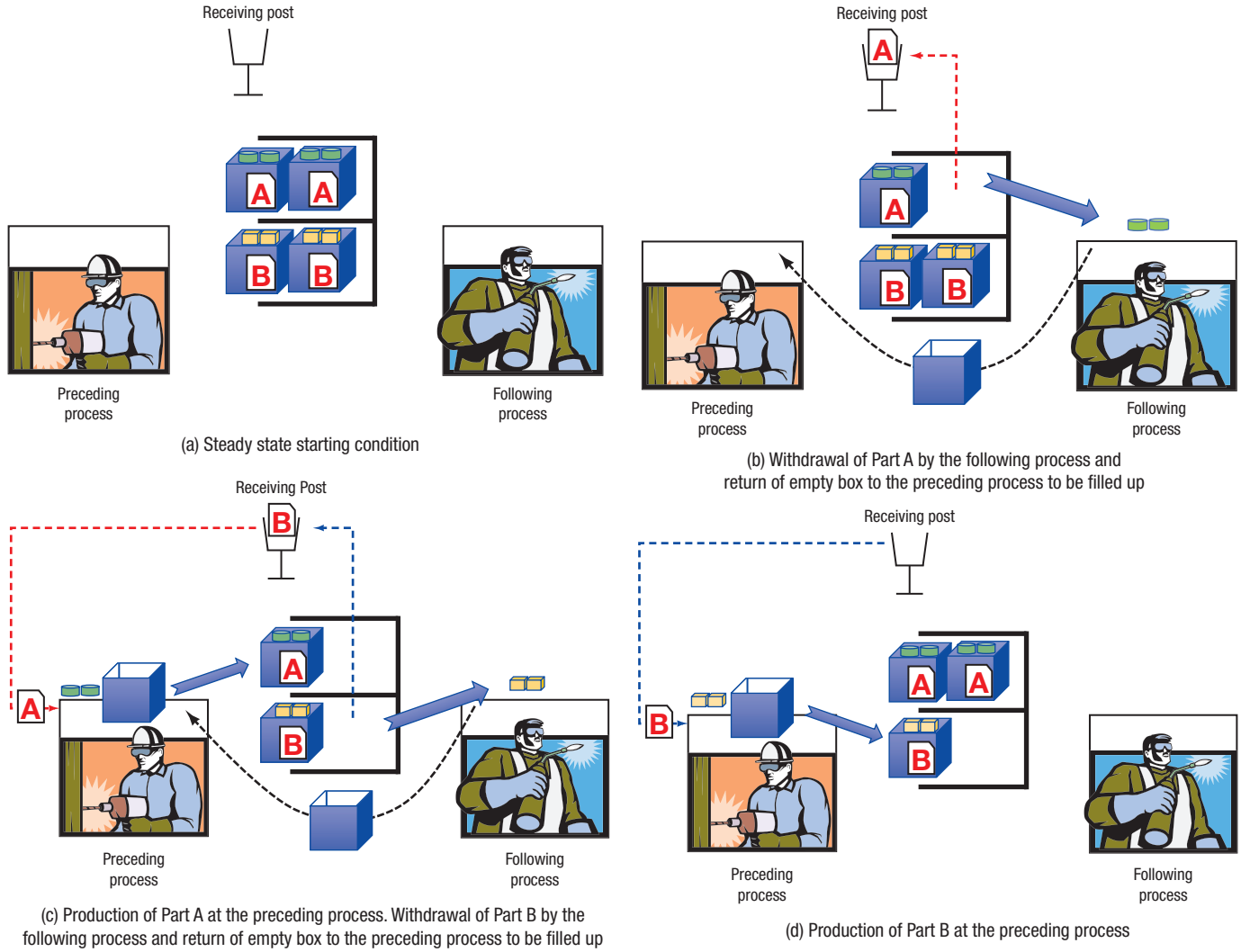
(b) As the following process needs a part, it pulls a full container from inventory. The Kanban card for part A is detached from the container and scheduled to be produced by the preceding process in a receiving post. The empty box also returns to the preceding process to be filled up.

(c) Part A begins production at the preceding process, and when completed, the full container with the Kanban card will be placed at the inventory to replenish the parts consumed by the following process. At the same time, the following process is withdrawing from inventory a full container of part B items. The Kanban for B parts is now taken to the receiving post, and the empty container is taken to be filled up by the preceding process.

(d) The Kanban signals the preceding process to begin producing part B, and when completed, the full container with the Kanban card will be placed in the inventory location between the two processes.

(e) The preceding process will have to wait for the following process to withdraw a container and a Kanban card to be taken to the receiving post to begin replenishment again.

Such a Kanban system allows firms to use a pull method of workflow to manufacture products in a typically make-to-stock production environment.



▲ **FIGURE 4.6**
Kanban System illustration

General Operating Rules

The operating rules for Kanban systems are simple and are designed to facilitate the flow of materials while maintaining control of inventory levels.

1. A full container must always have a Kanban card.
2. The preceding process will never produce parts without a Kanban card.
3. The following process must post the Kanban card at the receiving post before beginning consumption of the parts inside the containers.
4. The containers should always contain the same number of good parts (the Kanban card describes the number of parts per container). The use of nonstandard containers or irregularly filled containers disrupts the production flow of the assembly line.
5. Only non-defective parts should be put into inventory with the Kanban card to make the best use of materials and worker's time. This rule reinforces the notion of building quality at the source, which is an important characteristic of lean systems, and guarantees that the following process will have enough inventory.

Determining the Number of Containers

The number of authorized containers in the TPS determines the amount of authorized inventory. Management must make two determinations: (1) the number of units to be held by each container, and (2) the number of containers flowing back and forth between the supplier station and the user station. The first decision amounts to determining the size of the production lot.

The number of containers flowing back and forth between two stations directly affects the quantities of work-in-process inventory, which includes any safety stock inventory to cover for unexpected requirements.[5] The containers spend some time in production, in a line waiting, in a storage location, or in transit. The key to determining the number of containers required is to estimate the average lead time needed to produce a container of parts. The lead time is a function of the processing time per container at the supplier station, the waiting time during the production process, and the time required for materials handling. Little's law, which says that the average work-in-process (WIP) inventory equals the average demand rate multiplied by the average time a unit spends in the manufacturing process, can be used to determine the number of containers needed to support the user station (see Supplement B, "Waiting Lines").

WIP = (average demand rate)(average time a container spends in the manufacturing process) + safety stock

In this application of determining the number of containers needed for a part, WIP is the product of κ, the number of containers, and c, the number of units in each container. Consequently,

$$\kappa c = \bar{d}(\bar{\omega} + \bar{\rho})(1 + \alpha)$$

$$\kappa = \frac{\bar{d}(\bar{\omega} + \bar{\rho})(1 + \alpha)}{c}$$

where

κ = number of containers for a part

$\bar{d}$ = expected daily demand for the part, in units

$\bar{\omega}$ = average waiting time during the production process plus materials handling time per container, in fractions of a day

$\bar{\rho}$ = average processing time per container, in fractions of a day

c = quantity in a standard container of the part

α = a policy variable that adds safety stock to cover for unexpected circumstances (Toyota uses a value of no more than 10 percent)

The number of containers must, of course, be an integer. Rounding κ up provides more inventory than desired, whereas rounding κ down provides less. The container quantity, c, and the efficiency factor, α, are variables that management can use to control inventory. Adjusting c changes the size of the production lot, and adjusting α changes the amount of safety stock. The Kanban system allows management to fine-tune the flow of materials in the system in a straightforward way. For example, removing cards from the system reduces the number of authorized containers of the part, thus reducing the inventory of the part. Thus, a major benefit is the simplicity of the system, whereby product mix or volume changes can easily be accomplished by adjusting the number of Kanbans in the system. Example 4.1 shows how to determine the appropriate number of containers for a manufacturing process.

EXAMPLE 4.1 Determining the Appropriate Number of Containers

The Westerville Auto Parts Company produces rocker-arm assemblies for use in the steering and suspension systems of four-wheel-drive trucks. A typical container of parts spends 0.02 day in processing and 0.08 day in materials handling and waiting during its manufacturing cycle. The daily demand for the part is 2,000 units. Management believes that demand for the rocker-arm assembly is uncertain enough to warrant a safety stock equivalent of 10 percent of its authorized inventory.

a. If each container contains 22 parts, how many containers should be authorized?

b. Suppose that a proposal to revise the plant layout would cut materials handling and waiting time per container to 0.06 day. How many containers would be needed?

SOLUTION

a. If $\bar{d}$ = 2,000 units/day, $\bar{\rho}$ = 0.02 day, α = 0.10, $\bar{\omega}$ = 0.08 day, and c = 22 units,

$$\kappa = \frac{2{,}000(0.08 + 0.02)(1.1)}{22} = \frac{220}{22} = \textbf{10} \text{ containers}$$

b. Figure 4.7 from OM Explorer shows that the number of containers drops to **8**.

▼ **FIGURE 4.7**
OM Explorer Solver for Number of Containers

Solver-Number of Containers
Enter data in yellow-shaded area.

Daily Expected Demand	2000
Quantity in Standard Container	22
Container Waiting Time (days)	0.06
Processing Time (days)	0.02
Policy Variable	10%
Containers Required	8

[5]We discuss safety stocks, and their use, in more detail in Chapter 9, "Inventory Management," and Chapter 12, "Supply Chain Design."

DECISION POINT

The average lead time per container is $\bar{\omega} + \bar{\rho}$. With a lead time of 0.10 day, 10 containers are needed. However, if the improved facility layout reduces the materials handling time and waiting time to $\bar{\omega} = 0.06$ day, only 8 containers are needed. The maximum authorized inventory of the rocker-arm assembly is κC. Thus, in part (a), the maximum authorized inventory is 220 units, but in part (b), it is only 176 units. Reducing $\bar{\omega} + \bar{\rho}$ by 20 percent reduces the inventory of the part by 20 percent. Management must balance the cost of the layout change (a one-time charge) against the long-term benefits of inventory reduction.

Other Kanban Signals

Cards are not the only way to signal the need for more production of a part. Other, less formal methods are possible, including container and containerless systems.

Container System Sometimes, the container itself can be used as a signal device: An empty container signals the need to fill it. Unisys took this approach for low-value items. Adding or removing containers adjusts the amount of inventory of the part. This system works well when the container is specially designed for a particular part and no other parts could accidentally be put in the container. Such is the case when the container is actually a pallet or fixture used to position the part during precision processing.

Containerless System Systems requiring no containers have been devised. In assembly-line operations, operators use their own workbench areas to put completed units on painted squares, one unit per square. Each painted square represents a container, and the number of painted squares on each operator's bench is calculated to balance the line flow. When the subsequent user removes a unit from one of the producer's squares, the empty square signals the need to produce another unit. McDonald's uses a containerless system. Information entered by the order taker at the cash register is transmitted to the cooks and assemblers, who produce the sandwiches requested by the customer.

value stream mapping (VSM)

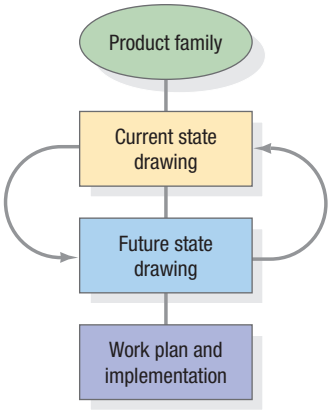
A qualitative lean tool for eliminating waste, or *muda*, that involves a current state drawing, a future state drawing, and an implementation plan.

Value Stream Mapping

Value stream mapping (VSM) is a widely used qualitative lean tool aimed at eliminating waste, or *muda*. Waste in many processes, also referred to as value streams, can be as high as 99 percent. Value stream mapping is helpful because it creates a visual representation of every process involved in the flow of materials and information in a product's value stream, which can be used to identify the lean tools needed to reduce waste. These maps consist of a current state drawing, a future state drawing, and an implementation plan. Value stream mapping spans the supply chain from the firm's receipt of raw materials or components to the delivery of the finished good to the customer. Thus, it tends to be broader in scope, displaying far more information than a typical process map or a flowchart used with Six Sigma process improvement efforts. Creating such a big picture representation helps managers identify the source of wasteful nonvalue-added activities.

▼ **FIGURE 4.8**
Value Stream Mapping Steps

Source: Mike Rother and John Shook, Learning to See (Cambridge, MA: The Lean Enterprise Institute, 2003), p. 9. ©Copyright 2003 Lean Enterprise Institute, Inc. Cambridge, MA, lean.org. All rights reserved.



Current State Map

Value stream mapping follows the steps shown in Figure 4.8. The first step is to focus on one product family for which mapping can be done. It is then followed by drawing a current state map of the existing processes. Analysts start from the customer end and work upstream to draw the map by hand and record actual process times rather than rely on information not obtained by firsthand observation. Information for drawing the material and information flows can be gathered from the shop floor, including the data related to each process: cycle time (C/T), setup or changeover time (C/O), uptime (on-demand available machine time expressed as a percentage), production batch sizes, number of people required to operate the process, number of product variations, pack size (for moving the product to the next stage), working time (minus breaks), and scrap rate. Value stream mapping uses a standard set of icons for material flow, information flow, and general information (to denote operators, safety stock buffers, etc.). Even though the complete VSM glossary is extensive, a representative set of these icons is shown in Figure 4.9. These icons provide a common language for describing in detail how a facility should operate to create a better flow.

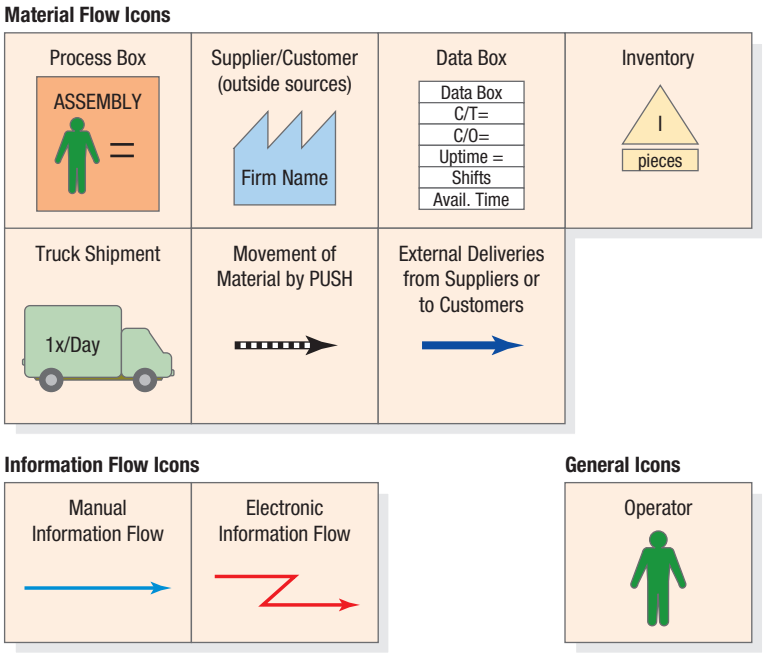


FIGURE 4.9
Selected Set of Value Stream Icons Used for Mapping Current State

Example 4.2 demonstrates the construction of a value stream map and the determination of the takt time and capacity for the current state of a bearing company.

EXAMPLE 4.2 Determining the Value Stream Map, Takt Time, and Total Capacity

Jensen Bearings Incorporated, a ball-bearing manufacturing company located in Lexington, South Carolina, receives raw material sheets from Kline Steel Company every Monday for a product family of retainers (casings in which ball bearings are held), and then ships its finished product on a daily basis to a second-tier automotive manufacturing customer named GNK Enterprises. The product family of the bearing manufacturing company under consideration consists of two types of retainers—large (L) and small (S)—that are packaged for shipping in returnable trays with 40 retainers in each tray. The manufacturing process consists of a value stream containing pressing operation; a piercing and forming cell, and a finish grind operation, after which the two types of retainers are staged for shipping. The information collected by the operations manager at Jensen Bearings Inc. is shown in Table 4.3.

TABLE 4.3 | OPERATIONS DATA FOR A FAMILY OF RETAINERS AT JENSEN BEARINGS INC.

Overall Process Attributes	**Average demand: 3,200/week (1,000 "L"; 2,200 "S")** **Batch size: 40** **Number of shifts per day: 1** **Availability: 8 hours per shift with two 30-minute lunch breaks**	
Process Step 1	Press	Cycle time = 12 seconds Setup time = 10 min Uptime = 100% Operators = 1 WIP = 5 days of sheets (Before Press)
Process Step 2	Pierce & Form	Cycle time = 34 seconds Setup time = 3 minutes Uptime = 100% Operators = 1 WIP = 1,000 "L," 1,250 "S" (Before Pierce & Form)

Overall Process Attributes	**Average demand: 3,200/week (1,000 "L"; 2,200 "S")** **Batch size: 40** **Number of shifts per day: 1** **Availability: 8 hours per shift with two 30-minute lunch breaks**	
Process Step 3	Finish Grind	Cycle time = 35 seconds Setup time = 0 minutes Uptime = 100% Operators = 1 WIP = 1,050 "L," 2,300 "S" (Before Finish Grind)
Process Step 4	Shipping	WIP = 500 "L," 975 "S" (After Finish Grind)
Customer Shipments	One shipment of 640 units each day in trays of 40 pieces, for a total of 3,200 each week	
Information Flow	All communications from the customer are electronic: 180/90/60/30/day Forecasts Daily Order All communications to the supplier are electronic 4-Week Forecast Email There is a weekly schedule manually delivered to Press, Pierce & Form, and Finish Grind and a Daily Ship Schedule manually delivered to Shipping All material is pushed	

a. Using data shown in Table 4.3, create a value stream map for Jensen Bearings Inc. and show how the data box values are calculated.

b. What is the takt time for this value stream?

c. What is the production lead time at each process in the value stream?

d. What is the total processing time of this value stream?

e. What is the capacity of this value stream?

SOLUTION

a. We use the VSM icons to illustrate in Figure 4.10 what a current state map would look like for Jensen Bearings Inc. The process characteristics and inventory buffers in front of each process are shown in the current state map of Figure 4.10. One worker occupies each station. The process flows shown at the bottom of Figure 4.10 are similar to the flowcharts discussed in Chapter 2, "Process Strategy and Analysis," except that more detailed information is presented here for each process. However, what really sets the value stream maps apart from flowcharts is the inclusion of information flows at the top of Figure 4.10, which plan and coordinate all the process activities. The value stream maps are more comprehensive than process flowcharts and meld together planning and control systems (discussed in detail in Chapter 11, "Resource Planning") with detailed flowcharts (discussed in Chapter 2) to create a comprehensive supply chain view that includes both information and material flows between the firm and its suppliers and customers.

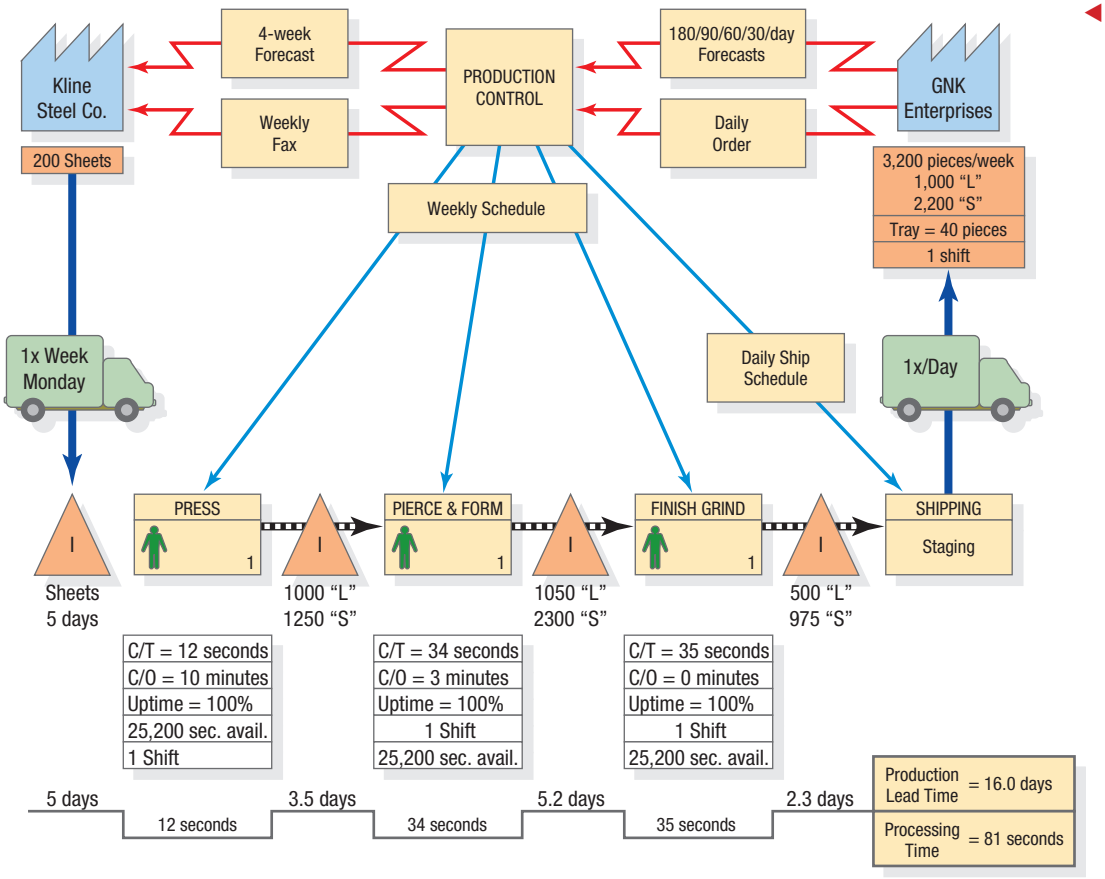


FIGURE 4.10
Current State Map for a Family of Retainers at Jensen Bearings Incorporated

b. The value stream's takt time is the rate at which the cell must produce units to match demand.

Daily Demand = [(1,000 + 2,200) pieces per week]/5 working days per week]
= 640 pieces per day

Daily Availability = (7 hours per day) × (3,600 seconds per hour) = 25,200 seconds per day

Takt Time = Daily Availability/Daily Demand = (25,200 seconds per day)/640 pieces per day
= **39.375** seconds per piece

c. The production lead time (in days) is calculated by summing the inventory held between each processing step divided by daily demand.

Raw Material lead time = 5.0 days

WIP lead time between Press and Pierce & Form = (2,250/640) = 3.5 days

WIP lead time between Pierce & Form and Finish Grind = (3,350/640) = 5.2 days

WIP lead time between Finish Grind and Shipping = (1,475/640) = 2.3 days

Total Production Lead time = (5 + 3.5 + 5.2 + 2.3) = **16** days

d. The value stream's total processing time is calculated by adding the processing times of each individual process. The processing time is the lead time through a process, which for Jensen Bearings is the same as the cycle time because all process steps are processing one part at a time. The value stream's total processing time is (12 + 34 + 35) = **81** seconds.

e. The value stream's capacity may be calculated by locating the bottleneck and computing the number of units that it can process in the available time per day at that bottleneck with the given batch size of 40 units.

Capacity at Press	Capacity at Pierce & Form	Capacity at Finish Grind
Cycle time = 12 seconds	Cycle time = 34 seconds	Cycle time = 35 seconds
Setup Time = (10 min * 60 seconds per min)/40 units per batch = **15.0 seconds**	Setup Time = (3 minutes * 60 seconds per minute)/40 units per batch = **4.5 seconds**	Setup Time = (0 minutes * 60 seconds per minute)/40 units per batch = **0.0 seconds**
Per Unit Processing Time = (12 + 15) = **27 seconds**	Per Unit Processing Time = (34 + 4.5) = **38.5 seconds**	Per Unit Processing Time = (35 + 0.0) = **35.0 seconds**

At a batch size of 40 units, Pierce & Form process is the bottleneck.

Availability at Pierce & Form = 25,200 seconds per day

Time at bottleneck (with setup) = 38.5 seconds

Capacity (Availability/Time at bottleneck) = 25,200/38.5 = **654** units per day

DECISION POINT

Although the total processing time for each retainer is only 81 seconds, it takes 16 days for the cumulative production lead time. Clearly, *muda*, or waste, is present, and opportunities exist for reconfiguring the existing processes with the goal of eliminating inventories and reducing cumulative production lead time.

Future State Map

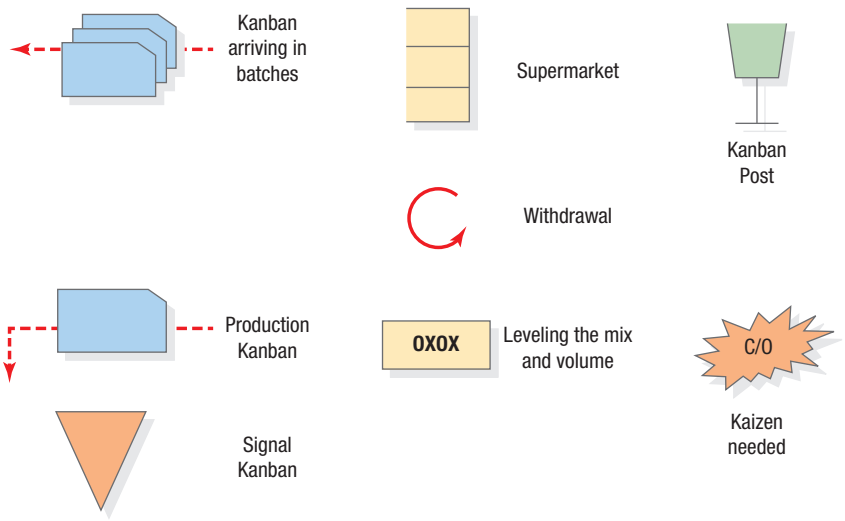
Once the current state map is done, the analysts can then use principles of lean systems to create a future state map with more streamlined product flows. The future state drawing eliminates the sources of waste identified on the current state drawing. Figure 4.11 shows the selected set of value stream icons used for mapping future state. The first step toward creating the future state is to determine if the process steps are capable of producing according to the takt time. If not, concepts from the theory of constraints, Chapter 6, "Constraint Management," can be used to make the value stream capable of producing at the same rate as the customer demand.

The second step is to identify where in the value stream inventories can be totally eliminated by combining process steps. While there may be several different paths to creating the future state map, we present one potential solution here. In Jensen Bearings map, the process steps of Pierce & Form and Finish Grind have similar cycle times, which indicates that these two steps could be reorganized into one single manufacturing cell. For that to be possible, the changeover time of the Pierce & Form needs to be reduced to less than 1 minute, which can be addressed by using the concept of single-digit setup.

The third step to create the future state map is to design pull systems to manage the remaining inventories. Starting from the inventory closest to the customer and working toward the beginning of the value stream, inventories should work as pull systems, connecting all the process production rates to the customer's actual demand. Jensen Bearing ships one truckload per day for this product family, and parts are going to be withdrawn from a finished goods inventory. For every tray of retainers pulled from the finished goods inventory, a Kanban card will send a signal to the newly created Pierce & Form and Finish Grind manufacturing cell informing the need to replenish the finished goods inventory. A Kanban card will have the same quantity per tray, 40 retainers. To replenish the finished goods Kanban, operators in the Pierce & Form and Finish Grind manufacturing cell will withdraw the WIP part from the upstream supermarket, and this withdrawal will also initiate a Kanban signal for the upstream Press process step.

Finally, the raw materials inventory of sheets is also managed by Kanban cards that are sent to Production Control, when sheets are used in the Press step process. Production Control will gather all Kanban cards for raw materials and send daily information to suppliers. To guarantee a more frequent delivery without increasing transportation costs, Jensen Bearings will need to establish Close Supplier Ties (another lean concept)

▼ **FIGURE 4.11**
Selected Set of Value Stream Icons Used for Mapping Future State



with Kline Steel Co. The size of the inventories in different stages of the Kanban system can be calculated as shown in Example 4.1 by estimating demand rates, lead times, and safety stocks needed for desired service levels.

When comparing the current state and the future state value stream map shown in Figure 4.12, we can see that Jensen Bearings can reduce their production lead time and inventory from 16 days to 5.5 days, which represents a 65 percent reduction.

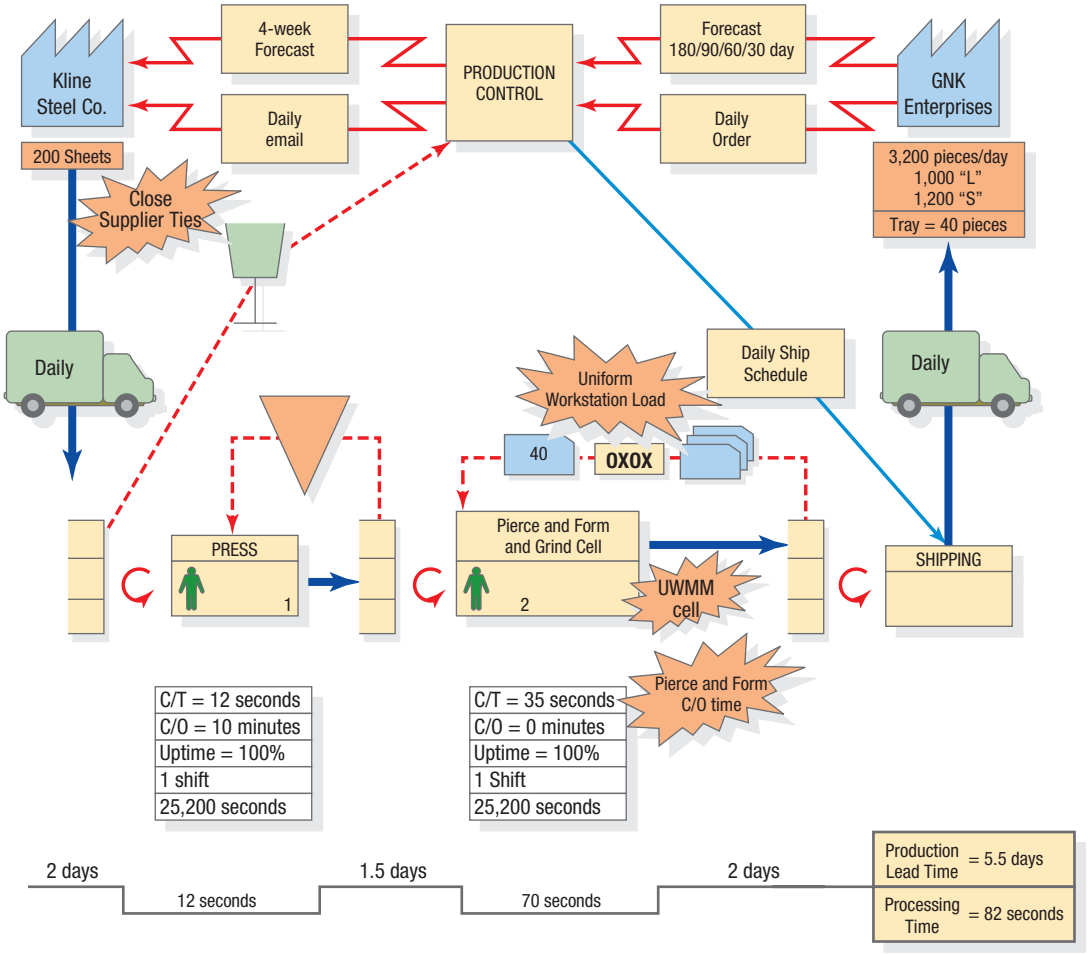


FIGURE 4.12
Future State Map for a Family of Retainers at Jensen Bearings Incorporated

The last step in value stream mapping is preparing and actively using an implementation plan to achieve the future state. It may take only a couple of days from the creation of a future state map to the point where implementation can begin for a single product family. At this stage, the future state map becomes a blueprint for implementing a lean system and is fine-tuned as implementation progresses. As the future state becomes reality, a new future state map is drawn, thus denoting continuous improvement at the value stream level.

Unlike the theory of constraints (see Chapter 6, "Constraint Management"), which accepts the existing system bottlenecks and then strives to maximize the throughput given that set of constraint(s), value stream mapping endeavors to understand through current state and future state maps how existing processes can be altered to eliminate bottlenecks and other wasteful activities. The goal is to bring the production rate of the entire process closer to the customer's desired demand rate. The benefits of applying this tool to the waste-removal process include reduced lead times and WIP inventories, reduced rework and scrap rates, lower indirect labor costs, and increased direct labor productivity.



wunkley/Alamy Stock Photo

After the pathology lab at the University of Pittsburgh Medical Center adopted a lean operations approach based on a line system versus a batch-and-queue system, the time it took to process samples dropped from days to just hours. Diagnoses were made more quickly as a result, and patients' stays at the hospital were shortened.

Operational Benefits and Implementation Issues

To gain competitive advantage and to make dramatic improvements, a lean system can be the solution. Lean systems can be an integral part of a corporate strategy based on speed because they cut cycle times, improve inventory turnover, and increase labor productivity. Recent studies also show that practices representing different components of lean systems such as JIT, TQM, Six Sigma, total productive maintenance (TPM), and human resource management (HRM), individually as well as cumulatively, improve the performance of manufacturing plants as well as service facilities. Lean systems also involve a considerable amount of employee participation through small-group interaction sessions, which have resulted in improvements in many aspects of operations, not the least of which is service or product quality.

Even though the benefits of lean systems can be outstanding, problems can still arise after a lean system has long been operational, which was witnessed recently in product recalls and a perceived shift away from tightly controlled quality that has always been the standard at Toyota. In addition, implementing a lean system can take a long time. We address next some of the issues managers should be aware of when implementing a lean system.

Organizational Considerations

Implementing a lean system requires management to consider issues of worker stress, cooperation and trust among workers and management, and reward systems and labor classifications.

The Human Costs of Lean Systems Lean systems can be coupled with statistical process control (SPC) to reduce variations in output. However, this combination requires a high degree of regimentation and sometimes stresses the workforce. For example, in the TPS, workers must meet specified cycle times, and with SPC, they must follow prescribed problem-solving methods. Such systems might make workers feel pushed and stressed, causing productivity losses or quality reductions. In addition, workers might feel a loss of some autonomy because of the close linkages in workflows between stations with little or no excess capacity or safety stocks. Managers can mitigate some of these effects by allowing for some slack in the system—either safety stock inventories or capacity slack—and by emphasizing workflows instead of worker pace. Managers also can promote the use of work teams and allow them to determine their task assignments within their domains of responsibility.

Cooperation and Trust In a lean system, workers and first-line supervisors must take on responsibilities formerly assigned to middle managers and support staff. Activities such as scheduling, expediting, and improving productivity become part of the duties of lower-level personnel. Consequently, the work relationships in the organization must be reoriented in a way that fosters cooperation and mutual trust between the workforce and management. However, this environment can be difficult to achieve, particularly in light of the historical adversarial relationship between the two groups.

Reward Systems and Labor Classifications In some instances, the reward system must be revamped when a lean system is implemented. At General Motors, for example, a plan to reduce stock at one plant ran into trouble because the production superintendent refused to cut back on the number of unneeded parts being made. Why? Because his or her salary was based on the plant's production volume.

The realignment of reward systems is not the only hurdle. Labor contracts traditionally crippled a company's ability to reassign workers to other tasks as the need arose. For example, a typical automobile plant in the United States has several unions and dozens of labor classifications. Generally, the people in each classification are allowed to do only a limited range of tasks. In some cases, companies have managed to give these employees more flexibility by agreeing to other types of union concessions and benefits. In other cases, however, companies relocated their plants to take advantage of nonunion or foreign labor.

Process Considerations

Firms using lean systems typically have some dominant workflows. To take advantage of lean practices, firms might have to change their existing layouts. Certain workstations might have to be moved closer together, and cells of machines devoted to particular component families may have to be established. However, rearranging a plant to conform to lean practices can be costly. For example, many plants currently receive raw materials and purchased parts by rail, but to facilitate smaller and more frequent shipments, truck deliveries would be preferable. Loading docks might have to be reconstructed or expanded and certain operations relocated to accommodate the change in transportation mode and quantities of arriving materials.

Inventory and Scheduling

Manufacturing firms need to have stable master production schedules, short setups, and frequent, reliable supplies of materials and components to achieve the full potential of the lean systems concept.

Schedule Stability Daily production schedules in high-volume, make-to-stock environments must be stable for extended periods. At Toyota, the master production schedule is stated in fractions of days over a 3-month period and is revised only once a month. The first month of the schedule is frozen to avoid disruptive changes in the daily production schedule for each workstation; that is, the workstations execute the same work schedule each day of the month (see Chapter 11, "Resource Planning," for more details on master production schedules and freezing). At the beginning of each month, Kanbans are reissued for the new daily production rate. Stable schedules are needed so that production lines can be balanced and new assignments found for employees who otherwise would be underutilized. Lean systems used in high-volume, make-to-stock environments cannot respond quickly to scheduling changes because little slack inventory or capacity is available to absorb these changes.

Setups If the inventory advantages of a lean system are to be realized, small lot sizes must be used. However, because small lots require a large number of setups, companies must significantly reduce setup times. Some companies have not been able to achieve short setup times and, therefore, have to use large-lot production, negating some of the advantages of lean practices. Also, lean systems are vulnerable to lengthy changeovers to new products because the low levels of finished goods inventory will be insufficient to cover demand while the system is down. If changeover times cannot be reduced, large finished goods inventories of the old product must be accumulated to compensate. In the automobile industry, every week that a plant is shut down for new-model changeover costs between $16 and $20 million in pretax profits.

Purchasing and Logistics The shipments of raw materials and components must be reliable because of the low inventory levels in lean systems. A plant can be shut down because of a lack of materials. Similarly, recovery becomes more prolonged and difficult in a lean system after supply chains are disrupted, which is what happened immediately after 9/11.

Process design and continuous improvement are key elements of a successful operations strategy. In this chapter, we focused on lean systems as a directive for efficient process design and an approach to achieve continuous improvement. We showed how JIT systems, a popular lean systems approach, can be used for continuous improvement and how a Kanban system can be used to control the amount of work-in-process inventory. Transforming a current process design to one embodying a lean systems philosophy is a constant challenge for management, often fraught with implementation issues. However, adopting appropriate tools and management approaches can facilitate such a transformation, as exemplified by firms like Nike, Aldi, Alcoa, and Toyota, among others.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
4.1 Describe how lean systems can facilitate the continuous improvement of processes.	See the section "Continuous Improvement Using a Lean Systems Approach." Review Figure 4.1 and the opening vignette on the Nike Corporation.	
4.2 Identify the strategic supply chain and process characteristics of lean systems.	See the subsections "Supply Chain Considerations in Lean Systems" and "Process Considerations in Lean Systems." The subsection "Toyota Production System" illustrates how one firm implements lean characteristics to gain strategic advantage over its competition.	
4.3 Explain the differences between one-worker, multiple-machine (OWMM) and group technology (GT) approaches to lean system layouts.	The section "Designing Lean System Layouts" shows you how to differentiate between two different types of layouts used to implement line flows, when volumes are not high to justify a single line of multiple workers to a single product.	
4.4 Understand Kanban systems for creating a production schedule in a lean system.	The section "The Kanban System" shows how firms like Toyota use simple visual systems to pull production and make exactly what the market demands. Example 4.1 shows how to calculate the number of Kanban cards needed.	**OM Explorer Tutor:** 4.1: Calculate Number of Containers in a Kanban System **OM Explorer Solver:** Number of Containers

Learning Objective	Guidelines for Review	Online Resources
4.5 Understand value stream mapping and its role in waste reduction.	The section "Value Stream Mapping" shows you how to construct value stream maps and identify waste in the processes. Review Example 4.2 for details on mapping and creating data boxes, both the current and the future states.	
4.6 Explain the implementation issues associated with the application of lean systems.	The section "Operational Benefits and Implementation Issues" reviews organizational and process considerations needed to successfully deploy lean systems and gain their benefits.	**Case:** Copper Kettle Catering

Key Equations

The Kanban System

Number of containers:

$$\kappa = \frac{\bar{d}(\bar{\omega} + \bar{\rho})(1 + \alpha)}{c}$$

Key Terms

Five S (5S) 173
group technology (GT) 176
heijunka 172
jidoka 170
just-in-time (JIT) system 166
Kanban 177
lean systems 165
lot 169
mixed-model assembly 172
one-worker, multiple-machines (OWMM) cell 176
poka-yoke 170
pull method 169
push method 169
single-digit setup 169
takt time 172
value stream mapping (VSM) 180

Solved Problem 1

A company using a Kanban system has an inefficient machine group. For example, the daily demand for part L105A is 3,000 units. The average waiting time for a container of parts is 0.8 day. The processing time for a container of L105A is 0.2 day, and a container holds 270 units. Currently, 20 containers are used for this item.

a. What is the value of the policy variable, α?

b. What is the total planned inventory (work-in-process and finished goods) for item L105A?

c. Suppose that the policy variable, α, was 0. How many containers would be needed now? What is the effect of the policy variable in this example?

SOLUTION

a. We use the equation for the number of containers and then solve for α:

$$\kappa = \frac{\bar{d}(\bar{\omega} + \bar{\rho})(1 + \alpha)}{c}$$

$$20 = \frac{3{,}000(0.8 + 0.2)(1 + \alpha)}{270}$$

and

$$(1 + \alpha) = \frac{20(270)}{3{,}000(0.8 + 0.2)} = 1.8$$

$$\alpha = 1.8 - 1 = \mathbf{0.8}$$

b. With 20 containers in the system and each container holding 270 units, the total planned inventory is $20(270) = \mathbf{5{,}400}$ units.

c. If $\alpha = 0$

$$\kappa = \frac{3{,}000(0.8 + 0.2)(1 + 0)}{270} = 11.11, \text{ or } \mathbf{12} \text{ containers}$$

The policy variable adjusts the number of containers. In this case, the difference is quite dramatic because $\bar{\omega} + \bar{\rho}$ is fairly large and the number of units per container is small relative to daily demand.

Solved Problem 2

Metcalf, Inc., manufactures engine assembly brackets for two major automotive customers. The manufacturing process for the brackets consists of a cell containing a forming operation, a drilling operation, a finish grinding operation, and packaging, after which the brackets are staged for shipping. The information collected by the operations manager at Metcalf, Inc., is shown in Table 4.4.

TABLE 4.4 | OPERATIONS DATA FOR BRACKETS AT METCALF, INC.

Overall Process Attributes	**Average demand: 2,700/day** **Batch size: 50** **Number of shifts per day: 2** **Availability: 8 hours per shift with a 30-minute lunch break**	
Process Step 1	Forming	Cycle time = 11 seconds Setup time = 3 minutes Uptime = 100% Operators = 1 WIP = 4,000 units (Before Forming)
Process Step 2	Drilling	Cycle time = 10 seconds Setup time = 2 minutes Uptime = 100% Operators = 1 WIP = 5,000 units (Before Drilling)
Process Step 3	Grinding	Cycle time = 17 seconds Setup time = 0 minutes Uptime = 100% Operators = 1 WIP = 2,000 units (Before Grinding)
Process Step 4	Packaging	Cycle time = 15 seconds Setup time = 0 minutes Uptime = 100% Operators = 1 WIP = 1,600 units (Before Packaging) WIP = 15,700 units (Before Shipping)
Customer Shipments	One shipment of 13,500 units each week	
Information Flow	All communications with customer are electronic There is a weekly order release to Forming All material is pushed	

a. Using data shown in Table 4.4, create a current value stream map for Metcalf, Inc., and show how the data box values are calculated.

b. What is the takt time for this value stream?

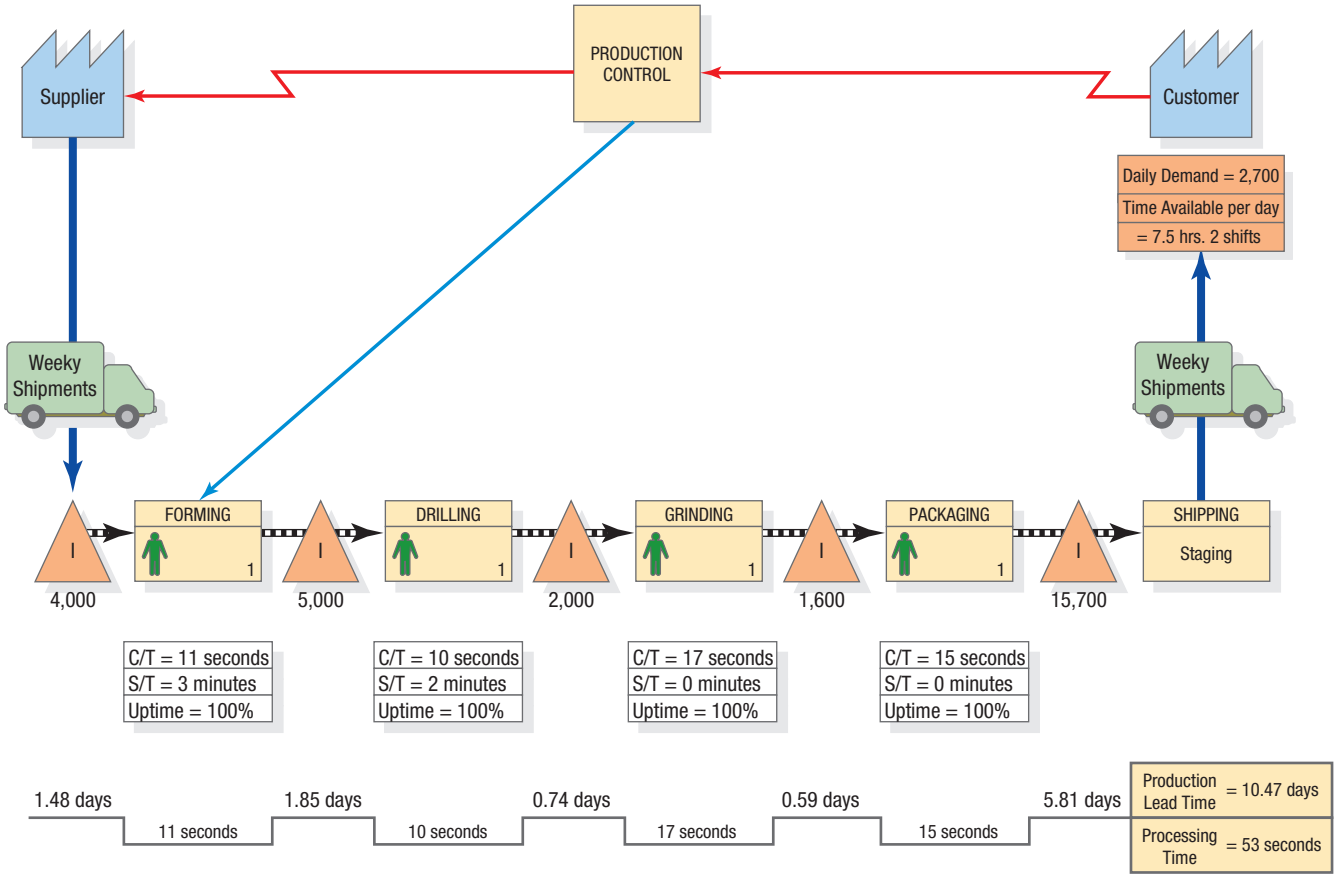
c. What is the production lead time at each process in the value stream?

d. What is the total processing time of this value stream?

e. What is the capacity of this value stream?

SOLUTION

a. Figure 4.13 shows the current value stream state map for Metcalf, Inc.



▲ **FIGURE 4.13**
Current State Value Stream Map for Metcalf, Inc.

b. Daily Demand = 2,700 units per day

Daily Availability = (7.5 hours per day) × (3,600 seconds per hour) × (2 shifts per day)
= 54,000 seconds per day

Takt Time = Daily Availability/Daily Demand = 54,000 seconds per day/2,700 units per day
= **20** seconds per unit

c. The production lead time (in days) is calculated by summing the inventory held between each processing step divided by daily demand.

Raw Material lead time = [4,000/2,700] = 1.48 days

WIP lead time between Forming and Drilling = [5,000/2,700] = 1.85 days

WIP lead time between Drilling and Grinding = [2,000/2,700] = 0.74 day

WIP lead time between Grinding and Packaging = [1,600/2,700] = 0.59 day

Finished Goods lead time before Shipping = [15,700/2,700] = 5.81 days

The cell's total production lead time is 1.48 + 1.85 + 0.74 + 0.59 + 5.81 = **10.47** days

d. The manufacturing cell's total processing time is (11 + 10 + 17 + 15) = **53** seconds.

e. The cell's capacity may be calculated by locating the bottleneck and computing the number of units that it can process in the available time per day at that bottleneck.

Capacity at Forming	Capacity at Drilling	Capacity at Grinding	Capacity at Packaging
Cycle time = 11 seconds	Cycle time = 10 seconds	Cycle time = 17 seconds	Cycle time = 15 seconds
Setup Time = (3 minutes * 60 seconds per minute)/ 50 units per batch = **3.6 seconds**	Setup Time = (2 minutes * 60 seconds per minute)/ 50 units per batch = **2.4 seconds**	Setup Time = **zero seconds**	Setup Time = **zero seconds**

Capacity at Forming	Capacity at Drilling	Capacity at Grinding	Capacity at Packaging
Per Unit Processing Time = (11 + 3.6) = **14.6 seconds**	Per Unit Processing Time = (10 + 2.4) = **12.4 seconds**	Per Unit Processing Time = (17 + 0) = **17.0 seconds**	Per Unit Processing Time = (15 + 0) = **15.0 seconds**

a. At a batch size of 50 units, Finish Grinding process is the bottleneck

b. Availability at Grinding = 54,000 seconds per day

c. Time at bottleneck (with setup) = 17.0 seconds

d. Capacity (Availability/Time at bottleneck) = 54,000/17 = **3,176** units per day

Discussion Questions

1. Compare and contrast the following two situations:
   a. A company's lean system stresses teamwork. Employees feel more involved, and therefore, productivity and quality increase at the company. The problem is that workers also experience a loss of individual autonomy.
   b. A humanities professor believes that all students want to learn. To encourage students to work together and learn from each other—thereby increasing the involvement, productivity, and the quality of the learning experience—the professor announces that all students in the class will receive the same grade and that it will be based on the performance of the group.
2. Which elements of lean systems would be most troublesome for manufacturers to implement? Why?
3. List the pressures that lean systems pose for supply chains, whether in the form of process failures due to inventory shortages or labor stoppages, and so forth. Reflect on how these pressures may apply to a firm that is actually implementing lean philosophy in its operations.
4. Assume you are a management consultant tasked with improving the efficiency of a production process of an FMCG product of your choice. List the steps you will take to draw the value stream map. Who will you engage and what data will you collect? Identify challenges you might encounter in this process.

Problems

The OM Explorer, POM for Windows, and Active Model software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software replaces entirely the manual calculations.

Strategic Characteristics of Lean Systems

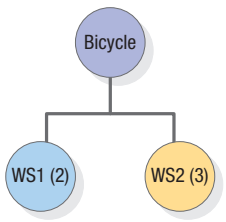
1. Swenson Saws produces bow, frame, dovetail, and tenon saws used by craft furniture makers. During an 8-hour shift, a saw is produced every 6 minutes. The demand for bow, frame, and dovetail saws is about the same, but the demand for tenon saws is twice the demand for the other three.
   a. If mixed-model scheduling is used, how many of each saw will be produced before the cycle is repeated?
   b. Determine a satisfactory production sequence for one unit production. How often is this sequence repeated?
   c. How many of each saw does Swenson produce in one shift?
2. The Harvey Motorcycle Company produces three models: the Tiger, a sure-footed dirt bike; the LX2000, a nimble café racer; and the Golden, a large interstate tourer. This month's master production schedule calls for the production of 54 Goldens, 42 LX2000s, and 30 Tigers per 7-hour shift.
   a. What average cycle time is required for the assembly line to achieve the production quota in 7 hours?
   b. If mixed-model scheduling is used, how many of each model will be produced before the production cycle is repeated?
   c. Determine a satisfactory production sequence for the ultimate in small-lot production: one unit.
   d. The design of a new model, the Cheetah, includes features from the Tiger, LX2000, and Golden models. The resulting blended design has an indecisive character and is expected to attract some sales from the other models. Determine a mixed-model schedule resulting in 52 Goldens, 39 LX2000s, 26 Tigers, and 13 Cheetahs per 7-hour shift. Although the total number of motorcycles produced per day will increase only slightly, what problem might be anticipated in implementing this change from the production schedule indicated in part (b)?
3. The Farm-4-Less tractor company produces a grain combine (GC) in addition to both a large (LT) and small size tractor (SM). Its production manager desires to produce to customer demand using a mixed-model production line. The current sequence of production, which is repeated 30 times during a shift, is SM-GC-SM-LT-SM-GC-LT-SM. A new machine is produced every 2 minutes. The plant operates two 8-hour shifts. There is no downtime because the 4 hours between each shift are dedicated to maintenance and restocking raw material. Based on this information, answer the following questions.
   a. How long does it take the production cycle to be completed?
   b. How many of each type of machine does Farm-4-Less produce in a shift?

The Kanban System

4. A fabrication cell at Spradley's Sprockets uses the pull method to supply gears to an assembly line. George Jitson is in charge of the assembly line, which requires 500 gears per day. Containers typically wait 0.20 day in the fabrication cell. Each container holds 20 gears, and one container requires 1.8 days in machine time. Setup times are negligible. If the policy variable for unforeseen contingencies is set at 5 percent, how many containers should Jitson authorize for the gear replenishment system?

5. A bread manufacturing firm has recently implemented a Kanban system for tracking the consumption of raw materials, especially wheat flour. The average daily demand for wheat is 2,500 kg. The firm's records show that it takes around 4 hours for the flour to be transformed into bread and another 4 hours in material handling and waiting time during the manufacturing cycle. Due to uncertain demand, the firm has a safety stock of 25 percent. Each container can hold 250 kg of wheat flour.
   a. Calculate the number of containers required by the firm.
   b. Management is planning to reduce the number of containers used. A reliable supplier has been identified, which eliminates the need for additional stock. Determine the required reduction in waiting time if one container is removed.

6. Terai Motors buys semi-finished products from suppliers and assembles them based on customer preferences. During the customization process, two wheels, one handlebar, one seat, and a luggage box are attached to develop the end product. Wheels are attached in workstation 1, while handlebar, seat, and luggage box are attached in workstation 2, as shown in Figure 4.14. The daily production quota on the assembly line is 80 bikes. The container for wheel assembly can hold eight units, and the policy variable for workstation 1 is 0.10. The average waiting time for container of wheels is 0.09 day, while 0.06 day is required for processing. The container for workstation 2 can hold 50 units, and the policy variable for workstation 2 is 0.08. The average waiting time for workstation 2 is 0.14 day, while processing time is 0.20 day.



◀ **FIGURE 4.14**
Components for End Item Bicycle

   a. Calculate the number of containers needed in workstation 1.
   b. Calculate the number of containers needed in workstation 2.

7. Gestalt, Inc., uses a Kanban system in its automobile production facility in Germany. This facility operates 8 hours per day to produce the Jitterbug, a replacement for the obsolete but immensely popular Jitney Beetle. Suppose that a certain part requires 150 seconds of processing at machine cell 33B and a container of parts average 1.6 hours of waiting time there. Management allows a 10 percent buffer for unexpected occurrences. Each container holds 30 parts, and 8 containers are authorized. How much daily demand can be satisfied with this system? (*Hint:* Recall that ρ is the average processing time per container, not per individual part.)

8. A watch manufacturing company in Switzerland is considering the number of trays it must deploy in its manufacturing process. Watches are hand-assembled by a team of experienced watchmakers and sent in a purpose-built watch holding tray for quality assurance. Each tray can hold 30 watches. The quality professional first examines the dial, sets the time, and loads the tray onto a metal container which simulates movement 24 hours. This process takes 2 minutes per watch. The watches are reexamined for time accuracy which takes another 45 seconds per watch and if they pass the test, they are sent for strap attachment. The empty trays are returned to the assembly line from the strap attachment department. How many trays should circulate between the assembly line and the strap attachment department if 1000 watches are to be examined during an 8-hour shift? The average processing time and waiting time is 2 days. The value of the safety stock policy variable, α, is zero.

9. The production schedule at Mazda calls for 1,200 Mazdas to be produced during each of 22 production days in January and 900 Mazdas to be produced during each of 20 production days in February. Mazda uses a Kanban system to communicate with Gesundheit, a nearby supplier of tires. Mazda purchases four tires per vehicle from Gesundheit. The safety stock policy variable, α, is 0.15. The container (a delivery truck) size is 200 tires. The average waiting time plus materials handling time is 0.16 day per container. Assembly lines are rebalanced at the beginning of each month. The average processing time per container in January is 0.10 day. The February processing time will average 0.125 day per container. How many containers should be authorized for January? How many for February?

10. Jitsmart is a retailer of plastic action-figure toys. The action figures are purchased from Tacky Toys, Inc., and arrive in boxes of 48. Full boxes are stored on high shelves out of reach of customers. A small inventory is maintained on child-level shelves. Depletion of the lower-shelf inventory signals the need to take down a box of action figures to replenish the inventory. A reorder card is then removed from the box and sent to Tacky Toys to authorize replenishment of a container of action figures. The average demand rate for a popular action figure, Agent 99, is 36 units per day. The total lead time (waiting plus processing) is 11 days. Jitsmart's safety stocky policy variable, α, is 0.25. What is the authorized stock level for Jitsmart?

11. Markland First National Bank of Rolla utilizes Kanban techniques in its check processing facility. The following information is known about the process. Each Kanban container can hold 50 checks and spends 24 minutes a day in profcessing and 2 hours a day in materials handling and waiting. Finally, the facility operates 24 hours per day and utilizes a policy variable for unforeseen contingencies of 0.25.
   a. If 20 Kanban containers are in use, what is the current daily demand of the check processing facility?
   b. If the *muda*, or the waste, in the system were eliminated completely, how many containers would then be needed?

Value Stream Mapping

12. Figure 4.15 provides a new current state value stream map for the family of retainers at the Jensen Bearings, Inc. firm described in Example 4.1. This map depicts the value stream after Kline Steel agrees to accept daily orders for steel sheets and Jensen Bearings continues to deliver the finished goods on a daily basis.

Calculate each component of the new value stream's reduced lead time.

- **a.** How many days of raw material does the Bearing's plant now hold?
- **b.** How many days of work-in-process inventory is held between Press and Pierce & Form?
- **c.** How many days of work-in-process inventory is held between Pierce & Form and Finish Grind?
- **d.** How many days of work-in-process inventory is held between Finish Grind and Shipping?
- **e.** What is the new value steam's production lead time?
- **f.** What is the new value stream's processing time?

13. A garment manufacturer is interested in using the data collected during value stream mapping to evaluate the current state performance of the capacity of its manual assembly line process and would like to identify the ideal batch size for its operations. The productive capacity of the staff is 420 minutes per day. To manufacture a garment after design approval, clothes are cut into desired shape, followed by sewing of front and back, and then attachments of hand, collars, and buttons. The current operating characteristics of each processing step are found in the accompanying table. Note that each step can only process one part at a time and all steps must process the same sized batches.

	Shape	Sewing	Hand	Collar	Buttons
Cycle time per shirt	2 minutes	7 minutes	3 minutes	5 minutes	6 minutes
Setup time per batch	15 minutes	18 minutes	0 minutes	10 minutes	20 minutes

- **a.** Calculate the average processing time per unit and the capacity at each step assuming batch sizes of:
  - **i.** 20 shirts
  - **ii.** 30 shirts
  - **iii.** 35 shirts
  - **iv.** 40 shirts
- **b.** Identify the bottleneck operation for each batch size.
- **c.** What is the optimum batch size after which there will be no improvement in the line's processing capacity?

14. The manager at Ormonde, Inc., collected the value stream mapping data from the plant's most problematic manufacturing cell that fabricates parts for washing machines. These data are shown in Table 4.5. Using these data, calculate the current state performance of the cell and answer the following questions.

- **a.** What is the cell's current inventory level?
- **b.** What is the takt time for this manufacturing cell?
- **c.** What is the production lead time at each process in the manufacturing cell?
- **d.** What is the total processing time of this manufacturing cell?
- **e.** What is the capacity of this manufacturing cell?

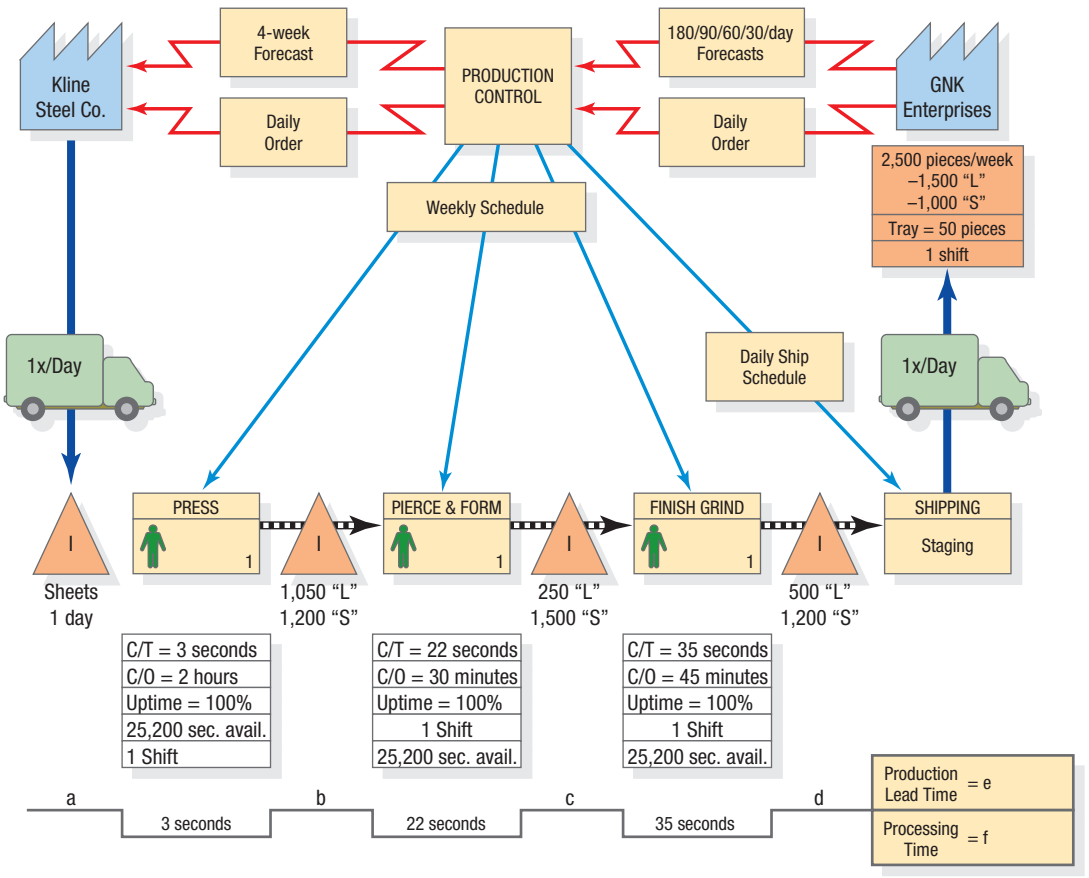


FIGURE 4.15 New Current State Value Stream Map at Jensen Bearings, Inc.

TABLE 4.5 | OPERATIONS DATA FOR ORMONDE, INC.

Overall Process Attributes	**Average demand: 550/day** **Batch size: 20** **Number of shifts per day: 3** **Availability: 8 hours per shift with a 45-minute lunch break**	
Process Step 1	Cutting	Cycle time = 120 seconds Setup time = 3 minutes Uptime = 100% Operators = 1 WIP = 400 units (Before Cutting)
Process Step 2	Bending	Cycle time = 100 seconds Setup time = 5 minutes Uptime = 100% Operators = 1 WIP = 500 units (Before Bending)
Process Step 3	Punching	Cycle time = 140 seconds Setup time = none Uptime = 100% Operators = 1 WIP = 200 units (Before Punching) WIP = 1,000 units (After Punching)
Customer Shipments	One shipment of 2,750 units each week	
Information Flow	All communications with customer are electronic There is a weekly order release to Cutting All material is pushed	

CASE Copper Kettle Catering

Copper Kettle Catering (CKC) is a full-service catering company that provides services ranging from box lunches for picnics or luncheon meetings to large wedding, dinner, or office parties. Established as a lunch delivery service for offices in 1972 by Wayne and Janet Williams, CKC has grown to be one of the largest catering businesses in Raleigh, North Carolina. The company divides customer demand into two categories: deliver only and deliver and serve.

The deliver-only side of the business delivers boxed meals consisting of a sandwich, salad, dessert, and fruit. The menu for this service is limited to six sandwich selections, three salads or potato chips, and a brownie or fruit bar. Grapes and an orange slice are included with every meal, and iced tea can be ordered to accompany the meals. The overall level of demand for this service throughout the year is fairly constant, although the mix of menu items delivered varies. The planning horizon for this segment of the business is short: Customers usually call no more than a day ahead of time. CKC requires customers to call deliver-only orders in by 10:00 A.M. to guarantee delivery the same day.

The deliver-and-serve side of the business focuses on catering large parties, dinners, and weddings. The extensive range of menu items includes a full selection of hors d'oeuvres, entrées, beverages, and special-request items. The demand for these services is much more seasonal, with heavier demands occurring in the late spring–early summer for weddings and the late fall–early winter for holiday parties. However, this segment also has a longer planning horizon. Customers book dates and choose menu items weeks or months ahead of time.

CKC's food preparation facilities support both operations. The physical facilities layout resembles that of a job process. Five major work areas consist of a stove–oven area for hot food preparation, a cold area for salad preparation, an hors d'oeuvre preparation area, a sandwich preparation area, and an assembly area where deliver-only orders are boxed and deliver-and-serve orders are assembled and trayed. Three walk-in coolers store foods requiring refrigeration, and a large pantry houses nonperishable goods. Space limitations and the risk of spoilage limit the amount of raw materials and prepared food items that can be carried in inventory at any one time. CKC purchases desserts from outside vendors. Some deliver the desserts to CKC; others require CKC to send someone to pick up desserts at their facilities.

The scheduling of orders is a two-stage process. Each Monday, Wayne and Janet develop the schedule of deliver-and-serve orders to be processed each day. CKC typically has multiple deliver-and-serve orders to fill each day of the week. This level of demand allows a certain efficiency in the preparation of multiple orders. The deliver-only orders are scheduled day to day, owing to the short-order lead times. CKC sometimes runs out of ingredients for deliver-only menu items because of the limited inventory space.

Wayne and Janet have 10 full-time employees: two cooks and eight food preparation workers, who also work as servers for the deliver-and-serve orders.

In periods of high demand, they hire additional part-time servers. The position of cook is specialized and requires a high degree of training and skill. The rest of the employees are flexible and move between tasks as needed.

The business environment for catering is competitive. The competitive priorities are high-quality food, delivery reliability, flexibility, and cost—in that order. "The quality of the food and its preparation is paramount," states Wayne Williams. "Caterers with poor-quality food will not stay in business long." Quality is measured by both freshness and taste. Delivery reliability encompasses both on-time delivery and the time required to respond to customer orders (in effect, the order lead time). Flexibility focuses on both the range of catering requests that a company can satisfy and menu variety.

Recently, CKC began to notice that customers are demanding more menu flexibility and faster response times. Small specialty caterers who entered the market are targeting specific well-defined market segments. One example is a small caterer called Lunches-R-Us, which located a facility in the middle of a large office complex to serve the lunch trade and competes with CKC on cost.

Wayne and Janet Williams are impressed by the lean systems concept, especially the ideas related to increasing flexibility, reducing lead times, and lowering costs. They sound like what CKC needs to remain competitive. However, the Williamses wonder whether lean concepts and practices are transferable to a service business.[6]

QUESTIONS

1. Are the operations of Copper Kettle Catering conducive to the application of lean concepts and practices? Explain.
2. What, if any, are the major barriers to implementing a lean system at Copper Kettle Catering?
3. What would you recommend that Wayne and Janet Williams do to take advantage of lean concepts in operating CKC?

VIDEO CASE Lean Systems at Autoliv

Autoliv is a world-class example of lean manufacturing. This Fortune 500 company makes automotive safety components such as seat belts, airbags, and steering wheels, and has over 80 plants in more than 32 countries. Revenues in 2007 topped $6.7 billion. Autoliv's lean manufacturing environment is called the Autoliv Production System (APS) and is based on the principles of lean manufacturing pioneered by Toyota, one of the world's largest automobile manufacturers, and embodied in its Toyota Production System (TPS).

At the heart of Autoliv is a system that focuses on continuous improvement. Based on the "House of Toyota," Autoliv's Ogden, Utah, airbag module plant puts the concepts embodied in the house to work every day. The only difference between the Toyota house and the one at Autoliv is that the company has added a third pillar to its house to represent employee involvement in all processes because a culture of involvement, while the norm in Japan, is not always found in the United States.

Autoliv started its lean journey back in 1995. At that time, the Ogden plant was at manufacturing capacity with 22 work cells. Company managers acknowledge that, back then, Autoliv was "broken" and in need of significant and immediate change if it was to survive. This meant that everyone—from senior management to employees and suppliers—needed to be onboard with rebuilding the company. It was not that the company could not fulfill the needs of its automaker customers; however, with increasing demand for both reliable and cost-effective component supplies, pressure to change became obvious. Recognizing the value of Toyota's approach, senior management made the commitment to embark on its own journey to bring the transformative culture of lean manufacturing to Autoliv.

In 1998, *sensei* Takashi Harada arrived from Japan to spend 3 years teaching top company managers the principles, techniques, and culture of the lean system. This helped managers create an environment in which continuous improvement could be fostered and revered as an essential activity for long-term success. Because the environment was changing, it made it difficult at first for suppliers to meet Autoliv's constantly changing and unstable processes. It also made problems visible and forced the company to address and resolve the problems instead of finding ways to work around them, as had been done in the past. Daily audits, monthly training, and more in-depth education programs were created to help focus attention on where changes needed to be made. Workers and management were organized into teams that were held accountable for common goals and tasked with working toward common success.

By 2004, the lean culture was integrated into the company, and it now hosts regular visits by other corporations who want to learn from Autoliv's journey and experiences. Compared to 1995, the space required for a typical work cell has been reduced by 88.5 percent, while the number of cells has grown over 400 percent. This has allowed Autoliv to dramatically increase its production capacity with minimal investment.

Lean concepts play out every day in each plant. For example, everyone gathers at the start of the workday for preshift stretching and a brief meeting—this is part of the employee involvement pillar in the APS House. Then, workers head to one of 104 work cells on the plant floor. Heijunka Room team members deliver heijunka cards to each cell to communicate the work to be done in that cell. Lot sizes may vary with each card delivered to the cell. Everything the workers need to make the lot is in the cell and regularly replenished through the Kanban card system. Every 24 minutes, another heijunka card comes to the cell to signal workers what they will build next. This is part of the JIT pillar in the house.

Since a culture of continuous improvement requires employees at every level to be responsible for quality, a worker may identify an "abnormal condition" during work execution that slows down the work of the cell, or stops it altogether. This is embodied in the right pillar of the Toyota house—jidoka, which Autoliv interprets as "stop and fix." This is a rare occurrence, however, since both Autoliv and its suppliers are expected to deliver defect-free products. When a supplier is new or has experienced quality issues, the supplier pays for inspection in Autoliv's receiving dock area until Autoliv is certain the supplier can meet quality expectations for all future deliveries. In this manner, workers in the cells know they can trust the integrity of the raw materials arriving through the Kanban system into their cells for assembly. Jidoka may also come into play when a machine does not operate properly or an employee notices a process that has deviated from the standard. When workers "stop and fix" a problem at the point of its creation, they save the company from added cost as well as lost confidence in the eyes of the customer.

[6] *Source:* This case was prepared by Dr. Brooke Saladin, Wake Forest University, as a basis for classroom discussion. Copyright © Brooke Saladin. Reprinted by permission.



Autoliv employee folds an air bag in a Toyota-inspired production cell.

Pearson Education

To help focus worker efforts daily, Autoliv has a blue "communication wall" that all workers see as they head to their worksite. The wall contains the company's "policy deployment," which consists of company-wide goals for customer satisfaction, shareholder/financial performance, and safety and quality. The policy deployment begins with the company-wide goals, which then flow down to the plant level through the plant manager's goals, strategies, and actions for the facility. These linked activities ensure that Autoliv achieves its goals. By communicating this information—and more—in a visual manner, the central pillar of the APS House is supported. Other visual communication and management methods are in place as well. For example, each cell has an overhead banner that states how that cell is doing each month in the areas of safety, quality, employee involvement, cost, and delivery. These all tie into the policy deployment shown on the communication wall.

Another visual communication method is to use a "rail" for the management of the heijunka cards in each cell. The rail has color-coded sections. As each card is delivered, it slides down a color-coded railing to the team. At the end nearest the cell, the rail is green, indicating that any cards that fall into this area can be completed within normal working hours. The middle of the rail is yellow, indicating overtime for the cell that day. The end is red, meaning weekend overtime is required to bring work processes back into harmony with customer demand. As a heijunka card slides down the rail, it stops when it hits the end or stacks up behind another card. If the cell is not performing at the required pace to meet customer demand, the cards will stack up on the rail and provide a very visual cue that the cell is not meeting expectations. This provides an opportunity for cell team members as well as management to implement immediate countermeasures to prevent required overtime if the situation is not remedied.

All aisles and walkways surrounding cells are to be clear of materials, debris, or other items. If anything appears in those areas, everyone can quickly see the abnormality. As team members work together to complete their day's work, the results of their efforts are displayed boldly on each cell's "communi-cube." This four-sided rotating display visually tells the story of the cell's productivity, quality, and 5S performance. The cube also contains a special section for the management of kaizen suggestions for the team itself. These kaizens enable the team to continuously improve the work environment as well as drive the achievement of team results.

Autoliv's lean journey embodied in the Autoliv Production System has led to numerous awards and achievement of its policy deployment goals. Product defects have been dramatically reduced, inventory levels are lower, and inventory turnover is approaching world-class levels of 50. Employee turnover is close to 5 percent and remains well below that of other manufacturers in the industry. Yet the destination has not been reached. The company continues its emphasis on driving systemic improvement to avoid complacency and loss of competitive advantage. Best practices from sources beyond each immediate area of the organization are studied and integrated. And finding ways to engage and reward Autoliv's workforce in a maturing market is critical. Kaizen suggestions in the most recent year at the Ogden plant totaled 74,000, or nearly 60 per employee, indicating the culture of continuous improvement in Autoliv's APS House is alive and well.

QUESTIONS

1. Why is a visual management approach such an integral part of Autoliv's lean system?
2. Describe the JIT considerations presented in the chapter as they relate to Autoliv's manufacturing environment.
3. Which method of workflow is embodied in Autoliv's system? Why is this approach most suitable to its lean environment?
4. When Autoliv started its lean journey, a number of operational benefits and implementation issues had to be addressed. What were they, and how were they addressed?

5

CAPACITY PLANNING

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

5.1 Define long-term capacity and its relationship with economies and diseconomies of scale.

5.2 Understand the main differences between the expansionist and wait-and-see capacity timing and sizing strategies.

5.3 Identify a systematic four-step approach for determining long-term capacity requirements and associated cash flows.

5.4 Describe how the common tools for capacity planning, such as waiting-line models, simulation, and decision trees, assist in capacity decisions.

3M



NARONG JHANWATTANA/Shutterstock

3M produces the N95 type respirator masks for the coronavirus.

Minnesota Mining and Manufacturing (3M) company is a diversified conglomerate that has operations in more than 70 countries. It manufactures over 60,000 products, such as adhesives, window films, paint protection films, laminates, and consumer products like Scotch tape and Post-its, among others, that are used in the health care, manufacturing, and construction industries, as well as several others. With nearly $33 billion in sales and 93,500 employees in 2018, 3M has been an icon of innovation and steady growth since its founding as a mining company in Minnesota in 1902.

3M is also the manufacturer of N95 respirator masks, which are so named because they can block 95% of airborne particles as small as 0.3 micron, which is 1/100 the thickness of human hair, from entering the mouth of the wearer. They were critically needed to protect frontline health care workers in hospitals and clinics when the global COVID-19 pandemic came to the U.S. shores early in 2020, and then escalated dramatically in March 2020. Manufacturing plants that make these masks are located in China, Latin America, Europe, and the United States. The demand soon far outstripped the available capacity, and the shortage was so acute that the U.S. government requested 3M not only to stop exporting N95 masks manufactured in the United States, but, through the Defense Production Act, also required 3M to import 166.5 million masks from its Shanghai plant over a 3-month period starting in April. Along with Honeywell and Kimberly Clark, 3M is the only major producer of such masks in the United States.

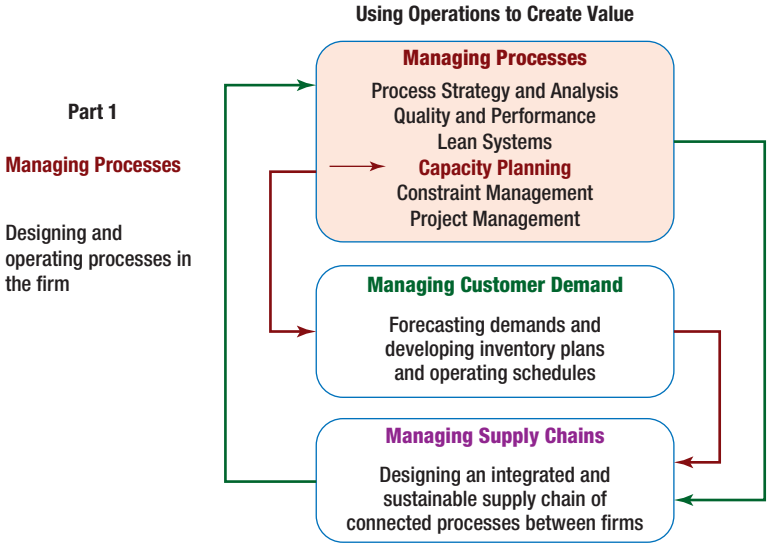
How does a firm increase its production capacity in such a short time to meet massive demand that could not have been foreseen ahead of time? Learning from the SARS epidemic in 2002–2003, 3M built "surge capacity" in its respirator manufacturing plants across the globe to prepare for such emergencies. Factories added assembly lines that would not be used in normal times, and suppliers were similarly put on alert to be ready when needed. 3M also started sourcing its materials for respirators close to its assembly plants, from which it served its customers in the same markets. Having secured over $200 million worth of federal contracts, 3M is now using this surge capacity and localized supply chains to make more than a billion masks by the end of 2020. At its 450,000-square-foot respirator mask factory in Aberdeen, South Dakota, idle machine capacity installed for this purpose was activated. Robots and other automation loaded assembly lines with mask components such as respirator cups, filters, nose clips, and nose foam. Its 650 workers started working overtime to keep packaging and other operations running 7 days a week, while maintaining a safe 6-foot social distancing rule by placing yellow markers on the shop floor. An additional 500 workers were hired and underwent medical exams and training before starting work. Workers generally take great pride in working at a respirator mask manufacturing plant.

3M has doubled its global production to 95 million masks a month in just 2 months, and is investing in new equipment to build two new N95 assembly lines at its Aberdeen, South Dakota plant. It is also building an N95 assembly line in Wisconsin, which will eventually move to Aberdeen, South Dakota. These additions in capacity will push its global output to two billion N95 masks within 12 months. Through astute forward planning, flawless execution, and massive capacity expansion, 3M could literally prove to be a life saver in the fight against a global pandemic that has shown little sign of abating since its advent in late 2019.[1]

[1] *Sources:* Brian Gruley and Rick Clough, "How 3M Plans to Make More Than a Billion Masks by End of Year," *Bloomberg Businessweek* (March 25, 2020), https://www.bloomberg.com/news/features/2020-03-25/3m-doubled-production-of-n95-face-masks-to-fight-coronavirus (June 29, 2020); Dee DePass, "3M Wins Defense Contract, Boosting US N95 Production Even More to 95M Monthly," *Star Tribune* (May 7, 2020); https://en.wikipedia.org/wiki/3M (June 29, 2020); https://www.assemblymag.com/articles/95705-m-to-triple-monthly-us-production-of-n95-masks (June 29, 2020).

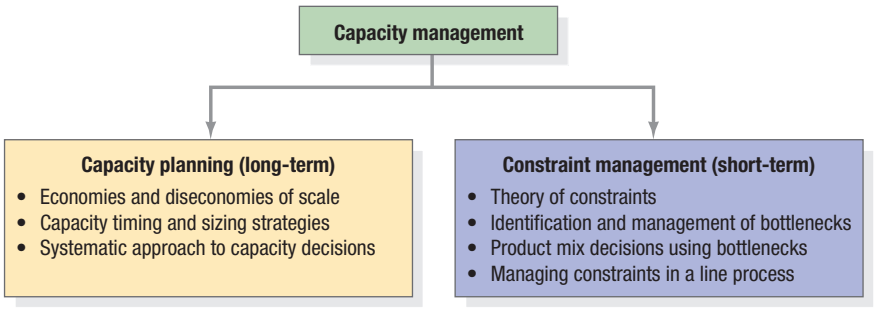
capacity
The maximum rate of output of a process or a system.

Capacity is the maximum rate of output of a process or a system. Managers are responsible for ensuring that the firm has the capacity to meet current and future demand. Otherwise, the organization will miss out on opportunities for growth and profits. Making adjustments to decrease capacity, or to increase it, is therefore an important part of the job. Acquisition of new capacity requires extensive planning and often involves significant expenditure of resources and time. Bringing new capacity online can take several years, for instance, in the semiconductor industry or in the construction of new nuclear power plants. Sometimes firms do not have enough time available to build new plants in order to meet sudden demand, and so must plan ahead by investing in excess surge capacity, as illustrated by 3M.



Capacity decisions related to a process need to be made in light of the role the process plays within the organization and the supply chain as a whole, because changing the capacity of a process will have an impact on other processes within the firm and across the chain. As such, capacity decisions have implications for different functional areas throughout the organization. Accounting needs to provide the cost information needed to evaluate capacity expansion decisions. Finance performs the financial analysis of proposed capacity expansion investments and raises funds to support them. Marketing provides demand forecasts required to identify capacity gaps. Management information systems design the electronic infrastructure that is needed to make data such as cost information, financial performance measures, demand forecasts, and work standards available to those needing it to analyze capacity options. Operations is involved in the selection of capacity strategies that can be implemented to effectively meet future demand. Purchasing facilitates acquisition of outside capacity from suppliers. Finally, human resources focuses on hiring and training employees needed to support internal capacity plans. So, all departments in a firm get involved with and are affected by long-term capacity planning decisions.

Increasing or decreasing capacity by itself is not as important as ensuring that the entire supply chain, from order entry to delivery, is designed for effectiveness. Capacity decisions must be made in light of several long-term issues such as the firm's economies and diseconomies of scale, capacity cushions, timing and sizing strategies, and trade-offs between customer service and capacity utilization. Therefore, this chapter focuses on how managers can best revise capacity levels and best determine when to add or reduce capacity for the long term. The type of capacity decisions differ for different time horizons. Both long-term and short-term issues associated with planning capacity and managing constraints are important and must be understood in conjunction with one another. While we deal with the long-term decisions here in the capacity management framework, short-term decisions centered on making the most of existing capacity by managing constraints are more fully explored in Chapter 6, "Constraint Management."



Planning Long-Term Capacity

Long-term capacity plans deal with investments in new facilities and equipment at the organizational level and require top management participation and approval because they are not easily reversed. These plans cover at least 2 years into the future, but construction lead times can sometimes be longer and result in longer planning time horizons.

Long-term capacity planning is central to the success of an organization. Too much capacity can be as agonizing as too little. Often entire industries can fluctuate over time between too much and too little capacity, as evidenced in the airline and cruise ship industry over the past 20 years. When choosing a capacity strategy, managers must consider questions such as the following: How much of a cushion is needed to handle variable, or uncertain, demand? Should we expand capacity ahead of demand, as Tesla did with battery production by building the world's largest battery



Sheila Fitzgerald/Shutterstock

Tesla Supercharger station with 40 charging stations all on solar power. Supercharger stations allow Tesla cars to be fast-charged at the network within an hour. Tesla's battery charging stations emphasize the close connection between the electric car and the batteries that serve as the main source of energy for this new generation automobile. Tesla's long-term growth strategies are therefore tied to also expanding its battery manufacturing capacity.

factory at an expense of $4 to $5 billion, or wait until demand is more certain? Even before these questions can be answered, a manager needs to be able to measure a process's capacity. So, a systematic approach is needed to answer these and similar questions and to develop a capacity strategy appropriate for each situation.

Measures of Capacity and Utilization

No single capacity measure is best for all situations. A retailer measures capacity as annual sales dollars generated per square foot, whereas an airline measures capacity as available seat-miles (ASMs) per month. A theater measures capacity as number of seats, while a job shop measures capacity as number of machine hours. In general, capacity can be expressed in one of two ways: in terms of output measures or input measures.

Output Measures of Capacity *Output measures* of capacity are best utilized when applied to individual processes within the firm or when the firm provides a relatively small number of standardized services and products. High-volume processes, such as those in a car manufacturing plant, are a good example. In this case, capacity would be measured in terms of the number of cars produced per day. However, many processes produce more than one service or product. As the amount of customization and variety in the product mix increases, output-based capacity measures become less useful. Then input measures of capacity become the usual choice for measuring capacity.

Input Measures of Capacity *Input measures* are generally used for low-volume, flexible processes, such as those associated with a custom furniture maker. In this case, the furniture maker might measure capacity in terms of inputs such as number of workstations or number of workers. The problem with input measures is that demand is invariably expressed as an output rate. If the furniture maker wants to keep up with demand, he or she must convert the business's annual demand for furniture into labor hours and number of employees required to fulfill those hours. We will explain precisely how this input–output conversion is done later in the chapter.

utilization

The degree to which equipment, space, or the workforce is currently being used, and is measured as the ratio of average output rate to maximum capacity (expressed as a percent).

Utilization **Utilization** is the degree to which a resource such as equipment, space, or the workforce is currently being used and is measured as the ratio of average output rate to maximum capacity (expressed as a percent). The average output rate and the capacity must be measured in the same terms—that is, time, customers, units, or dollars. The utilization rate indicates the need for adding extra capacity or eliminating unneeded capacity.

$$\text{Utilization} = \frac{\text{Average output rate}}{\text{Maximum capacity}} \times 100\%$$

Here, we refer to maximum capacity as the greatest level of output that a process can reasonably sustain for a longer period, using realistic employee work schedules and the equipment currently in place. In some processes, this capacity level implies a one-shift operation; in others, it implies a three-shift operation. A process can be operated above its capacity level using marginal methods of production, such as overtime, extra shifts, temporarily reduced maintenance activities, overstaffing, and subcontracting. Although they help with temporary peaks, these options cannot be sustained for long. For instance, being able to handle 40 customers for a 1-week peak is quite different from sustaining it for 6 months. Employees do not want to work excessive overtime for extended periods, so quality drops. In addition, the costs associated with overtime drive up the firm's costs. So operating processes close to (or even temporarily above) their maximum capacity can result in low customer satisfaction, minimal profits, and even losing money despite high sales levels. Such was the case with U.S. aircraft manufacturers in the late 1980s, which culminated in Boeing acquiring McDonnell Douglas in 1997 to rein in skyrocketing costs and plummeting profits.

economies of scale

A concept that states that the average unit cost of a service or good can be reduced by increasing its output rate.

Economies of Scale

Deciding on the best level of capacity involves consideration for the efficiency of the operations. A concept known as **economies of scale** states that the average unit cost of a service or good can be reduced by increasing its output rate. Four principal reasons explain why economies of scale can

drive costs down when output increases: (1) Fixed costs are spread over more units; (2) construction costs are reduced; (3) costs of purchased materials are cut; and (4) process advantages are found.

Spreading Fixed Costs In the short term, certain costs do not vary with changes in the output rate. These fixed costs include heating costs, debt service, and managers' salaries. The depreciation of plant and equipment already owned is also a fixed cost in the accounting sense. When the average output rate—and, therefore, the facility's utilization rate—increases, the average unit cost drops because fixed costs are spread over more units.

Reducing Construction Costs Certain activities and expenses are required to build small and large facilities alike: building permits, architects' fees, and rental of building equipment. Doubling the size of the facility usually does not double construction costs.

Cutting Costs of Purchased Materials Higher volumes can reduce the costs of purchased materials and services. They give the purchaser a better bargaining position and the opportunity to take advantage of quantity discounts. Retailers such as Walmart reap significant economies of scale because their national and international stores buy and sell huge volumes of each item.

Finding Process Advantages High-volume production provides many opportunities for cost reduction. At a higher output rate, the process shifts toward a line process, with resources dedicated to individual products. Firms may be able to justify the expense of more efficient technology or more specialized equipment. The benefits from dedicating resources to individual services or products may include speeding up the learning effect, lowering inventory, improving process and job designs, and reducing the number of changeovers.

Diseconomies of Scale

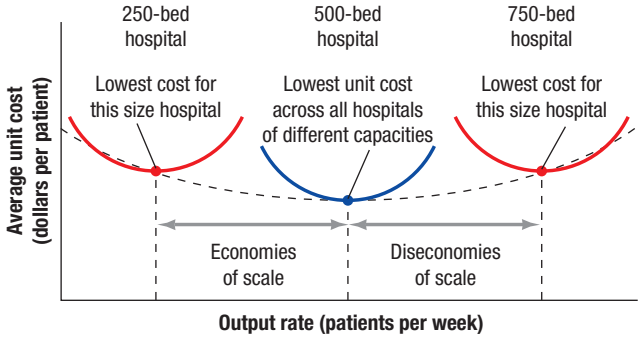
Bigger is not always better, however. At some point, a facility can become so large that **diseconomies of scale** set in; that is, the average cost per unit increases as the facility's size increases. The reason is that excessive size can bring complexity, loss of focus, and inefficiencies that raise the average unit cost of a service or product. Too many layers of employees and bureaucracy can cause management to lose touch with employees and customers. A less agile organization loses the flexibility needed to respond to changing demand. Many large companies become so involved in analysis and planning that they innovate less and avoid risks. The result is that small companies outperform corporate giants in numerous industries.

diseconomies of scale
Occurs when the average cost per unit increases as the facility's size increases.

Figure 5.1 illustrates the transition from economies of scale to diseconomies of scale. The 500-bed hospital shows economies of scale because the average unit cost at its *best operating level*, represented by the blue dot at which the lowest average unit cost is attained, is less than that of the 250-bed hospital. However, assuming that sufficient demand exists, further expansion to a 750-bed hospital leads to higher average unit costs and diseconomies of scale. One reason the 500-bed hospital enjoys greater economies of scale than the 250-bed hospital is that the cost of building and equipping it is less than twice the cost for the smaller hospital. The 750-bed facility would enjoy similar savings. Its higher average unit costs can be explained only by diseconomies of scale, which outweigh the savings realized in construction costs.

Figure 5.1 does not mean that the optimal size for all hospitals is 500 beds. Optimal size depends on the number of patients per week to be served. On the one hand, a hospital serving a small community could have lower costs by choosing a 250-bed capacity rather than the 500-bed capacity. On the other hand, a large community might be served more efficiently by two 500-bed hospitals than by one 1,000-bed facility if diseconomies of scale exist at the bigger size.

▼ **FIGURE 5.1**
Economies and Diseconomies of Scale



Capacity Timing and Sizing Strategies

Operations managers must examine three dimensions of capacity strategy before making capacity decisions: (1) sizing capacity cushions, (2) timing and sizing expansion, and (3) linking process capacity and other operating decisions.

Sizing Capacity Cushions

Average utilization rates for any resource should not get too close to 100 percent over the long term, though it may occur for some processes from time to time in the short run. If the demand keeps increasing over time, then long-term capacity must be increased as well to provide some buffer against uncertainties. When average utilization rates approach 100 percent, it is usually a signal to increase capacity or decrease order acceptance to avoid declining productivity.

capacity cushion
The amount of reserve capacity a process uses to handle sudden increases in demand or temporary losses of production capacity; it measures the amount by which the average utilization (in terms of total capacity) falls below 100 percent.

The **capacity cushion** is the amount of reserve capacity a process uses to handle sudden increases in demand or temporary losses of production capacity; it measures the amount by which the average utilization (in terms of total capacity) falls below 100 percent. Specifically,

$$\text{Capacity cushion, } C = 100\ (\%) - \text{Average Utilization rate } (\%)$$

The appropriate size of the cushion varies by industry. In the capital-intensive paper industry, where machines can cost hundreds of millions of dollars each, cushions well under 10 percent are preferred. The less capital-intensive hotel industry breaks even with a 60 to 70 percent utilization (40 to 30 percent cushion), and begins to suffer customer-service problems when the cushion drops to 20 percent. The more capital-intensive cruise ship industry prefers cushions as small as 5 percent. Large cushions are particularly vital for front-office processes where customers expect fast service times.

Businesses find large cushions appropriate when demand varies. In certain service industries (the grocery industry, for example), demand on some days of the week is predictably higher than on other days, and even hour-to-hour changes are typical. Long customer waiting times are not acceptable because customers grow impatient if they have to wait in a supermarket checkout line for more than a few minutes. Prompt customer service requires supermarkets to maintain a capacity cushion large enough to handle peak demand. Large cushions also are necessary when future demand is uncertain, particularly if resource flexibility is low. Simulation and waiting-line analysis (see Supplement B, "Waiting Lines") can help managers better anticipate the relationship between capacity cushion and customer service.

Another type of demand uncertainty occurs with a changing product mix. Though total demand measured in monetary terms might remain stable, the load can shift unpredictably from one workstation to another as the product mix changes. Supply uncertainty tied to delivery of purchased materials also makes large capacity cushions helpful. Capacity often comes in large increments because a complete machine has to be purchased even if only a fraction of its available capacity is needed, which in turn creates a large cushion. Firms also need to build in excess capacity to allow for employee absenteeism, vacations, holidays, and any other delays. If a firm is experiencing high overtime costs and frequently needs to rely on subcontractors, it perhaps needs to increase its capacity cushions.

The argument in favor of small cushions is simple: Unused capacity costs money. For capital-intensive firms, minimizing the capacity cushion is vital. Studies indicate that businesses with high capital intensity achieve a low return on investment when the capacity cushion is high. This strong correlation does not exist for labor-intensive firms, however. Their return on investment is about the same because the lower investment in equipment makes high utilization less critical. Small cushions have other advantages. By implementing a small cushion, a company can sometimes uncover inefficiencies that were difficult to detect when cushions were larger. These inefficiencies might include employee absenteeism or unreliable suppliers. Once managers and workers identify such problems, they often can find ways to correct them.

Timing and Sizing Expansion

The second issue of capacity strategy concerns when to adjust capacity levels and by how much. At times, capacity expansion can be done in response to changing market trends. General Motors decided to increase production capacity of the four-seat series hybrid car Chevrolet Volt from 30,000 units to 45,000 units in 2012 because of strong public interest. While we deal with this issue from the perspective of capacity expansion in greater detail here, it must be noted that firms may not always be looking to expand capacity but at times may be forced to retrench, as evidenced by the situation in the airlines industry, where all major airlines have consolidated routes and reduced the total number of flights in the face of increasing oil costs. Some of this consolidation has been achieved through mergers like United Airlines and Continental to create the world's largest airline company, as well as the merger between Delta and Northwest Airlines.

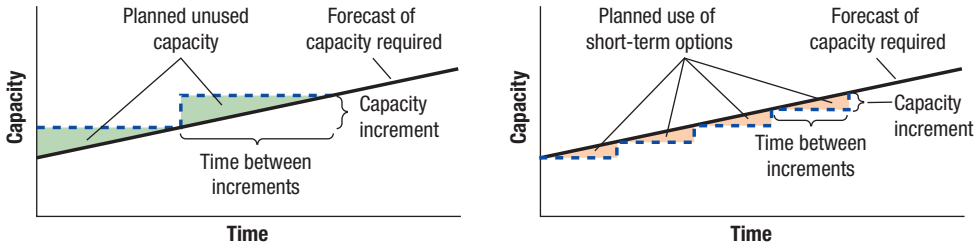
Figure 5.2 illustrates two extreme strategies for expanding capacity: the *expansionist strategy*, which involves large, infrequent jumps in capacity, and the *wait-and-see strategy*, which involves smaller, more frequent jumps.

Expansionist Strategy The timing and sizing of expansion are related; that is, if demand is increasing and the time between increments increases, the size of the increments must also increase. The expansionist strategy, which stays ahead of demand, minimizes the chance of sales lost to insufficient capacity.

Several factors favor the expansionist strategy. Expansion can result in economies of scale and a faster rate of learning, thus helping a firm reduce its costs and compete on price. This strategy might increase the firm's market share or act as a form of preemptive marketing. By making a large capacity expansion or announcing that one is imminent, the firm can preempt the expansion of other firms. These other firms must sacrifice some of their market share or risk burdening

the industry with overcapacity. To be successful, however, the preempting firm must have the credibility to convince the competition that it will carry out its plans—and must signal its plans before the competition can act.

Wait-and-See Strategy The conservative wait-and-see strategy is to expand in smaller increments, such as by renovating existing facilities rather than building new ones. The wait-and-see strategy lags behind demand. To meet any shortfalls, it relies on short-term options, such as use of overtime, temporary workers, subcontractors, stockouts, and the postponement of preventive maintenance on equipment. It reduces the risks of overexpansion based on overly optimistic demand forecasts, obsolete technology, or inaccurate assumptions regarding the competition.



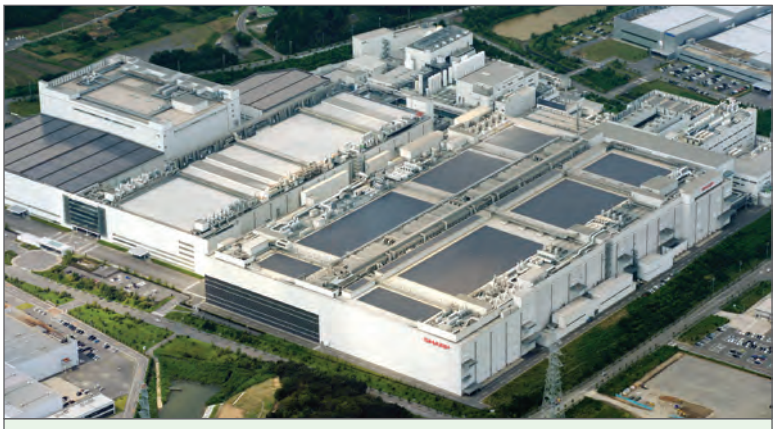
(a) Expansionist strategy

(b) Wait-and-see strategy

◀ **FIGURE 5.2**
Two Capacity Strategies

However, this strategy has its own risks, such as being preempted by a competitor or being unable to respond if demand is unexpectedly high. Critics claim the wait-and-see strategy is a short-term strategy typical of some U.S. management styles. Managers on the fast track to corporate advancement tend to take fewer risks. They earn promotions by avoiding the big mistakes and maximizing short-term profits and return on investment. The wait-and-see strategy fits this short-term outlook but can erode market share over the long run.

Management may choose one of these two strategies or one of the many between these extremes. With strategies in the more moderate middle, firms can expand more frequently (on a smaller scale) than they can with the expansionist strategy without lagging behind demand as with the wait-and-see strategy. An intermediate strategy could be to *follow the leader*, expanding when others do. If others are right, so are you, and nobody gains a competitive advantage. If others make a mistake and overexpand, so do you, but everyone shares in the agony of overcapacity. Such a situation was noted for the airlines industry, and may yet occur in the liquid crystal display (LCD) industry due to large capacity expansions by Sharp Corporation, Sony, and Samsung.



Kyodo/Newscom

Sharp's Kameyama plant No. 2 in Japan.

Linking Capacity and Other Decisions

Capacity decisions should be closely linked to processes and supply chains throughout the organization. When managers make decisions about designing processes, determining degree of resource flexibility and inventory, and locating facilities, they must consider its impact on capacity cushions. Capacity cushions in the long run buffer the organization against uncertainty, as do resource flexibility, inventory, and longer customer lead times. If a change is made in any one decision area, the capacity cushion may also need to be changed to compensate. For example, capacity cushions for a process can be lowered if less emphasis is placed on fast deliveries (*competitive priorities*), if yield losses (*quality*) drop, or if investment in capital-intensive equipment increases or worker flexibility increases (*process design*). Capacity cushions can also be lowered if the company is willing to smooth the output rate by raising prices when inventory is low and decreasing prices when it is high.

As the following Managerial Challenge shows, selection of the best strategy for expanding capacity is situational. In addition, a well-thought-out approach is needed for making long-term capacity decisions that can not only flesh out all the alternatives but also systematically evaluate them to achieve organizational goals.

MANAGERIAL CHALLENGE Operations

The Tower Medical Center (TMC) is a level II trauma center with 520 beds and 16 operating rooms. The emergency department (ED) has experienced an increase from 40,000 visits annually to over 55,000 this year. The increase in volume has increased the wait times for service and the length of stay until discharge. Further, 3,000 patients left the ED last year without being seen and given a medical evaluation. These are indicators of overcrowding, and lead to increased costs for admitted patients and even increased patient mortality.

The ED is not the only area experiencing capacity pressure. The OR performs over 10,000 surgeries annually. However, demand for surgeries is increasing. In the first 8 months of this year, TMC has experienced a net increase of 1,200 new cases relative to last year. The perioperative department, which does ward admission, anesthesia, surgery, and recovery, is experiencing high levels of utilization that threaten the quality of care.

Nirav Patel, facility manager at TMC, must develop a capacity plan for the ED and the OR departments. The ER experiences patient volumes that not only are increasing but also vary substantially throughout the year, particularly during specific seasons and holidays. Does the ER staff have the appropriate capacity cushion for the changes in demand? Can the staffing pattern, such as the timing of hires and shift schedules, be changed to match demands? Can short-term capacity options such as overtime be used? Can the volume increase be trusted to continue into the future? Should Nirav use an expansionist or a wait-and-see strategy for the ED?

The OR poses a different problem. While the staffing pattern of the perioperative personnel can be restructured, such as changing nurse shifts to 12-hour shifts and adding some personnel, the opportunity exists to add some machinery to the OR. A DaVinci surgical robot would reduce surgical times and therefore increase patient throughput. It would actually bring the capacity above the projected patient volume. However, the robot would cost in excess of $2 million and add about $200,000 a year in maintenance. Nirav has to decide what strategy to take. The remainder of this chapter will provide Nirav guidance in selecting the best long-term strategy and capacity plans for the ED and the OR departments.

A Systematic Approach to Long-Term Capacity Decisions

Long-term decisions for capacity would typically include whether to add a new plant or warehouse or to reduce the number of existing ones, how many workstations a given department should have, or how many workers are needed to staff a given process. Some of these decisions can take years to become operational. Hence, a systematic approach is needed to plan for long-term capacity decisions.

Although each situation is somewhat different, a four-step procedure generally can help managers make sound capacity decisions. (In describing this procedure, we assume that management already performed the preliminary steps of determining the process's existing capacity and assessing whether its current capacity cushion is appropriate.)

1. Estimate future capacity requirements.
2. Identify gaps by comparing requirements with available capacity.
3. Develop alternative plans for reducing the gaps.
4. Evaluate each alternative, both qualitatively and quantitatively, and make a final choice.

capacity requirement

What a process's capacity should be for some future time period to meet the demand of customers (external or internal), given the firm's desired capacity cushion.

planning horizon

The set of consecutive time periods considered for planning purposes.

Step 1: Estimate Capacity Requirements

A process's **capacity requirement** is what its capacity should be for some future time period to meet the forecasted demand of the firm's customers (external or internal), given the firm's desired capacity cushion. Larger cushions than normal should be planned for those processes or workstations that could potentially become bottlenecks in the future.

Capacity requirements can be expressed in one of two ways: with an output measure or with an input measure. Either way, the foundation for the estimate is forecasts of demand, productivity, competition, and technological change. These forecasts normally need to be made for several time periods in a **planning horizon**, which is the set of consecutive time periods considered for planning purposes. Long-term capacity plans need to consider more of the future (perhaps a whole decade) than do short-term plans. Unfortunately, the further ahead you look, the more chance

you have of making an inaccurate forecast. See Chapter 8, "Forecasting," for a complete discussion of forecast errors and their origins.

Using Output Measures The simplest way to express capacity requirements is as an output rate. As discussed earlier, output measures are appropriate for high-volume processes with little product variety or process divergence. Here, demand forecasts for future years are used as a basis for extrapolating capacity requirements into the future. If demand is expected to double in the next 5 years, then the capacity requirements also double. For example, if a process's current demand is 50 customers per day, then the demand in 5 years would be 100 customers per day. If the desired capacity cushion is 20 percent, management should plan for enough capacity to serve $[100/(1-0.2)] = 125$ customers in 5 years.

Using Input Measures Output measures may be insufficient in the following situations:

- Product variety and process divergence is high.
- The product or service mix is changing.
- Productivity rates are expected to change.
- Significant learning effects are expected.

In such cases, it is more appropriate to calculate capacity requirements using an input measure, such as the number of employees, machines, computers, or trucks. Using an input measure for the capacity requirement brings together demand forecasts, process time estimates, and the desired capacity cushion. When just one service or product is processed at an operation and the time period is a particular year, the capacity requirement, M, is

$$\text{Capacity requirement} = \frac{\text{Processing hours required for years demand}}{\text{Hours available from a single capacity unit (such as an employee or machine) per year, after deducting desired cushion}}$$

$$M = \frac{Dp}{N[1 - (C/100)]}$$

where

D = demand forecast for the year (number of customers served or units produced)

p = processing time (in hours per customer served or unit produced)

N = total number of hours per year during which the process operates

C = desired capacity cushion (expressed as a percent)

M = the number of input units required

M should be calculated for each year in the time horizon. The processing time, p, depends on the process and methods selected to do the work. The denominator is the total number of hours, N, available for the year from one unit of capacity (an employee or machine), multiplied by a proportion that accounts for the desired capacity cushion, C. The proportion is simply $1.0 - C/100$, where C is converted from a percent to a proportion by dividing by 100. For example, a 20 percent capacity cushion means that $1.0 - C/100 = 0.80$.

Setups may be involved if multiple products are being manufactured. **Setup time** is the time required to change a process or an operation from making one service or product to making another. The total setup time is found by dividing the number of units forecast per year, D, by the number of units made in each lot, Q (number of units processed between setups), which gives the number of setups per year, and then multiplying by the time per setup, s. For example, if the annual demand is 1,200 units and the average lot size is 100, there are $1{,}200/100 = 12$ setups per year. Accounting for both processing and setup times for multiple services (products), we get

setup time
The time required to change a process or an operation from making one service or product to making another.

$$\text{Capacity requirement} = \frac{\text{Processing and setup hours required for year's demand, summed over all services or products}}{\text{Hours available from a single capacity unit per year, after deducting desired cushion}}$$

$$M = \frac{[Dp + (D/Q)s]_{\text{product 1}} + [Dp + (D/Q)s]_{\text{product 2}} + \cdots + [Dp + (D/Q)s]_{\text{product } n}}{N[1 - (C/100)]}$$

where

Q = number of units in each lot

s = setup time in hours per lot

What to do when M is not an integer depends on the situation. For example, it is impossible to buy a fractional machine. In this case, round up the fractional part, unless it is cost efficient to use short-term options, such as overtime or stockouts, to cover any shortfalls. If, instead, the capacity unit is the number of employees at a process, a value of 23.6 may be achieved using just 23 employees and a modest use of overtime (equivalent to having 60 percent of another full-time person). Here, the fractional value should be retained as useful information.

Example 5.1 shows how to calculate capacity requirements using input measures of capacity.

EXAMPLE 5.1 Estimating Capacity Requirements When Using Input Measures

A copy center in an office building prepares bound reports for two clients. The center makes multiple copies (the lot size) of each report. The processing time to run, collate, and bind each copy depends on, among other factors, the number of pages. The center operates 250 days per year, with one 8-hour shift. Management believes that a capacity cushion of 15 percent (beyond the allowance built into time standards) is best. It currently has three copy machines. Based on the following table of information, determine how many machines are needed at the copy center.

Item	Client X	Client Y
Annual demand forecast (copies)	2,000	6,000
Standard processing time (hour/copy)	0.5	0.7
Average lot size (copies per report)	20	30
Standard setup time (hours)	0.25	0.40

SOLUTION

$$M = \frac{[Dp + (D/Q)s]_{\text{product 1}} + [Dp + (D/Q)s]_{\text{product 2}} + \cdots + [Dp + (D/Q)s]_{\text{product } n}}{N\,[1 - (C/100)]}$$

$$= \frac{[2{,}000(0.5) + (2{,}000/20)(0.25)]_{\text{client X}} + [6{,}000(0.7) + (6{,}000/30)(0.40)]_{\text{client Y}}}{[(250 \text{ days/year})(1 \text{ shift/day})(8 \text{ hours/day})][1.0 - (15/100)]}$$

$$= \frac{5{,}305}{1{,}700} = \mathbf{3.12}$$

Rounding up to the next integer gives a requirement of four machines.

DECISION POINT

The copy center's capacity is being stretched and no longer has the desired 15 percent capacity cushion with the existing three machines. Not wanting customer service to suffer, management decided to use overtime as a short-term solution to handle past-due orders. If demand continues at the current level or grows, it will acquire a fourth machine.

Step 2: Identify Gaps

capacity gap
Positive or negative difference between projected demand and current capacity.

A **capacity gap** is any difference (positive or negative) between projected capacity requirements (M) and current capacity. Complications arise when multiple operations and several resource inputs are involved. Expanding the capacity of some operations may increase overall capacity. However, as we will learn later in Chapter 6, "Constraint Management," if one operation is more constrained than others, total process capacity can be expanded only if the capacity of the constrained operation is expanded.

Step 3: Develop Alternatives

base case
The act of doing nothing and losing orders from any demand that exceeds current capacity, or incur costs because capacity is too large.

The next step is to develop alternative plans to cope with projected gaps. One alternative, called the **base case**, is to do nothing and simply lose orders from any demand that exceeds current capacity or incur costs because capacity is too large. Other alternatives if expected demand exceeds current capacity are various timing and sizing options for adding new capacity, including the expansionist and wait-and-see strategies illustrated in Figure 5.2. Additional possibilities include expanding at a different location and using short-term options, such as overtime, temporary workers, and subcontracting. Alternatives for reducing capacity include the closing of plants or warehouses, laying off employees, or reducing the days or hours of operation.

Step 4: Evaluate the Alternatives

In this final step, the manager evaluates each alternative, both qualitatively and quantitatively.

Qualitative Concerns Qualitatively, the manager looks at how each alternative fits the overall capacity strategy and other aspects of the business not covered by the financial analysis. Of particular concern might be uncertainties about demand, competitive reaction, technological change, and cost estimates. Some of these factors cannot be quantified and must be assessed on the basis of judgment and experience. Others can be quantified, and the manager can analyze each alternative by using different assumptions about the future. One set of assumptions could represent a worst case, in which demand is less, competition is greater, and construction costs are higher than expected. Another set of assumptions could represent the most optimistic view of the future. This type of "what-if" analysis allows the manager to get an idea of each alternative's implications before making a final choice. Qualitative factors would tend to dominate when a business is trying to enter new markets or change the focus of its business strategy.

Quantitative Concerns Quantitatively, the manager estimates the change in cash flows for each alternative over the forecast time horizon compared to the base case. **Cash flow** is the difference between the flows of funds into and out of an organization over a period of time, including revenues, costs, and changes in assets and liabilities. The manager is concerned here only with calculating the cash flows attributable to the project. Example 5.2 shows how cash flow is used to evaluate capacity alternatives.

cash flow

The difference between the flows of funds into and out of an organization over a period of time, including revenues, costs, and changes in assets and liabilities.

EXAMPLE 5.2 Evaluating the Alternatives

Grandmother's Chicken Restaurant is experiencing a boom in business. The owner expects to serve 80,000 meals this year. Although the kitchen is operating at 100 percent capacity, the dining room can handle 105,000 diners per year. Forecasted demand for the next 5 years is 90,000 meals for next year, followed by a 10,000-meal increase in each of the succeeding years. One alternative is to expand both the kitchen and the dining room now, bringing their capacities up to 130,000 meals per year. The initial investment would be $200,000, made at the end of this year (year 0). The average meal is priced at $10, and the before-tax profit margin is 20 percent. The 20 percent figure was arrived at by determining that, for each $10 meal, $8 covers variable costs and the remaining $2 goes to pretax profit.

What are the pretax cash flows from this project for the next 5 years compared to those of the base case of doing nothing?

Online Resource

Tutor 4.2 in OM Explorer provides a new example to practice projecting cash flows for capacity decisions.



Atstock Productions/Shutterstock

SOLUTION

Recall that the base case of doing nothing results in losing all potential sales beyond 80,000 meals. With the new capacity, the cash flow would equal the extra meals served by having a 130,000-meal capacity, multiplied by a profit of $2 per meal. In year 0, the only cash flow is − $200,000 for the initial investment. In year 1, the 90,000-meal demand will be completely satisfied by the expanded capacity, so the incremental cash flow is (90,000 − 80,000)($2) = $20,000. For subsequent years, the figures are as follows:

Year 2: Demand = 100,000; Cash flow = (100,000 − 80,000)($2) = $40,000
Year 3: Demand = 110,000; Cash flow = (110,000 − 80,000)($2) = $60,000
Year 4: Demand = 120,000; Cash flow = (120,000 − 80,000)($2) = $80,000
Year 5: Demand = 130,000; Cash flow = (130,000 − 80,000)($2) = $100,000

If the new capacity were smaller than the expected demand in any year, we would subtract the base case capacity from the new capacity (rather than the demand). The owner should account for the time value of money, applying such techniques as the net present value or internal rate of return methods (see online Supplement F, "Financial Analysis"). For instance, the net present value (NPV) of this project at a discount rate of 10 percent is calculated here, and equals $13,051.76.

$$\begin{aligned}\text{NPV} &= -200{,}000 + [20{,}000/1.1] + [40{,}000/(1.1)^2] + [60{,}000/(1.1)^3] + [80{,}000/(1.1)^4] + [100{,}000/(1.1)^5] \\ &= -\$200{,}000 + \$18{,}181.82 + \$33{,}057.85 + \$45{,}078.89 + \$54{,}641.07 + \$62{,}092.13 \\ &= \mathbf{\$13{,}051.76}\end{aligned}$$

DECISION POINT

Before deciding on this capacity alternative, the owner should also examine the qualitative concerns, such as future location of competitors. In addition, the homey atmosphere of the restaurant may be lost with expansion. Furthermore, other alternatives should be considered (see Solved Problem 2).

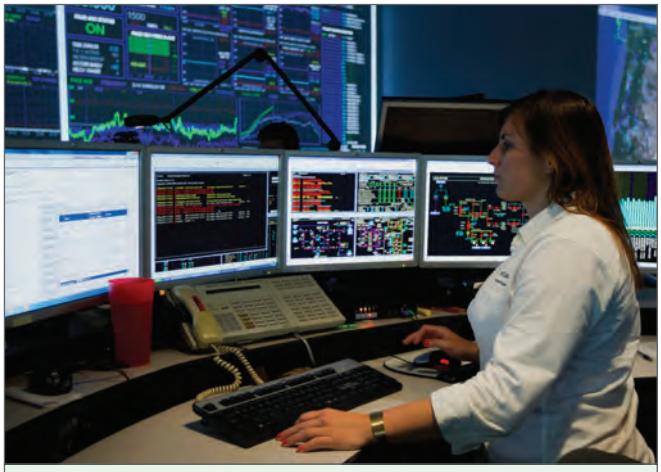
Tools for Capacity Planning

Capacity planning requires demand forecasts for an extended period of time. Unfortunately, forecast accuracy declines as the forecasting horizon lengthens. In addition, anticipating what competitors will do increases the uncertainty of demand forecasts. Demand during any period of time may not be evenly distributed; peaks and valleys of demand may (and often do) occur within the time period. These realities necessitate the use of capacity cushions. In this section, we introduce three tools that deal more formally with demand uncertainty and variability: (1) waiting-line models, (2) simulation, and (3) decision trees. Waiting-line models and simulation account for the random, independent behavior of many customers, in terms of both their time of arrival and their processing needs. Decision trees allow anticipation of events, such as competitors' actions, which requires a sequence of decisions regarding capacities.

Managerial Practice 5.1 shows how PacifiCorp used sophisticated optimization and simulation tools to evaluate different alternatives for long-term capacity planning, including balancing demand and supply of energy from multiple sources.

MANAGERIAL PRACTICE 5.1 Capacity Planning at PacifiCorp

Energy demand in the United States is volatile, making it difficult to predict, while power generation facilities age over time and eventually need to be replaced. Therefore, one of the key decisions for utility companies is planning for the best capacity resource portfolio that is both cost effective and compliant with local government regulations. Capacity decision making in utility companies follows a standardized guideline known as Integrated Resource Planning (IRP). The IRP concept started in the late 1980s between state governments and local utility companies in response to the oil price fluctuations and the introduction of low-cost nuclear energy. An integrated resource plan is a long-term capacity plan for utilities to meet the growing forecasted annual energy demand. Extra capacity cushions are built into the plan to deal with peak demands while meeting the varying state requirements regarding planning horizons, frequency of plan updates, resources to be considered, and stakeholder involvement.



Natalie Behring/Bloomberg via Getty Images

A grid operator works at the PacifiCorp Transmissions Grid Operations center in Portland, Oregon, U.S. PacifiCorp, a unit of Warren Buffett's Berkshire Hathaway Energy that operates the largest transmission system in the western United States, and delivers power to customers in Oregon, Washington, California, Utah, Wyoming, and Idaho. The utility is the second-largest owner of wind generation, behind only another Berkshire subsidiary.

PacifiCorp is a utility company that is a subsidiary of Berkshire Hathaway Energy, and currently operates one of the largest privately held transmission systems in the United States, serving the Western Energy Imbalance Market in multiple states such as Oregon, Washington, California, Idaho, Utah, and Wyoming. Headquartered in Portland, Oregon, PacifiCorp's two business units, Pacific Power and Rocky Mountain Power, serve a combined market of over 1.6 million residential customers, 202,000 commercial customers, and 37,000 industrial and irrigation customers. The service area is 143,000 square miles, and transmission lines add up to 16,500 miles along with 64,000 miles of distribution lines and 900 substations. To prepare for future customer needs, PacifiCorp evaluates a 20-year study period for capacity planning, but mainly focuses on the first 10 years in its assessment of capacity requirements. In the planning horizon of 2011–2020, PacifiCorp forecasted that system peak load will grow at 2.1% per year, and that general energy needs will grow by 1.8% per year. The current capacity was estimated to fall short right from the first year (2011) of the forecast by 326 MW. This deficit was predicted to grow to 3,852 MW by 2020. PacifiCorp has set up plans to introduce additional measures such as demand-side management initiatives (reducing electricity use by promoting saving campaigns, or by implementing efficient load management systems such as smart grid technology), renewable energy, and market purchases. Yet the initial projection of shortfall in the available long-term capacity was significant.

On the basis of these plans, PacifiCorp developed the 2020 capacity mix portfolio using a comprehensive model called System Optimizer. The System Optimizer allows PacifiCorp to determine when and how much to expand resource capacity, run cost simulations on various resource portfolios, and assess the risks. Altogether, PacifiCorp defined 67 input scenarios for the portfolio development. Each scenario was based on alternative transmission configurations, varying carbon dioxide emission control costs and regulation types, natural gas prices, and renewable resource policies. A subsequent sensitivity analysis examined additional incremental costs

for coal plants, alternative load forecasts, renewable generation costs and incentives, and demand-side management resource availability. The best resource portfolios were chosen on the basis of the risk-adjusted total cost, 10-year customer rating impact, carbon dioxide emissions, supply reliability, resource diversity, and uncertainty risk from the regulatory policy change. The chosen portfolio showed a capacity mix of 62.5 percent traditional thermal resources, 13 percent of demand-side management initiatives, and 2.6 percent of renewables. Because the sophisticated simulation model at PacifiCorp can comprehensively evaluate the impact of efficiency-improving demand-side management practices on capacity, the company can make more accurate decisions on whether to add additional resources to its portfolio. This increased precision in capacity estimation saved PacifiCorp from investing in an additional 2,500 MW of supply-side resources, which would have been costly.

Still, the usefulness of the capacity optimization model developed by PacifiCorp is only as good as the input assumptions. For example, the changing political environment is pressing on PacifiCorp to reduce the reliance on fossil fuels, even as it still operates 17 thermal electric facilities that generate electricity from coal, natural gas, or geothermal sources. Even though PacifiCorp's power plants use specialized equipment to control environmental emissions, they are more and more looking toward increasing the proportion of renewable resources in the company's portfolio. Factoring the environmental and compliance pressures into the capacity decision model would be the next challenge that PacifiCorp has to meet.[2]

Waiting-Line Models

Waiting-line models often are useful in capacity planning, such as selecting an appropriate capacity cushion for a high-customer-contact process. Waiting lines tend to develop in front of a work center, such as an airport ticket counter, a machine center, or a central computer. The reason is that the arrival time between jobs or customers varies, and the processing time may vary from one customer to the next. Waiting-line models use probability distributions to provide estimates of average customer wait time, average length of waiting lines, and utilization of the work center. Managers can use this information to choose the most cost-effective capacity, balancing customer service and the cost of adding capacity.

Supplement B, "Waiting Lines," follows this chapter and provides a fuller treatment of these models. It introduces formulas for estimating important characteristics of a waiting line, such as average customer waiting time and average facility utilization for different facility designs. For example, a facility might be designed to have one or multiple lines at each operation and to route customers through one or multiple operations. Given the estimating capability of these formulas and cost estimates for waiting and idle time, managers can select cost-effective designs and capacity levels that also provide the desired level of customer service.

Figure 5.3 shows output from POM for Windows for waiting lines. A professor meeting students during office hours has students arriving on average every 20 minutes (three per hour) and can address their questions in 10 minutes (6 per hour). The professor's utilization is 50 percent; therefore the capacity cushion is 50 percent. With that large a capacity cushion, you might expect that students would experience little or no waiting time. However, the output shows that the probability of having two or more students in line, prob(num in sys > 1), is 0.25. This probability might be surprisingly high, given the large capacity cushion.

k	Prob (num in sys = k)	Prob (num in sys <= k)	Prob (num in sys >k)
0	.5	.5	.5
1	.25	.75	.25
2	.13	.88	.13
3	.06	.94	.06
4	.03	.97	.03
5	.02	.98	.02
6	.01	1	.01
7	.0	1	.0

◀ **FIGURE 5.3**
POM for Windows Output for Waiting Lines during Office Hours

Simulation

More complex waiting-line problems must be analyzed with simulation. It can identify the process's bottlenecks and appropriate capacity cushions, even for complex processes with random demand patterns and predictable surges in demand during a typical day. The SimQuick simulation package available online allows you to build dynamic models and systems. Other simulation packages can be found with Extend, Simprocess, ProModel, and Witness.

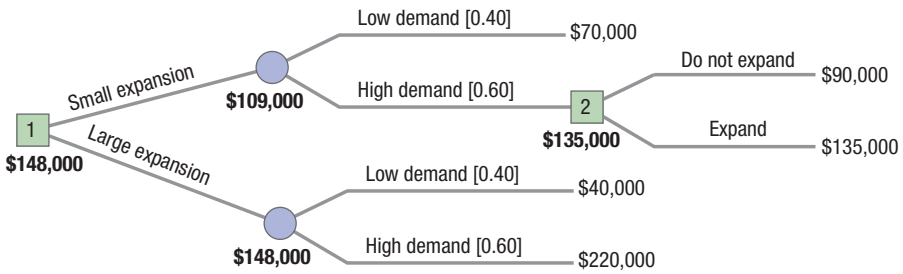
[2] *Sources:* Rachel Wilson and Bruce Biewald, "Best Practices in Electric Utility Integrated Resource Planning," *Synapse Energy Economics, Inc.* (June, 2013); PacifiCorp, "Integrated Resource Plan: Volume 1," http://pacificorp.com/irp (March, 2011); U.S. Department of Energy, "What Is the Smart Grid?" https://www.smartgrid.gov/the_smart_grid/smart_grid.html; https://en.wikipedia.org/wiki/PacifiCorp (June 27, 2020); https://www.pacificorp.com/energy/thermal.html#:~:text=PacifiCorp%20operates%2017%20thermal%20electric%20facilities%20that%20generate, and %20comply%20with%20all%20state%20and%20federal%20requirements (June 27, 2020).

Decision Trees

A decision tree can be particularly valuable for evaluating different capacity expansion alternatives when demand is uncertain and sequential decisions are involved (see Supplement A, "Decision Making"). For example, the owner of Grandmother's Chicken Restaurant (see Example 5.2) may expand the restaurant now, only to discover in year 4 that demand growth is much higher than forecasted. In that case, she needs to decide whether to expand further. In terms of construction costs and downtime, expanding twice is likely to be much more expensive than building a larger facility from the outset. However, making a large expansion now, when demand growth is low, means poor facility utilization. Much depends on the demand.

Figure 5.4 shows a decision tree for this view of the problem, with new information provided. Demand growth can be either low or high, with probabilities of 0.40 and 0.60, respectively. The initial expansion in year 1 (square node 1) can either be small or large. The second decision node (square node 2), whether to expand at a later date, is reached only if the initial expansion is small and demand turns out to be high. If demand is high and if the initial expansion was small, a decision must be made about a second expansion in year 4. Payoffs for each branch of the tree are estimated. For example, if the initial expansion is large, the financial benefit is either $40,000 or $220,000, depending on whether demand is low or high. Weighting these payoffs by the probabilities yields an expected value of $148,000. This expected payoff is higher than the $109,000 payoff for the small initial expansion, so the better choice is to make a large expansion in year 1.

FIGURE 5.4 ▶
A Decision Tree for Capacity Expansion



LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
5.1 Define long-term capacity and its relationship with economies and diseconomies of scale.	Review the section "Measures of Capacity and Utilization" and understand why and how capacity measured in high-volume processes is different from its measurement in low-volume, flexible processes. Also see the section on "Economies of Scale" and "Diseconomies of Scale". Figure 5.1 illustrates the relationship between average unit cost and output rate, and shows different output ranges over which economies and diseconomies of scale can occur.	
5.2 Understand the main differences between the expansionist and wait-and-see capacity timing and sizing strategies.	The section "Capacity Timing and Sizing Strategies" and Figure 5.2 differentiate between the expansionist and wait-and-see strategies. Understand the notion of capacity cushions, and how they link to other decisions in the firm.	
5.3 Identify a systematic four-step approach for determining long-term capacity requirements and associated cash flows.	The section "A Systematic Approach to Long-Term Capacity Decisions" shows you how capacity requirements can be estimated for both input-based and output-based measures. Focus on how different alternatives can be developed to fill the capacity gaps between requirements and current capacity.	**OM Explorer Solvers:** Capacity Requirements **OM Explorer Tutors:** 5.1: Capacity Requirements; 5.2: Projecting Cash Flows **Online Supplements:** F. Financial Analysis; H. Measuring Output Rates; I. Learning Curve Analysis **Case:** Fitness Plus B
5.4 Describe how the common tools for capacity planning, such as waiting-line models, simulation, and decision trees, assist in capacity decisions.	The section "Tools for Capacity Planning" illustrates several different methods and tools that can be used to arrive at capacity decisions. Read Managerial Practice 5.1 to understand how these tools can actually be used in the real world.	

Key Equations

Planning Long-Term Capacity

1. Utilization, expressed as a percent:

$$\text{Utilization} = \frac{\text{Average output rate}}{\text{Maximum capacity}} \times \mathbf{100\%}$$

Capacity Timing and Sizing Strategies

2. Capacity cushion, C, expressed as a percent:

$$C = 100\% - \text{Average Utilization rate (\%)}$$

A Systematic Approach to Long-Term Capacity Decisions

3. Capacity requirement for one service or product:

$$M = \frac{Dp}{N[1 - (C/100)]}$$

4. Capacity requirement for multiple services or products:

$$M = \frac{[Dp + (D/Q)s]_{\text{product 1}} + [Dp + (D/Q)s]_{\text{product 2}} + \cdots + [Dp + (D/Q)s]_{\text{product } n}}{N[1 - (C/100)]}$$

Key Terms

base case 206
capacity 199
capacity cushion 202
capacity gap 206
capacity requirement 204
cash flow 207
diseconomies of scale 201
economies of scale 200
planning horizon 204
setup time 205
utilization 200

Solved Problem 1

You have been asked to put together a capacity plan for a critical operation at the Surefoot Sandal Company. Your capacity measure is number of machines. Three products (men's, women's, and children's sandals) are manufactured. The time standards (processing and setup), lot sizes, and demand forecasts are given in the following table. The firm operates two 8-hour shifts, 5 days per week, 50 weeks per year. Experience shows that a capacity cushion of 5 percent is sufficient.

	TIME STANDARDS			
Product	**Processing (hr/pair)**	**Setup (hr/pair)**	**Lot Size (pairs/lot)**	**Demand Forecast (pairs/yr)**
Men's sandals	0.05	0.5	240	80,000
Women's sandals	0.10	2.2	180	60,000
Children's sandals	0.02	3.8	360	120,000

a. How many machines are needed?

b. If the operation currently has two machines, what is the capacity gap?

SOLUTION

a. The number of hours of operation per year, N, is N = (2 shifts/day)(8 hours/shifts)(250 days/machine-year) = 4,000 hours/machine-year

The number of machines required, M, is the sum of machine-hour requirements for all three products divided by the number of productive hours available for one machine:

$$M = \frac{[Dp + (D/Q)s]_{\text{men}} + [Dp + (D/Q)s]_{\text{women}} + [Dp + (D/Q)s]_{\text{children}}}{N[1 - (C/100)]}$$

$$= \frac{\begin{array}{c}[80{,}000(0.05) + (80{,}000/240)0.5] + [60{,}000(0.10) + (60{,}000/180)2.2] \\ + [120{,}000(0.02) + (120{,}000/360)3.8]\end{array}}{4{,}000[1 - (5/100)]}$$

$$= \frac{14{,}567 \text{ hours/years}}{3{,}800 \text{ hours/machine} - \text{year}} = \textbf{3.83 or 4} \text{ machines}$$

b. The capacity gap is 1.83 machines (3.83 − 2). Two more machines should be purchased, unless management decides to use short-term options to fill the gap.

The *Capacity Requirements* Solver in OM Explorer confirms these calculations, as Figure 5.5 shows, using only the "Expected" scenario for the demand forecasts.

FIGURE 5.5 ▶
Using the *Capacity Requirements* Solver for Solved Problem 1

Shifts/Day	2
Hours/Shift	8
Days/Week	5
Weeks/Year	50
Cushion (as %)	5%
Current capacity	2

Components 3

More Components
Fewer Components

Components	Processing (hr/unit)	Setup (hr/lot)	Lot Size (units/lot)	Demand Forecasts Pessimistic	Expected	Optimistic
Men's sandals	0.05	0.5	240		80,000	
Women's sandals	0.10	2.2	180		60,000	
Children's sandals	0.02	3.8	360		120,000	

Productive hours from one capacity unit for a year: 3,800

	Pessimistic Process	Pessimistic Setup	Expected Process	Expected Setup	Optimistic Process	Optimistic Setup
Men's sandals	0	0.0	4,000	166.7	0	0.0
Women's sandals	0	0.0	6,000	733.3	0	0.0
Children's sandals	0	0.0	2,400	1,266.7	0	0.0
	0	0.0	12,400	2,166.7	0	0.0
Total hours required		0.0		14,566.7		0.0
Total capacity requirements (M)		0.00		3.83		0.00
Rounded		0		4		0
Scenarios that can be met with current system/capacity:				Pessimistic, Optimistic		
If capacity increased by		0%				
Expanded current capacity		3,800				
Total capacity requirements (M)		0.00		3.83		0.00
Rounded		0		4		0
Scenarios that can be met with expanded current capacity:				Pessimistic, Optimistic		

Solved Problem 2

The base case for Grandmother's Chicken Restaurant (see Example 5.2) is to do nothing. The capacity of the kitchen in the base case is 80,000 meals per year. A capacity alternative for Grandmother's Chicken Restaurant is a two-stage expansion. This alternative expands the kitchen at the end of year 0, raising its capacity from 80,000 meals per year to that of the dining area (105,000 meals per year). If sales in year 1 and 2 live up to expectations, the capacities of both the kitchen and the dining room will be expanded at the *end* of year 3 to 130,000 meals per year. This upgraded capacity level should suffice up through year 5. The initial investment would be $80,000 at the end of year 0 and an additional investment of $170,000 at the end

of year 3. The pretax profit is $2 per meal. What are the pretax cash flows for this alternative through year 5, compared with the base case?

SOLUTION

Table 5.1 shows the cash inflows and outflows. The year 3 cash flow is unusual in two respects. First, the cash inflow from sales is $50,000 rather than $60,000. The increase in sales over the base is 25,000 meals (105,000 − 10,000) instead of 30,000 meals (110,000 − 80,000) because the restaurant's capacity falls somewhat short of demand. Second, a cash outflow of $170,000 occurs at the end of year 3, when the second-stage expansion occurs. The net cash flow for year 3 is $50,000 − $170,000 = −$120,000.

For comparison purposes, the NPV of this project at a discount rate of 10 percent is calculated as follows, and equals negative $2,184.90.

$$\begin{aligned}\text{NPV} &= -80{,}000 + (20{,}000/1.1) + [40{,}000/(1.1)^2] - [120{,}000/(1.1)^3] + [80{,}000/(1.1)^4] + [100{,}000/(1.1)^5] \\ &= -\$80{,}000 + \$18{,}181.82 + \$33{,}057.85 - \$90{,}157.77 + \$54{,}641.07 + \$62{,}092.13 \\ &= \mathbf{-\$2{,}184.90}\end{aligned}$$

On a purely monetary basis, a single-stage expansion seems to be a better alternative than this two-stage expansion. However, other qualitative factors as mentioned earlier must be considered as well.

TABLE 5.1 | CASH FLOWS FOR TWO-STAGE EXPANSION AT GRANDMOTHER'S CHICKEN RESTAURANT

Year	Projected Demand (meals/yr)	Projected Capacity (meals/yr)	Calculation of Incremental Cash Flow Compared to Base Case (80,000 meals/yr)	Cash Inflow (outflow)
0	80,000	80,000	Increase kitchen capacity to 105,000 meals =	($80,000)
1	90,000	105,000	90,000 − 80,000 = (10,000 meals)($2/meal) =	$20,000
2	100,000	105,000	100,000 − 80,000 = (20,000 meals)($2/meal) =	$40,000
3	110,000	105,000	105,000 − 80,000 = (25,000 meals)($2/meal) =	$50,000
			Increase total capacity to 130,000 meals =	($170,000)
				($120,000)
4	120,000	130,000	120,000 − 80,000 = (40,000 meals)($2/meal) =	$80,000
5	130,000	130,000	130,000 − 80,000 = (50,000 meals)($2/meal) =	$100,000

Discussion Questions

1. What are the economies of scale in college class size? As class size increases, what symptoms of diseconomies of scale appear? How are these symptoms related to customer contact?
2. A young boy sets up a lemonade stand on the corner of College Street and Air Park Boulevard. Temperatures in the area climb to 100°F during the summer. The intersection is near a major university and a large construction site. Explain to this young entrepreneur how his business might benefit from economies of scale. Explain also some conditions that might lead to diseconomies of scale.
3. Excess capacity of a firm can lead to underutilization of its assets, while a decision to decrease capacity can result in lost opportunities. Identify examples where businesses have incurred substantial losses due to excess capacity and vice versa. Explain the reasons that may have resulted in this problem.

Problems

The OM Explorer, POM for Windows, and Active Model software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software replaces entirely the manual calculations.

Problems 19, 20, 21, 22, 23, and 24 require reading of Supplement A, "Decision Making." Problems 14, 15, 16, 23, and 24 require reading of online Supplement F, "Financial Analysis."

Planning Long-Term Capacity

1. The Dahlia Medical Center has 30 labor rooms, 15 combination labor and delivery rooms, 3 delivery rooms, and 1 special delivery room reserved for complicated births. All of these facilities operate around the clock. Time spent in labor rooms varies from hours to days, with an average of about a day. The average uncomplicated delivery requires about 1 hour in a delivery room.

   During an exceptionally busy 3-day period, 109 healthy babies were born at Dahlia Medical Center. Sixty babies were born in separate labor and delivery rooms, 45 were born in combined labor and delivery rooms, and only 4 babies required a labor room and the complicated delivery room. Which of the facilities (labor rooms, combination labor and delivery rooms, or delivery rooms) had the greatest utilization rate?

2. A process currently services an average of 50 customers per day. Observations in recent weeks show that its utilization is about 90 percent, allowing for just a 10 percent capacity cushion. If demand is expected to be 75 percent of the current level in 5 years and management wants to have a capacity cushion of just 5 percent, what capacity requirement should be planned?

3. A waste management company currently operates 25 trucks per day for collecting domestic waste. Observations in recent weeks show that the trucks are operating at a capacity of 70 percent, allowing for just a 10 percent capacity cushion. Due to population growth, more waste will be generated and trucks are expected to operate at 80 percent. If so, what would be the new capacity utilization?

4. A manufacturer of bespoke handmade candles employs 2 machine operators and 3 packers to process customer orders. This team of 5 works for 6 hours a day for 5 days a week (Monday–Friday). Together, they make 100 candles per hour which are packed in boxes of 10. A machine operator and a packer require approximately 4 minutes to manufacture and 2 minutes to pack each box of candle.
   - **a.** Calculate the utilization of both machine operators and packers.
   - **b.** In order to improve productivity, management decided to cross-train both operators and packers to perform both activities. Now, it takes 8 minutes for one individual to manufacture and pack each box of candle. Which of the processes has the greatest utilization rate?

5. Returning to Problem 4, the business now requires a 20 percent capacity cushion.
   - **a.** What would be the new capacity utilization if the capacity cushion is implemented?
   - **b.** How many employees should the business schedule if it wishes to keep the capacity utilization unchanged?
   - **c.** Calculate the capacity utilization for machine operator, packer, and cross-trained employees.

A Systematic Approach to Long-Term Capacity Decisions

6. A sandwich manufacturing firm makes sandwich platters with 20 pieces per platter. Each platter takes 30 minutes to prepare and pack. After 12 platters, the surface is cleaned and sanitized, which requires a 1-hour changeover. The company operates 7.5 hour shifts, 3 shifts per day, 220 days per year. If the firm manufactures 7000 platters per year, what is its capacity cushion?

7. Macon Controls produces three different types of control units used to protect industrial equipment from overheating. Each of these units must be processed by a machine that Macon considers to be its process bottleneck. The plant operates on two 8-hour shifts, 5 days per week, 52 weeks per year. Table 5.2 provides the time standards at the bottleneck, lot sizes, and demand forecasts for the three units. Because of demand uncertainties, the operations manager obtained three demand forecasts (pessimistic, expected, and optimistic). The manager believes that a 20 percent capacity cushion is best.

TABLE 5.2 | CAPACITY INFORMATION FOR MACON CONTROLS

	TIME STANDARD			DEMAND FORECAST		
Component	Processing (hr/unit)	Setup (hr/lot)	Lot Size (units/lot)	Pessimistic	Expected	Optimistic
A	0.05	1.0	60	15,000	18,000	25,000
B	0.20	4.5	80	10,000	13,000	17,000
C	0.05	8.2	120	17,000	25,000	40,000

   - **a.** How many machines are required to meet minimum (pessimistic) demand, expected demand, and maximum (optimistic) demand?
   - **b.** How many machines are required if the operations manager decides to double lot sizes?
   - **c.** If the operations manager has three machines and believes that the plant can reduce setup time by 20 percent through process improvement initiatives, does that plant have adequate capacity to meet all demand scenarios without increasing lot sizes?

8. Up, Up, and Away is a producer of kites and wind socks. Relevant data on a bottleneck operation in the shop for the upcoming fiscal year are given in the following table:

Item	Kites	Wind Socks
Demand forecast	30,000 units/year	12,000 units/year
Lot size	20 units	70 units
Standard processing time	0.3 hour/unit	1.0 hour/unit
Standard setup time	3.0 hours/lot	4.0 hours/lot

The shop works two shifts per day, 8 hours per shift, 200 days per year. Currently, the company operates four machines, and desires a 25 percent capacity cushion. How many machines should be purchased to meet the upcoming year's demand without resorting to any short-term capacity solutions?

9. Bespoke Furniture Mart assembles office chairs in a variety of colors, frame sizes, and models. These can be broadly categorized as work chairs and meeting chairs. Identical chairs are produced in lots of 50. The projected demand, lot size, and time standards are shown in the following table.

Item	Work Chair	Meeting Chair
Projected demand	7,000 units/year	14,000 units/year
Lot size	50	50
Standard assembly time	30 mins/unit	15 mins/unit
Standard set up time	3 hours/lot	1.5 hours/lot

The company operates 8 hours a day, 5 days a week, 220 days a year. It currently has 6 work workstations, each capable of assembling both types of chairs. How many workstations will be required if the company wants to maintain a capacity cushion of 15 percent?

10. Knott's Industries manufactures standard and super premium backyard swing sets. Currently it has four identical swing-set-making machines, which are operated 250 days per year and 8 hours each day. A capacity cushion of 20 percent is desired. The following information is also known:

	Standard Model	Super Premium Model
Annual Demand	20,000	10,000
Standard Processing Time	7 min	20 min
Average Lot Size	50	30
Standard Setup Time per Lot	30 min	45 min

a. Does Knott's have sufficient capacity to meet annual demand?

b. If Knott's was able to reduce the setup time for the Super Premium Model from 45 minutes to 30 minutes, would there be enough current capacity to produce 20,000 units of each type of swing set?

11. Best Water Limited is a provider of high-quality insulation material to trade and commercial establishments. It employs an army of sales agents who regularly work with architects and pitch their products. The sales agents are remunerated based on performance and are usually paid 20 percent of sales value. Manufacturing costs and overheads contributes to 30 percent of sales revenue. Business is affected by seasonality and the revenue generated varies per quarter is shown in the following table.

Year	Quarter	Sales (in 1000s)
1	1	300
	2	700
	3	900
	4	200
2	1	320
	2	735
	3	940
	4	220

a. Calculate the pretax profit based on the data provided.

b. In year 3, the company wishes to replace its existing product by importing a higher quality product from overseas, which reduces production costs from 30 percent to 15 percent. Sales is forecast to increase by 25 percent. However, the government has introduced an additional import duty of 10 percent. What will be the additional profits earned by Best Water through year 3?

12. The Astro World amusement park has the opportunity to expand its size now (the end of year 0) by purchasing adjacent property for $250,000 and adding attractions at a cost of $550,000. This expansion is expected to increase attendance by 30 percent over projected attendance without expansion. The price of admission is $30, with a $5 increase planned for the beginning of year 3. Additional operating costs are expected to be $100,000 per year. Estimated attendance for the next 5 years, *without expansion*, is as follows:

Year	1	2	3	4	5
Attendance	30,000	34,000	36,250	38,500	41,000

a. What are the pretax combined cash flows for years 0 through 5 that are attributable to the park's expansion?

b. Ignoring tax, depreciation, and the time value of money, determine how long it will take to recover (pay back) the investment.

13. Kim Epson operates a full-service car wash, which operates from 8 A.M. to 8 P.M., 7 days a week. The car wash has two stations: an automatic washing and drying station and a manual interior cleaning station. The automatic washing and drying station can handle 30 cars per hour. The interior cleaning station can handle 200 cars per day. On the basis of a recent year-end review of operations, Kim estimates that future demand for the interior cleaning

station for the 7 days of the week, expressed in average number of cars per day, would be as follows:

Day	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Sun.
Cars	160	180	150	140	280	300	250

By installing additional equipment (at a cost of $50,000), Kim can increase the capacity of the interior cleaning station to 300 cars per day. Each car wash generates a pretax contribution of $4.00. Should Kim install the additional equipment if she expects a pretax payback period of 3 years or less?

14. Roche Brothers is considering a capacity expansion of its supermarket. The landowner will build the addition to suit in return for $200,000 upon completion and a 5-year lease. The increase in rent for the addition is $10,000 per month. The annual sales projected through year 5 follow. The current effective capacity is equivalent to 500,000 customers per year. Assume a 2 percent pretax profit on sales.

Year	1	2	3	4	5
Customers	560,000	600,000	685,000	700,000	715,000
Average Sales per Customer	$50.00	$53.00	$56.00	$60.00	$64.00

a. If Roche expands its capacity to serve 700,000 customers per year now (end of year 0), what are the projected annual incremental pretax cash flows attributable to this expansion?

b. If Roche expands its capacity to serve 700,000 customers per year at the end of year 2, the landowner will build the same addition for $240,000 and a 3-year lease at $12,000 per month. What are the projected annual incremental pretax cash flows attributable to this expansion alternative?

15. A rice flour mill is seeking to maximize its productivity with an improved grinder. It can repair its existing machinery or buy a new one. For buying purposes, two alternative machines are in consideration. Machine A costs £125,000 but yields a 10 percent savings over the current machine used. Machine B costs £525,000 but yields a 35 percent savings over the current machine used. The repair and maintenance costs of the existing machine are provided in the following table.

a. Which machine should the mill purchase if a discount rate of 13 percent is considered?

b. Assuming the discount rate is reduced to 7 percent, will there be any change in the decision?

Year	Projected Cost
1	600,000
2	615,000
3	625,000
4	630,000
5	650,000

16. Several years ago, River City built a water purification plant to remove toxins and filter the city's drinking water. Because of population growth, the demand for water next year will be more than the plant's capacity of 120 million gallons per year. Therefore, the city must expand the facility. The estimated demand over the next 20 years is given in Table 5.3.

The city planning commission is considering three alternatives.

- *Alternative 1:* Expand enough at the end of year 0 to last 20 years, which means an 80 million gallon increase (200 − 120).
- *Alternative 2:* Expand at the end of year 0 and at the end of year 10.
- *Alternative 3:* Expand at the end of years 0, 5, 10, and 15.

Each alternative would provide the needed 200 million gallons per year at the end of 20 years, when the value of the plant would be the same regardless of the alternative chosen. Significant economies of scale can be achieved in construction costs: A 20-million-gallon expansion would cost $18 million; a 40-million-gallon expansion, $30 million; and an 80-million-gallon expansion, only $50 million. The level of future interest rates is uncertain, leading to uncertainty about the hurdle rate. The city believes that it could be as low as 12 percent and as high as 16 percent (see online Supplement F, "Financial Analysis").

a. Compute the cash flows for each alternative, compared to a base case of doing nothing. (*Note:* As a municipal utility, the operation pays no taxes.)

b. Which alternative minimizes the present value of construction costs over the next 20 years if the discount rate is 12 percent? 16 percent?

c. Because the decision involves public policy and compromise, what political considerations does the planning commission face?

TABLE 5.3 | WATER DEMAND

Year	Demand	Year	Demand	Year	Demand
0	120	7	148	14	176
1	124	8	152	15	180
2	128	9	156	16	184
3	132	10	160	17	188
4	136	11	164	18	192
5	140	12	168	19	196
6	144	13	172	20	200

17. Mars Incorporated is interested in going to market with a new fuel savings device that attaches to electrically powered industrial vehicles. The device, code named "Python," promises to save up to 15 percent of the electrical power required to operate the average electric forklift. Mars expects that modest demand expected during the introductory year will be followed by a steady increase in demand in subsequent years. The extent of this increase in demand will be based on customers' expectations regarding the future cost of electricity and is shown in Table 5.4. Mars expects to sell the device for $500 each and does not expect to be able to raise its price over the foreseeable future.

TABLE 5.4 | DEMAND FOR PYTHON POWER-SAVING DEVICE

	EXPECTED DEMAND OF THE DEVICE IN UNITS/YEAR	
Year	Small Increases in the Cost of Electrical Power	Large Increases in the Cost of Electrical Power
1	1,000	10,000
2	5,000	8,000
3	1,000	15,000
4	15,000	20,000
5	18,000	30,000

Mars is faced with two alternatives:

- *Alternative 1:* Make the device itself, which requires an initial outlay of $250,000 in plant and equipment and a variable cost of $75 per unit.
- *Alternative 2:* Outsource the production, which requires no initial investment, but incurs a per-unit cost of $300.

a. Assuming small increases in the cost of electrical power, compute the cash flows for each alternative. Over the next 5 years, which alternative maximizes the NPV of this project if the discount rate is 10 percent?

b. Assuming large increases in the cost of electrical power, compute the cash flows for each alternative. Over the next 5 years, which alternative maximizes the NPV of this project if the discount rate is 10 percent?

18. Mackelprang, Inc., is in the initial stages of building the premier planned community in the greater Phoenix, Arizona, metropolitan area. The main selling point will be the community's lush golf courses. Homes with golf course views will generate premiums far larger than homes with no golf course views, but building golf courses is expensive and takes up valuable space that nonview homes could be built upon. Mackelprang, Inc., has limited land capacity. To maximize its profits, it is faced with a decision as to how many golf courses it should build, which, in turn, will affect how many homes with and without golf course views it will be able to construct. Mackelprang, Inc., realizes that this decision is directly related to the premium buyers will be willing to spend to buy homes with golf course views. Mackelprang, Inc., is required to build at least one golf course but has enough space to build up to three golf courses. The following table indicates the costs and potential revenues for each course.

	Woodlands	The Cactus	Wildwood
Cost	$2.6M	$1.25M	$2.5M
Highest Possible Revenue	$4M	$2M	$2M
Probability of High Revenue	0.3	0.2	0.3
Likely Revenue	$2.5M	$1.5M	$4M
Probability of Likely Revenue	0.4	0.5	0.5
Lowest Possible Revenue	$1M	$1M	$1M
Probability of Low Revenue	0.3	0.3	0.2

a. Which golf course or courses should Mackelprang, Inc., build?

b. What is the expected payoff for this project?

19. Two new alternatives have come up for expanding Grandmother's Chicken Restaurant (see Solved Problem 2). They involve more automation in the kitchen and feature a special cooking process that retains the original-recipe taste of the chicken. Although the process is more capital intensive, it would drive down labor costs, so the pretax profit for *all* sales (not just the sales from the capacity added) would go up from 20 to 22 percent. This gain would increase the pretax profit by 2 percent of each sales dollar through $800,000 (80,000 meals × $10) and by 22 percent of each sales dollar between $800,000 and the new capacity limit. Otherwise, the new alternatives are much the same as those in Example 5.2 and Solved Problem 2.

- *Alternative 1:* Expand both the kitchen and the dining area now (at the end of year 0), raising the capacity to 130,000 meals per year. The cost of construction, including the new automation, would be $336,000 (rather than the earlier $200,000).
- *Alternative 2:* Expand only the kitchen now, raising its capacity to 105,000 meals per year. At the end of year 3, expand both the kitchen and the dining area to the 130,000 meals-per-year volume. Construction and equipment costs would be $424,000, with $220,000 at the end of year 0 and the remainder at the end of year 3. As with alternative 1, the contribution margin would go up to 22 percent.

With both new alternatives, the salvage value would be negligible. Compare the cash flows of all alternatives. Should Grandmother's Chicken Restaurant expand with the new or the old technology? Should it expand now or later?

Tools for Capacity Planning

20. Dawson Electronics is a manufacturer of high-tech control modules for lawn sprinkler systems. Denise, the CEO, is trying to decide if the company should develop one of two potential new products, the Water Saver 1000 or the Greener Grass 5000. With each product, Dawson can capture a bigger market share if it chooses to expand capacity by buying additional machines. Given different demand scenarios, their probabilities of occurrence, and capacity expansion versus no change in capacity, the potential sales of each product are summarized in Table 5.5.

a. What is the expected payoff for Water Saver 1000 and the Greener Grass 5000, with and without capacity expansion?

b. Which product should Denise choose to produce, and with which capacity expansion option?

TABLE 5.5 | DEMAND AND SALES INFORMATION FOR DAWSON ELECTRONICS

	Water Saver 1000 Dollar Sales ($1,000)	Greener Grass 5000 Dollar Sales ($1,000)	Probability of Occurrence
With Capacity Expansion			
Low Demand	1,000	2,500	0.25
Medium Demand	2,000	3,000	0.50
High Demand	3,000	5,000	0.25
Without Capacity Expansion			
Low Demand	700	1,000	0.25
Medium Demand	1,000	2,000	0.50
High Demand	2,000	3,000	0.25

21. A manager is trying to decide whether to buy one machine or two. If only one machine is purchased and demand proves to be excessive, the second machine can be purchased later. Some sales would be lost, however, because the lead time for delivery of this type of machine is 6 months. In addition, the cost per machine will be lower if both machines are purchased at the same time. The probability of low demand is estimated to be 0.30 and that of high demand to be 0.70. The after-tax NPV of the benefits from purchasing two machines together is $90,000 if demand is low and $170,000 if demand is high.

If one machine is purchased and demand is low, the NPV is $120,000. If demand is high, the manager has three options: (1) doing nothing, which has an NPV of $120,000; (2) subcontracting, with an NPV of $140,000; and (3) buying the second machine, with an NPV of $130,000.

a. Draw a decision tree for this problem.

b. What is the best decision and what is its expected payoff?

22. Brunel Engineering fabricates industrial ovens for hotels, schools, and restaurants. The company is planning to expand and export its products overseas. The current manual method of materials handling and assembly is inefficient. Brunel is considering a one-year lease of an industrial robot to increase capacity and improve manufacturing efficiency.

However, demand is uncertain and will depend on currency fluctuations and performance of the global economy. If demand for exports stays at the current level, the probability of which is 0.40, annual savings from utilizing the robot instead of paying wages to full-time employees will be £30,000. If demand rises, the robot will save £45,000 annually because of operating efficiencies in addition to new sales. Finally, if demand falls, the robot will result in an estimated annual loss of £60,000. The probability is estimated to be 0.35 for higher demand and 0.25 for lower demand.

a. If Brunel hires a full-time employee in place of the robot, annual payoffs will be £30,000 if demand is unchanged, £35,000 if demand rises, and −£30,000 if demand falls. Draw a decision tree for this problem.

b. Compute the expected value of the payoff for each alternative. Which is the best alternative, based on the expected values?

23. Referring to Problem 7, the operations manager at Macon Controls believes that pessimistic demand has a probability of 20 percent, expected demand has a probability of 50 percent, and optimistic demand has a probability of 30 percent. Currently, new machines must be purchased at a cost of $500,000 a piece, the price charged for each control unit is $110, and the variable cost of production is $50 per unit. (*Hint:* Since the price and variable cost for each control unit are the same, the profit-maximizing product mix will be the same as the mix that maximizes the total number of units produced.)

a. Draw a decision tree for this problem.

b. How many machines should the company purchase, and what is the expected payoff?

24. Darren Mack owns the Gas n' Go convenience store and gas station. After hearing a marketing lecture, he realizes that it might be possible to draw more customers to his high-margin convenience store by selling his gasoline at a lower price. However, the Gas n' Go is unable to qualify for volume discounts on its gasoline purchases, and therefore cannot sell gasoline for profit if the price is lowered. Each new pump will cost $95,000 to install, but will increase customer traffic in the store by 1,000 customers per year. Also, because the Gas n' Go would be selling its gasoline at no profit, Darren plans on increasing the profit margin on convenience store items incrementally over the next 5 years. Assume a discount rate of 8 percent. The projected convenience store sales per customer and the projected profit margin for the next 5 years are as follows:

Year	Projected Convenience Store Sales per Customer	Projected Profit Margin
1	$5.00	20%
2	$6.50	25%
3	$8.00	30%
4	$10.00	35%
5	$11.00	40%

a. What is the NPV of the next 5 years of cash flows if Darren had four new pumps installed?

b. If Darren required a payback period of 4 years, should he go ahead with the installation of the new pumps?

25. The vice president of operations at Dintell Corporation, a major supplier of passenger-side automotive air bags, is considering a $50 million expansion at the firm's Fort Worth, Texas, production complex. The most recent economic projections indicate a 0.60 probability that the overall market will be $400 million per year over the next 5 years and a 0.40 probability that the market will be only $200 million per year during the same period. The marketing department estimates that Dintell has a 0.50 probability of capturing 40 percent of the market and an equal probability of obtaining only 30 percent of the market. The cost of goods sold is estimated to be 70 percent of sales. For planning purposes, the company currently uses a 12 percent discount rate, a 40 percent tax rate, and the MACRS depreciation schedule. The criteria for investment decisions at Dintell are (1) the net expected present value must be greater than zero; (2) there must be at least a 70 percent chance that the net present value will be positive; and (3) there must be

no more than a 10 percent chance that the firm will lose more than 20 percent of the initial value.

a. On the basis of the stated criteria, determine whether Dintell should fund the project.

b. What effect will a probability of 0.70 of capturing 40 percent of the market have on the decision?

c. What effect will an increase in the discount rate to 15 percent have on the decision? A decrease to 10 percent?

d. What effect will the need for another $10 million in the third year have on the decision?

CASE Fitness Plus, Part A

Fitness Plus is a full-service health and sports club in Greensboro, North Carolina. The club provides a range of facilities and services to support three primary activities: fitness, recreation, and relaxation. Fitness activities generally take place in four areas of the club: (1) the aerobics room, which can accommodate 35 people per class; (2) a room equipped with free weights; (3) a workout room with 24 pieces of Nautilus equipment; and (4) a large workout room containing 29 pieces of cardiovascular equipment. This equipment includes nine stairsteppers, six treadmills, six life-cycle bikes, three Airdyne bikes, two cross-aerobics machines, two rowing machines, and one climber. Recreational facilities comprise eight racquetball courts, six tennis courts, and a large outdoor pool. Fitness Plus also sponsors softball, volleyball, and swim teams in city recreation leagues. Relaxation is accomplished through yoga classes held twice a week in the aerobics room, whirlpool tubs located in each locker room, and a trained massage therapist.

Situated in a large suburban office park, Fitness Plus opened its doors in 1995. During the first 2 years, membership was small and use of the facilities was light. By 1997, membership had grown as fitness began to play a large role in more and more people's lives. Along with this growth came increased use of club facilities. Records indicate that in 2000, an average of 15 members per hour checked into the club during a typical day. Of course, the actual number of members per hour varied by both day and time. On some days during a slow period, only six to eight members would check in per hour. At a peak time, such as Mondays from 4:00 P.M. to 7:00 P.M., the number would be as high as 40 per hour.

The club was open from 6:30 A.M. to 11:00 P.M. Monday through Thursday. On Friday and Saturday, the club closed at 8:00 P.M., and on Sunday the hours were 12:00 P.M. to 8:00 P.M.

As the popularity of health and fitness continued to grow, so did Fitness Plus. By May 2005, the average number of members arriving per hour during a typical day had increased to 25. The lowest period had a rate of 10 members per hour; during peak periods, 80 members per hour checked in to use the facilities. This growth brought complaints from members about overcrowding and unavailability of equipment. Most of these complaints centered on the Nautilus, cardiovascular, and aerobics fitness areas. The owners began to wonder whether the club was indeed too small for its membership. Past research indicated that individuals work out an average of 60 minutes per visit. Data collected from member surveys showed the following facilities usage pattern: 30 percent of the members do aerobics, 40 percent use the cardiovascular equipment, 25 percent use the Nautilus machines, 20 percent use the free weights, 15 percent use the racquetball courts, and 10 percent use the tennis courts. The owners wondered whether they could use this information to estimate how well existing capacity was being utilized.

If capacity levels were being stretched, now was the time to decide what to do. It was already May, and any expansion of the existing facility would take at least 4 months. The owners knew that January was always a peak membership enrollment month and that any new capacity needed to be ready by then. However, other factors had to be considered. The area was growing both in terms of population and geography. The downtown area just received a major facelift, and many new offices and businesses were moving back to it, causing a resurgence in activity.

With this growth came increased competition. A new YMCA was offering a full range of services at a low cost. Two new health and fitness facilities had opened within the past year in locations 10 to 15 minutes from Fitness Plus. The first, called the Oasis, catered to the young adult crowd and restricted the access of children under 16 years old. The other facility, Gold's Gym, provided excellent weight and cardiovascular training only.

As the owners thought about the situation, they had many questions: Were the capacities of the existing facilities constrained, and if so, where? If capacity expansion was necessary, should the existing facility be expanded? Because of the limited amount of land at the current site, expansion of some services might require reducing the capacity of others. Finally, owing to increased competition and growth downtown, was now the time to open a facility to serve that market? A new facility would take 6 months to renovate, and the financial resources were not available to do both.

Fitness Plus, Part B, explores alternatives to expanding a new downtown facility and is included in the Instructor's Resource Manual. If you are interested in this topic, ask your instructor for a preview.

QUESTIONS

1. What method would you use to measure the capacity of Fitness Plus? Has Fitness Plus reached its capacity?
2. Which capacity strategy would be appropriate for Fitness Plus? Justify your answer.
3. How would you link the capacity decision being made by Fitness Plus to other types of operating decisions?

VIDEO CASE Gate Turnaround at Southwest Airlines

Rollin King and Herb Kelleher started Southwest Airlines in 1971 with this idea: If they could take airline passengers where they want to go, on time, at the lowest possible price, and have a good time while doing it, people would love to fly their airline. The result? No other airline in the industry's history has enjoyed the customer loyalty and extended profitability for which Southwest is now famous.

There's more to the story, however, than making promises and hoping to fulfill them. A large part of the success of Southwest Airlines lies in its ability to plan long-term capacity to better match demand and also improving the utilization of its fleet by turning around an aircraft at the gate faster than its competitors. Capacity at Southwest is measured in seat-miles, and even a

single minute reduction in aircraft turnaround time systemwide means additional seat-miles being added to the available capacity of Southwest Airlines.

As soon as an aircraft calls "in range" at one of Southwest's airport locations, called a station, the local operations manager notifies the ground operations team so that the team can start mobilizing all the parties involved in servicing the aircraft in preparation for its next departure. The grounds operations team consists of a baggage transfer driver who has responsibility for getting connecting flight bags to their proper planes, a local baggage driver who moves bags to baggage claim for passenger pickup, a lavatory truck driver who handles restroom receptacle drainage, a lead gate agent to handle baggage carts and track incoming and outgoing bag counts, and a bin agent to manage baggage and cargo inside the plane. The ground operations team knows it must turn the plane around in 25 minutes or less. The clock starts when the pilot sets the wheel brakes.



Pearson Education

Baggage transfer starts less than 40 seconds after engine shutdown at Southwest Airlines.

Inbound and outbound flights are coordinated by the supervisors between all of Southwest's airport stations through the company's Operations Terminal Information System (OTIS). Each local supervisor is able to keep track of flights and manage any delays or problems that may have crept into the system by keeping in touch with headquarters in Dallas for systemwide issues that may affect a local station, along with using the OTIS information coming from stations sending flights their way.

Just what, exactly, does it take to turn around an aircraft? In-bound flight 3155 from Phoenix to Dallas's Love Field is a good example. In Phoenix, the operations coordinators and ground operations team push back the plane as scheduled at 9:50 A.M. The flight is scheduled to arrive at 3:35 P.M. in Dallas. The Phoenix team enters into OTIS the information the ground operations team will need in Dallas, such as wheelchairs, gate-checked baggage, cargo bin locator data, and other data needed to close out the flight on their end. This action lets the Dallas station know what to expect when the plane lands.

In Dallas, the local ground operations coordinators have been monitoring all 110 inbound flights and now see Phoenix flight 3155 in the system, scheduled for an on-time arrival. When the pilot calls "in range" as it nears Dallas, the ground crew prepares for action.

As the plane is guided to its "stop mark" at the gate, the lead agent waits for the captain's signal that the engines have been turned off and brakes set. Within just 10 seconds, the provisioning truck pulls up to open the back door for restocking supplies such as drinks and snacks. The waiting fuel truck extends its hose to the underwing connection and in less than 2 minutes picks up refueling instructions and starts to load fuel. As soon as the aircraft is in position, the operations team steers the jetway into position and locks it against the aircraft. The door is opened, the in-flight crew is greeted, and passengers start to deplane.

Outside, less than 40 seconds after engine shutdown, baggage is rolling off the plane and gets placed onto the first cart. Any transfer bags get sent to their next destination, and gate-checked bags are delivered to the top of the jetway stairs for passenger pickup.

While passengers make their way out of the plane, the in-flight crew helps clean up and prepare the cabin for the next flight. If all goes well, the last passenger will leave the plane after only 8 minutes. By this time, passengers waiting to board have already lined up in their designated positions for boarding. The gate agent confirms that the plane is ready for passenger boarding and calls for the first group to turn in their boarding passes and file down the jetway.

At the completion of boarding, the operations agent checks the fuel invoice, cargo bin loading schedule with actual bag counts in their bins from the baggage agents, and a lavatory service record confirming that cleaning has taken place. Final paperwork is given to the captain. The door to the aircraft is closed, and the jetway is retracted. Thirty seconds later, the plane is pushed back and the operations agent gives a traditional salute to the captain to send the flight on its way. Total elapsed time: less than 25 minutes.

Managing Southwest's capacity has been somewhat simplified by strategic decisions made early on in the company's life. First, the company's fleet of aircraft is all Boeing 737s. This single decision affects all areas of operations—from crew training to aircraft maintenance. The single-plane configuration also provides Southwest with crew scheduling flexibility. Since pilots and flight crews can be deployed across the entire fleet, there are no constraints with regard to training and certification pegged to specific aircraft types.

The way Southwest has streamlined its operations for tight turnarounds means it must maintain a high capacity cushion to accommodate variability in its daily operations. Anything from weather delays to unexpected maintenance issues at the gate can slow down the flow of operations to a crawl. To handle these unplanned but anticipated challenges, Southwest builds into its schedules enough cushion to manage these delays yet not so much that employees and planes are idle. Additionally, the company encourages discussion to keep on top of what's working and where improvements can be made. If a problem is noted at a downstream station—say, bags were not properly loaded—this information quickly travels back up to the originating station for correction so that it does not happen again.

Even with the tightly managed operations Southwest Airlines enjoys, company executives know that continued improvement is necessary if the company is to remain profitable into the future. Company executives know they have achieved their goals when internal and external metrics are reached. For example, the Department of Transportation (DOT) tracks on-time departures, customer complaints, and mishandled baggage for all airlines. The company sets targets for achievement on these dimensions and lets employees know on a monthly basis how the company is doing against those metrics and the rest of the industry. Regular communication with all employees is delivered via meetings, posters, and newsletters. Rewards such as prizes and profit sharing are given for successful achievement.

As for the future, Bob Jordan, Southwest's executive vice president for strategy and planning, puts it this way: "We make money when our planes are in the air, not on the ground. If we can save one minute off every turn system-wide, that's like putting five additional planes in the air. If a single plane generates annual revenue of $25 million, there's $125 million in profit potential from those time savings."

QUESTIONS

1. How can capacity and utilization be measured at an airline such as Southwest Airlines?
2. Which factors can adversely impact turnaround times at Southwest Airlines?
3. How does Southwest Airlines know it is achieving its goals?
4. What are the important long-term issues relevant for managing capacity, revenue, and customer satisfaction for Southwest Airlines?

SUPPLEMENT

B

WAITING LINES

LEARNING OBJECTIVES *After reading this supplement, you should be able to:*

B.1 Identify the structure of waiting lines in real situations.

B.2 Use the single-server, multiple-server, and finite-source models to analyze operations and estimate the operating characteristics of a process.

B.3 Describe the situations where simulation should be used for waiting-line analysis and the nature of the information that can be obtained.

B.4 Explain how waiting-line models can be used to make managerial decisions.

Anyone who has ever waited at a stoplight, at McDonald's, or at the registrar's office has experienced the dynamics of waiting lines. Perhaps one of the best examples of effective management of waiting lines is that of Walt Disney World. One day the park may have only 25,000 customers, but on another day the numbers may top 90,000. Careful analysis of process flows, technology for people-mover (materials handling) equipment, capacity, and layout keeps the waiting times for attractions to acceptable levels.

A **waiting line** is one or more "customers" waiting for service. The customers can be people or inanimate objects, such as machines requiring maintenance, sales orders waiting for shipping, or inventory items waiting to be used. A waiting line forms because of a temporary imbalance between the demand for service and the capacity of the system to provide the service. In most real-life waiting-line problems, the demand rate varies; that is, customers arrive at unpredictable intervals. Most often, the rate of producing the service also varies, depending on customer needs. Suppose that bank customers arrive at an average rate of 15 per hour throughout the day and that the bank can process an average of 20 customers per hour. Why would a waiting line ever develop? The answers are that the customer arrival rate varies throughout the day and the time required to process a customer can vary. During the noon hour, 30 customers may arrive at the bank. Some of them may have complicated transactions requiring above-average process times. The waiting line may grow to 15 customers for a period of time before it eventually disappears. Even though the bank manager provided for more than enough capacity on average, waiting lines can still develop.

waiting line
One or more "customers" waiting for service.

In a similar fashion, waiting lines can develop even if the time to process a customer is constant. For example, a subway train is computer controlled to arrive at stations along its route. Each train is programmed to arrive at a station, say, every 15 minutes. Even with the constant service time, waiting lines develop while riders wait for the next train or cannot get on a train because of the size of the crowd at a busy time of the day. Consequently, variability in the rate of demand determines the sizes of the waiting lines in this case. In general, if no variability in the demand or service rate occurs and enough capacity is provided, no waiting lines form.

Waiting-line theory applies to service as well as manufacturing firms, relating customer arrival and service-system processing characteristics to service-system output characteristics. In our discussion, we use the term *service* broadly—the act of doing work for a customer. The service system might be hair cutting at a hair salon, satisfying customer complaints, or processing a production order of parts on a certain machine. Other examples of customers and services include lines of theatergoers waiting to purchase tickets, trucks waiting to be unloaded at a warehouse, machines waiting to be repaired by a maintenance crew, and patients waiting to be examined by a physician. Regardless of the situation, waiting-line problems have several common elements.

The analysis of waiting lines is of concern to managers because it affects process design, capacity planning, process performance, and ultimately, supply chain performance. In this supplement we discuss why waiting lines form, the uses of waiting-line models in operations management, and the structure of waiting-line models. We also discuss the decisions managers address with these models. Waiting lines can also be analyzed using computer simulation. Software such as SimQuick or Excel spreadsheets can be used to analyze the problems in this supplement.

Structure of Waiting-Line Problems

Analyzing waiting-line problems begins with a description of the situation's basic elements. Each specific situation will have different characteristics, but four elements are common to all situations:

customer population
An input that generates potential customers.

service facility
A person (or crew), a machine (or group of machines), or both, necessary to perform the service for the customer.

priority rule
A rule that selects the next customer to be served by the service facility.

service system
The number of lines and the arrangement of the facilities.

1. An input, or **customer population**, that generates potential customers
2. A waiting line of customers
3. The **service facility**, consisting of a person (or crew), a machine (or group of machines), or both, necessary to perform the service for the customer
4. A **priority rule**, which selects the next customer to be served by the service facility

Figure B.1 shows these basic elements. The triangles, circles, and squares are intended to show a diversity of customers with different needs. The **service system** describes the number of lines and the arrangement of the facilities. After the service has been performed, the served customers leave the system.

Customer Population

A customer population is the source of input to the service system. If the potential number of new customers for the service system is appreciably affected by the number of customers already in the system, the input source is said to be *finite*. For example, suppose that a maintenance crew is assigned responsibility for the repair of 10 machines. The customer population for the maintenance crew is 10 machines in working order. The population generates customers for the maintenance crew as a function of the failure rates for the machines. As more machines fail and enter the service system, either waiting for service or for being repaired, the customer population becomes smaller or the rate at which it can generate another customer falls. Consequently, the customer population is said to be finite.

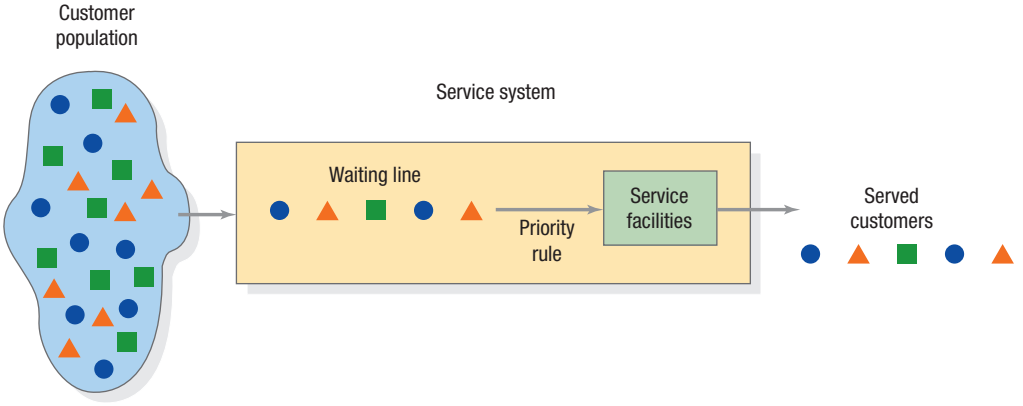


FIGURE B.1 ▶
Basic Elements of Waiting-Line Models

Alternatively, an *infinite* customer population is one in which the number of customers in the system does not affect the rate at which the population generates new customers. For example, consider a mail-order operation for which the customer population consists of shoppers who have received a catalog of products sold by the company. Because the customer population is so large and only a small fraction of the shoppers place orders at any one time, the number of new orders it generates is not appreciably affected by the number of orders waiting for service or being processed by the service system. In this case, the customer population is said to be infinite.

Customers in waiting lines may be *patient* or *impatient*, which has nothing to do with the colorful language a customer may use while waiting in line for a long time on a hot day. In the context of waiting-line problems, a patient customer is one who enters the system and remains there until being served; an impatient customer is one who either decides not to enter the system (balks) or leaves the system before being served (reneges). For the methods used in this supplement, we make the simplifying assumption that all customers are patient.

The Service System

The service system may be described by the number of lines and the arrangement of facilities.

Number of Lines Waiting lines may be designed to be a *single line* or *multiple lines.* Figure B.2 shows an example of each arrangement. Generally, single lines are utilized at airline counters, inside banks, and at some fast-food restaurants, whereas multiple lines are utilized in grocery stores, at drive-in bank operations, and in discount stores. When multiple servers are available and each one can handle general transactions, the single-line arrangement keeps servers uniformly busy and gives customers a sense of fairness. Customers believe that they are being served on the basis of when they arrived and not on how well they guessed their waiting time when selecting a particular line. The multiple-line design is best when some of the servers provide a limited set of services. In this arrangement, customers select the services they need and wait in the line where that service is provided, such as at a grocery store that provides special lines for customers paying with cash or having fewer than 10 items.

Sometimes customers are not organized neatly into "lines." Machines that need repair on the production floor of a factory may be left in place, and the maintenance crew comes to them. Nonetheless, we can think of such machines as forming a single line or multiple lines, depending on the number of repair crews and their specialties. Likewise, passengers who telephone for a taxi also form a line even though they may wait at different locations.



sladkozaponl/Shutterstock

Sometimes customers are not organized neatly into lines. Here cars, other vehicles, and people are caught in a messy traffic in Mumbai, one of India's largest cities.

Arrangement of Service Facilities Service facilities consist of the personnel and equipment necessary to perform the service for the customer. Service facility arrangement is described by the number of channels and phases. A **channel** is one or more facilities required to perform a given service. A **phase** is a single step in providing the service. Some services require a single phase, while others require a sequence of phases. Consequently, a service facility uses some combination of channels and phases. Managers should choose an arrangement based on customer volume and the nature of services provided. Figure B.3 shows examples of the five basic types of service facility arrangements.

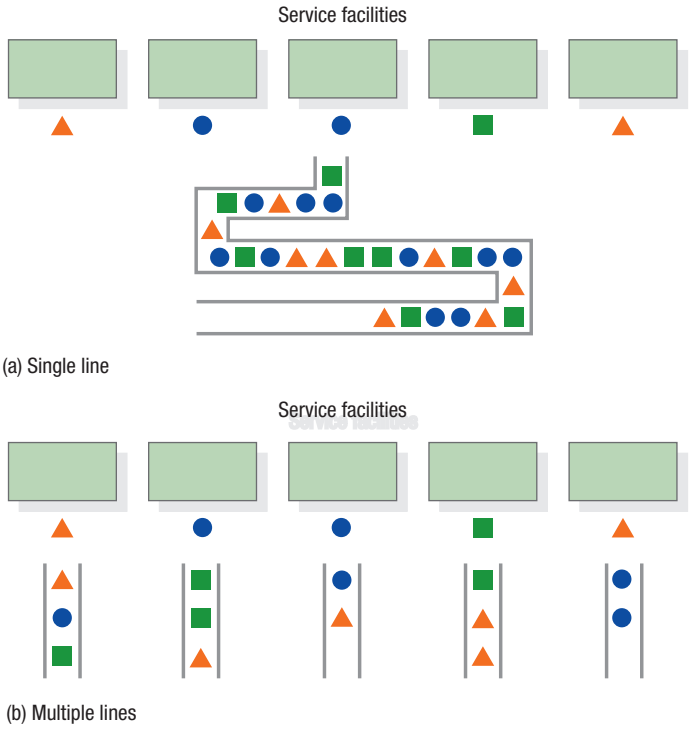
channel
One or more facilities required to perform a given service.

phase
A single step in providing a service.

In the *single-channel, single-phase* system, all services demanded by a customer can be performed by a single-server facility. Customers form a single line and go through the service facility one at a time. Examples are a drive-through car wash and a machine that must process several batches of parts.

The *single-channel, multiple-phase* arrangement is used when the services are best performed in sequence by more than one facility, yet customer volume or other constraints limit the design to one channel. Customers form a single line and proceed sequentially from one service facility to the next. An example of this arrangement is a McDonald's drive-through, where the first facility takes the order, the second takes the money, and the third provides the food.

The *multiple-channel, single-phase* arrangement is used when demand is large enough to warrant providing the same service at more than one facility or when the services offered by the



▲ **FIGURE B.2**
Waiting-Line Arrangements

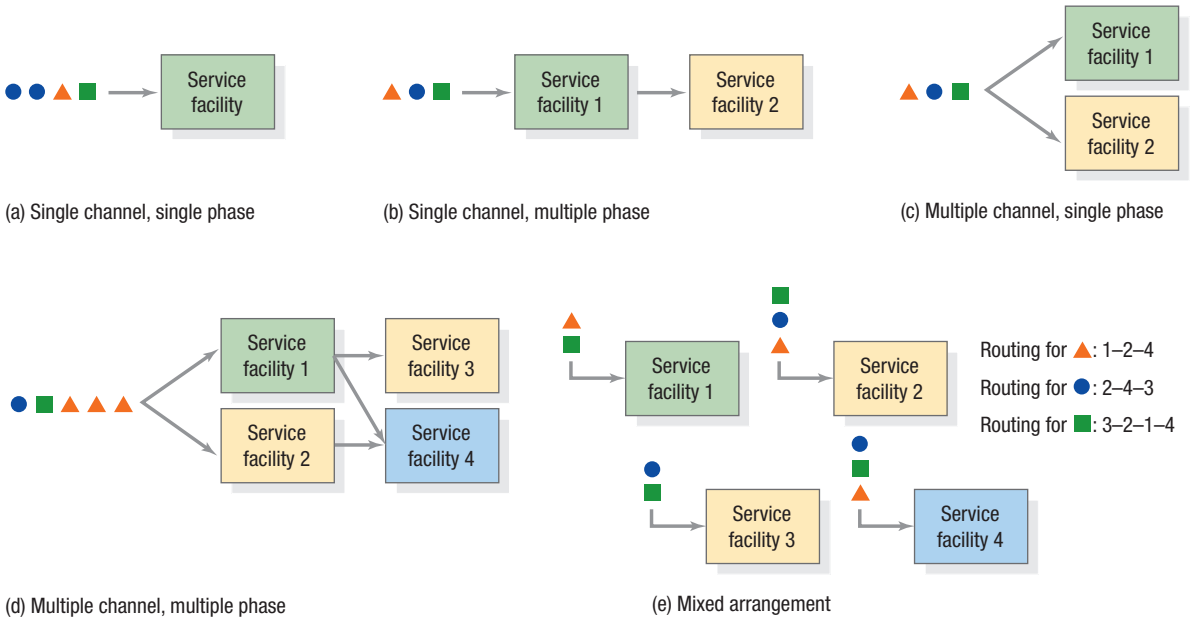
facilities are different. Customers form one or more lines, depending on the design. In the single-line design, the first available server serves customers, as is usually done in the lobby of a bank. If each channel has its own waiting line, customers wait until the server for their line can serve them, as at a bank's drive-through facilities.

The *multiple-channel, multiple-phase* arrangement occurs when customers can be served by one of the first-phase facilities but then require service from a second-phase facility, and so on. In some cases, customers cannot switch channels after service has begun; in others they can. An example of this arrangement is a laundromat. Washing machines are the first-phase facilities, and dryers are the second-phase facilities. Some of the washing machines and dryers may be designed for extra-large loads, thereby providing the customer a choice of channels.

The most complex waiting-line problem involves customers who have unique sequences of required services; consequently, service cannot be described neatly in phases. A *mixed* arrangement is used in such a case. In the mixed arrangement, waiting lines can develop in front of each facility, as in a medical center, where a patient goes to an exam room for a nurse to take his or her blood pressure and weight, goes back to the waiting room until the doctor can see him or her, and after consultation proceeds to the laboratory to give a blood sample, radiology to have an X-ray taken, or the pharmacy for prescribed drugs, depending on specific needs.

Priority Rule

The priority rule determines which customer to serve next. Most service systems that you encounter use the first-come, first-served (FCFS) rule. The customer at the head of the waiting line has the highest priority, and the customer who arrived last has the lowest priority. Other priority disciplines might take the customer with the earliest promised due date (EDD) or the customer with the shortest expected processing time (SPT).[1]



▲ **FIGURE B.3**
Examples of Service Facility Arrangements

[1]We focus on FCFS in this supplement. See Chapter 10, "Operations Planning and Scheduling," for additional discussion of FCFS and EDD. See also Supplement J, "Operations Scheduling," for SPT and additional rules.

A **preemptive discipline** is a rule that allows a customer of higher priority to interrupt the service of another customer. For example, in a hospital emergency room, patients with the most life-threatening injuries receive treatment first, regardless of their order of arrival. Modeling of systems having complex priority disciplines is usually done using computer simulation.

preemptive discipline
A rule that allows a customer of higher priority to interrupt the service of another customer.

Probability Distributions

The sources of variation in waiting-line problems come from the random arrivals of customers and the variations in service times. Each of these sources can be described with a probability distribution.

Arrival Distribution

Customers arrive at service facilities randomly. The variability of customer arrivals often can be described by a Poisson distribution, which specifies the probability that n customers will arrive in T time periods:

$$P_n = \frac{(\lambda T)^n}{n!} e^{-\lambda T} \text{ for } n = 0, 1, 2, \ldots$$

where

P_n = probability of n arrivals in T time periods

λ = average number of customer arrivals per period

$e = 2.7183$

The mean of the Poisson distribution is λT, and the variance also is λT. The Poisson distribution is a discrete distribution; that is, the probabilities are for a specific number of arrivals per unit of time.

EXAMPLE B.1 Calculating the Probability of Customer Arrivals

Management is redesigning the customer service process in a large department store. Accommodating four customers is important. Customers arrive at the desk at the rate of two customers per hour. What is the probability that four customers will arrive during any hour?

SOLUTION

In this case $\lambda = 2$ customers per hour, $T = 1$ hour, and $n = 4$ customers. The probability that four customers will arrive in any hour is

$$P_4 = \frac{[2(1)]^4}{4!} e^{-2(1)} = \frac{16}{24} e^{-2} = \mathbf{0.090}$$

DECISION POINT

The manager of the customer service desk can use this information to determine the space requirements for the desk and waiting area. There is a relatively small probability that four customers will arrive in any hour. Consequently, seating capacity for two or three customers should be more than adequate unless the time to service each customer is lengthy. Further analysis on service times is warranted.

Another way to specify the arrival distribution is to do it in terms of customer **interarrival times**—that is, the time between customer arrivals. If the customer population generates customers according to a Poisson distribution, the *exponential distribution* describes the probability that the next customer will arrive, or that service to a customer will conclude, in the next T time periods.

interarrival times
The time between customer arrivals.

Service Time Distribution

The exponential distribution describes the probability that the service time of the customer at a particular facility will be no more than T time periods. The probability can be calculated by using the formula

$$P(t \leq T) = 1 - e^{-\mu T}$$

where

μ = average number of customers completing service per period

t = service time of the customer

T = target service time

The mean of the service time distribution is $1/\mu$, and the variance is $(1/\mu)^2$, As T increases, the probability that the customer's service time will be less than T approaches 1.0.

For simplicity, let us look at a single-channel, single-phase arrangement.

EXAMPLE B.2 **Calculating the Service Time Probability**

The management of the large department store in Example B.1 must determine whether more training is needed for the customer service clerk. The clerk at the customer service desk can serve an average of three customers per hour. What is the probability that a customer will require 10 minutes or less of service?

SOLUTION

We must have all the data in the same time units. Because $\mu = 3$ customers per hour, we convert minutes of time to hours, or $T = 10$ minutes $= 10/60$ hour $= 0.167$ hour. Then

$$P(t \leq T) = 1 - e^{-\mu T}$$

$$P(t \leq 0.167 \text{ hour}) = 1 - e^{-3(0.167)} = 1 - 0.61 = \mathbf{0.39}$$

DECISION POINT

The probability that the customer will require only 10 minutes or less is not high, which leaves the possibility that customers may experience lengthy delays. Management should consider additional training for the clerk so as to reduce the time it takes to process a customer request.

Some characteristics of the exponential distribution do not always conform to an actual situation. The exponential distribution model is based on the assumption that each service time is independent of those that preceded it. In real life, however, productivity may improve as human servers learn about the work. Another assumption underlying the model is that very small, as well as very large, service times are possible. However, real-life situations often require a fixed-length start-up time, some cutoff on total service time, or nearly constant service time.

Using Waiting-Line Models to Analyze Operations

Operations managers can use waiting-line models to balance the gains that might be made by increasing the efficiency of the service system against the costs of doing so. In addition, managers should consider the costs of *not* making improvements to the system: Long waiting lines or long waiting times may cause customers to balk or renege. Managers should therefore be concerned about the following operating characteristics of the system.

1. *Line Length.* The number of customers in the waiting line reflects one of two conditions. Short lines could mean either good customer service or too much capacity. Similarly, long lines could indicate either low server efficiency or the need to increase capacity.
2. *Number of Customers in System.* The number of customers in line and being served also relates to service efficiency and capacity. A large number of customers in the system cause congestion and may result in customer dissatisfaction, unless more capacity is added.
3. *Waiting Time in Line.* Long lines do not always mean long waiting times. If the service rate is fast, a long line can be served efficiently. However, when waiting time seems long, customers perceive the quality of service to be poor. Managers may try to change the arrival rate of customers or design the system to make long wait times seem shorter than they really are. For example, at Walt Disney World, customers in line for an attraction are entertained by videos and also are informed about expected waiting times, which seems to help them endure the wait.
4. *Total Time in System.* The total elapsed time from entry into the system until exit from the system may indicate problems with customers, server efficiency, or capacity. If some

customers are spending too much time in the service system, it may be necessary to change the priority discipline, increase productivity, or adjust capacity in some way.

5. *Service Facility Utilization.* The collective utilization of service facilities reflects the percentage of time that they are busy. Management's goal is to maintain high utilization and profitability without adversely affecting the other operating characteristics.

The best method for analyzing a waiting-line problem is to relate the five operating characteristics and their alternatives to dollars. However, placing a dollar figure on certain characteristics (such as the waiting time of a shopper in a grocery store) is difficult. In such cases, an analyst must weigh the cost of implementing the alternative under consideration against a subjective assessment of the cost of *not* making the change.

We now present three models and some examples showing how waiting-line models can help operations managers make decisions. We analyze problems requiring the single-server, multiple-server, and finite-source models, all of which are single-phase. References to more advanced models are cited at the end of this supplement.

Single-Server Model

The simplest waiting-line model involves a single server and a single line of customers, commonly referred to as a single-channel, single-phase system. To further specify the single-server model, we make the following assumptions:

1. The customer population is infinite and all customers are patient.
2. The customers arrive according to a Poisson distribution, with a mean arrival rate of λ.
3. The service distribution is exponential, with a mean service rate of μ.
4. The mean service rate exceeds the mean arrival rate.
5. Customers are served on a first-come, first-served basis.
6. The length of the waiting line is unlimited.



Zvonimir Atletic/Shutterstock

Teenagers waiting in line to enter the Line Friends cafe and shop in Shanghai, China.

With these assumptions, we can apply various formulas to describe the operating characteristics of the system:

$$\rho = \text{Average utilization of the system} = \frac{\lambda}{\mu}$$

$$P_n = \text{Probability that } n \text{ customers are in the system} = (1 - \rho)\rho^n$$

$$P_0 = \text{Probability that zero customers are in the system} = 1 - \rho$$

$$L = \text{Average number of customers in the service system} = \frac{\lambda}{\mu - \lambda}$$

$$L_q = \text{Average number of customers in the waiting line} = \rho L$$

$$W = \text{Average time spent in the system, including service} = \frac{1}{\mu - \lambda}$$

$$W_q = \text{Average waiting time in line} = \rho W$$

EXAMPLE B.3 Calculating the Operating Characteristics of a Single-Channel, Single-Phase System with the Single-Server Model

Online Resource
Active Model B.1 provides additional insight on the single-server model and its uses for this problem.

The manager of a grocery store in the retirement community of Sunnyville is interested in providing good service to the senior citizens who shop in her store. Currently, the store has a separate checkout counter for senior citizens. On average, 30 senior citizens per hour arrive at the counter, according to a Poisson distribution, and are served at an average rate of 35 customers per hour, with exponential service times. Find the following operating characteristics:

a. Probability of zero customers in the system
b. Average utilization of the checkout clerk
c. Average number of customers in the system
d. Average number of customers in line
e. Average time spent in the system
f. Average waiting time in line

SOLUTION

The checkout counter can be modeled as a single-channel, single-phase system. Figure B.4 shows the results from the *Waiting-Lines* Solver from OM Explorer. Manual calculations of the equations for the *single-server model* are demonstrated in the Solved Problem at the end of the supplement.

FIGURE B.4 ▶
Waiting-Lines Solver for Single-Channel, Single-Phase System

Servers		(Number of servers *s* assumed to be 1 in single-serve model)
Arrival Rate (λ)	30	
Service Rate (μ)	35	
Probability of zero customers in the system (P_0)		0.1429
Probability of exactly 0 customers in the system		0.1429
Average utilization of the server (ρ)		0.8571
Average number of customers in the system (L)		6.0000
Average number of customers in line (L_q)		5.1429
Average waiting/service time in the system (W)		0.2000
Average waiting time in line (W_q)		0.1714

Both the average waiting time in the system (W) and the average time spent waiting in line (Wq) are expressed in hours. To convert the results to minutes, simply multiply by 60 minutes/hour. For example, $W = 0.20(60) =$ **12.00** minutes, and $W_q = 0.1714(60) =$ **10.28** minutes.

EXAMPLE B.4 Analyzing Service Rates with the Single-Server Model

Online Resource
Tutor B.1 in OM Explorer provides a new example to practice the single-server model.

The manager of the Sunnyville grocery in Example B.3 wants answers to the following questions:

a. What service rate would be required so that customers averaged only 8 minutes in the system?
b. For that service rate, what is the probability of having more than four customers in the system?
c. What service rate would be required to have only a 10 percent chance of exceeding four customers in the system?

SOLUTION

The *Waiting-Lines* Solver from OM Explorer could be used iteratively to answer the questions. Here we show how to solve the problem manually.

a. We use the equation for the average time in the system and solve for μ.

$$W = \frac{1}{\mu - \lambda}$$

$$8 \text{ minutes} = 0.133 \text{ hour} = \frac{1}{\mu - 30}$$

$$0.133\mu - 0.133(30) = 1$$

$$\mu = \textbf{37.52} \text{ customers/hour}$$

b. The probability of more than four customers in the system equals 1 minus the probability of four or fewer customers in the system.

$$P = 1 - \sum_{n=0}^{4} P_n$$
$$= 1 \sum_{n=0}^{4} (1 - \rho)\rho^n$$

and

$$\rho = \frac{30}{37.52} = 0.80$$

Then,

$$P = 1 - 0.2(1 + 0.8 + 0.8^2 + 0.8^3 + 0.8^4)$$
$$= 1 - 0.672 = \mathbf{0.328}$$

Therefore, there is a nearly 33 percent chance that more than four customers will be in the system.

c. We use the same logic as in part (b), except that μ is now a decision variable. The easiest way to proceed is to find the correct average utilization first, and then solve for the service rate.

$$P = 1 - (1 - \rho)(1 + \rho + \rho^2 + \rho^3 + \rho^4)$$
$$= 1 - (1 + \rho + \rho^2 + \rho^3 + \rho^4) + \rho(1 + \rho + \rho^2 + \rho^3 + \rho^4)$$
$$= 1 - 1 - \rho - \rho^2 - \rho^3 - \rho^4 + \rho + \rho^2 + \rho^3 + \rho^4 + \rho^5$$
$$= \rho^5$$

or

$$\rho = P^{1/5}$$

If $P = 0.10$,

$$\rho = (0.10)^{1/5} = 0.63$$

Therefore, for a utilization rate of 63 percent, the probability of more than four customers in the system is 10 percent. For $\lambda = 30$, the mean service rate must be

$$\frac{30}{\mu} = 0.63$$
$$\mu = \mathbf{47.62} \text{ customers/hour}$$

DECISION POINT

The service rate would only have to increase modestly to achieve the 8-minute target. However, the probability of having more than four customers in the system is too high. The manager must now find a way to increase the service rate from 35 per hour to approximately 48 per hour. She can increase the service rate in several different ways, ranging from employing a high school student to help bag the groceries to installing self-checkout stations.

Multiple-Server Model

With the multiple-server model, customers form a single line and choose one of s servers when one is available. The service system has only one phase; consequently, we are focusing our discussion on multiple-channel, single-phase systems. We make the following assumptions in addition to those for the single-server model: There are s identical servers, and the service distribution for each server is exponential, with a mean service time of $1/\mu$. It should always be the case that $s\mu$ exceeds λ.



Randy Duchaine/Alamy Stock Photo

Multiple-server model of shoppers in checkout lines at a Costco store in Brooklyn, New York.

EXAMPLE B.5 Estimating Idle Time and Hourly Operating Costs with the Multiple-Server Model

Online Resource
Tutor B.2 in OM Explorer provides a new example to practice the multiple-server model.

Online Resource
Active Model B.2 provides additional insight on the multiple-server model and its uses for this problem.

The management of the American Parcel Service terminal in Verona, Wisconsin, is concerned about the amount of time the company's trucks are idle (not delivering on the road), which the company defines as waiting to be unloaded and being unloaded at the terminal. The terminal operates with four unloading bays. Each bay requires a crew of two employees, and each crew costs $30 per hour. The estimated cost of an idle truck is $50 per hour. Trucks arrive at an average rate of three per hour, according to a Poisson distribution. On average, a crew can unload a semitrailer rig in one hour, with exponential service times. What is the total hourly cost of operating the system?

SOLUTION

The *multiple-server model* for s = 4, $\mu = 1$, and $\lambda = 3$ is appropriate. To find the total cost of labor and idle trucks, we must calculate the average number of trucks in the system at all times.

Figure B.5 shows the results for the American Parcel Service problem using the *Waiting-Lines* Solver from OM Explorer. The results show that the four-bay design will be utilized 75 percent of the time and that the average number of trucks either being serviced or waiting in line is 4.53 trucks. That is, on average at any point in time, we have 4.53 idle trucks. We can now calculate the hourly costs of labor and idle trucks:

Labor cost:	$30(*s*) = $30(4) = $120.00
Idle truck cost:	$50(*L*) = $50(4.53) = $226.50
	Total hourly cost = **346.50**

FIGURE B.5 ▶
Waiting-Lines Solver for Multiple-Server Model

Servers	4
Arrival Rate (λ)	3
Service Rate (μ)	1

Probability of zero customers in the system (P_0)				0.0377
Probability of	exactly	0	customers in the system	0.0377
Average utilization of the servers (ρ)				0.7500
Average number of customers in the system (L)				4.5283
Average number of customers in line (L_q)				1.5283
Average waiting/service time in the system (W)				1.5094
Average waiting time in line (W_q)				0.5094

DECISION POINT

Management must now assess whether $346.50 per day for this operation is acceptable. Attempting to reduce costs by eliminating crews will only increase the waiting time of the trucks, which is more expensive per hour than the crews. However, the service rate can be increased through better work methods; for example, L can be reduced and daily operating costs will be less.

Little's Law

Little's law
Relates the number of customers in a waiting-line system to the arrival rate and the waiting time of customers.

One of the most practical and fundamental laws in waiting-line theory is **Little's law**, which relates the number of customers in a waiting-line system to the arrival rate and the waiting time of customers. Using the same notation we used for the single-server model, Little's law can be expressed as $L = \lambda W$ or $Lq = \lambda Wq$. However, this relationship holds for a wide variety of arrival processes, service-time distributions, and numbers of servers. The practical advantage of Little's law is that you only need to know two of the parameters to estimate the third. For example, consider the manager of a motor vehicle licensing facility who receives many complaints about the time people must spend either having their licenses renewed or getting new license plates. It would be difficult to obtain data on the times individual customers spend at the facility. However, the manager can have an assistant monitor the number of people who arrive at the facility each hour and compute the average (λ). The manager also could periodically count the number of people in the sitting area and at the stations being served and compute the average (L). Using Little's law, the manager can then estimate W, the average time each customer spent in the facility.

For example, if 40 customers arrive per hour and the average number of customers being served or waiting is 30, the average time each customer spends in the facility can be computed as

$$\text{Average time in the facility} = W = \frac{L \text{ customers}}{\lambda \text{ customers/hour}} = \frac{30}{40} = 0.75 \text{ hour, or } \mathbf{45} \text{ minutes}$$

If the time a customer spends at the facility is unreasonable, the manager can focus on either adding capacity or improving the work methods to reduce the time spent serving the customers.

Likewise, Little's law can be used for manufacturing processes. Suppose that a production manager knows the average time a unit of product spends at a manufacturing process (W) and the average number of units per hour that arrive at the process (λ). The production manager can then estimate the average work-in-process (L) using Little's law. *Work in process* (WIP) consists of items, such as components or assemblies, needed to produce a final product in manufacturing. For example, if the average time a gear case used for an outboard marine motor spends at a machine center is 3 hours, and an average of five gear cases arrive at the machine center per hour, the average number of gear cases waiting and being processed (or work in process) at the machine center can be calculated as

$$\text{Work-in-process} = L = \lambda W = (5 \text{ gear cases/hour})(3 \text{ hours}) = \mathbf{15} \text{ gear cases}$$

Knowing the relationship between the arrival rate, the lead time, and the work in process, the manager has a basis for measuring the effects of process improvements on the work in process at the facility. For example, adding some capacity to a bottleneck in the process can reduce the average lead time of the product at the process, thereby reducing the work-in-process inventory.

Even though Little's law is applicable in many situations in both service and manufacturing environments, it is not applicable in situations where the customer population is finite, which we address next.

Finite-Source Model

We now consider a situation in which all but one of the assumptions of the single-server model are appropriate. In this case, the customer population is finite, having only N potential customers. If N is greater than 30 customers, the single-server model with the assumption of an infinite customer population is adequate. Otherwise, the finite-source model is the one to use.

EXAMPLE B.6 Analyzing Maintenance Costs with the Finite-Source Model

The Worthington Gear Company installed a bank of 10 robots about 3 years ago. The robots greatly increased the firm's labor productivity, but recently attention has focused on maintenance. The firm does no preventive maintenance on the robots because of the variability in the breakdown distribution. Each machine has an exponential breakdown (or interarrival) distribution with an average time between failures of 200 hours. Each machine hour lost to downtime costs $30, which means that the firm has to react quickly to machine failure. The firm employs one maintenance person, who needs 10 hours on average to fix a robot. Actual maintenance times are exponentially distributed. The wage rate is $10 per hour for the maintenance person, who can be put to work productively elsewhere when not fixing robots. Determine the daily cost of labor and robot downtime.

Online Resources

Tutor B.3 in OM Explorer provides a new example to practice the finite-source model.

Active Model B.3 provides additional insight on the finite-source model and its uses for this problem.

SOLUTION

The *finite-source model* is appropriate for this analysis because the customer population consists of only 10 machines and the other assumptions are satisfied. Here, $\lambda = 1/200$, or 0.005 breakdown per hour, and $\mu = 1/10 = 0.10$ robot per hour. To calculate the cost of labor and robot downtime, we need to estimate the average utilization of the maintenance person and L, the average number of robots in the maintenance system at any time. Either OM Explorer or POM for Windows can be used to help with the calculations. Figure B.6 shows the results for the Worthington Gear Problem using the *Waiting-Lines* Solver from OM Explorer. The results show that the maintenance person is utilized only 46.2 percent of the time, and the average number of robots waiting in line or being repaired is 0.76 robot. However, a failed robot will spend an average of 16.43 hours in the repair system, of which 6.43 hours of that time is spent waiting for service. While an individual robot may spend more than 2 days with the maintenance person, the maintenance person has a lot of idle time with a utilization rate of only 42.6 percent. That is why there is only an average of 0.76 robot being maintained at any point of time.

FIGURE B.6 ▶
Waiting-Lines Solver for Finite-Source Model

Customers	10
Arrival Rate (λ)	0.005
Service Rate (μ)	0.1

Probability of zero customers in the system (P_0)				0.5380
Probability of	fewer than	0	customers in the system	#N/A
Average utilization of the server (p)				0.4620
Average number of customers in the system (L)				0.7593
Average number of customers in line (L_q)				0.2972
Average waiting/service time in the system (W)				16.4330
Average waiting time in line (W_q)				6.4330

The daily cost of labor and robot downtime is

Labor cost: ($10/hour)(8 hours/day)(0.462 utilization) = $36.96
Idle robot cost: (0.76 robot)($30/robot hour)(8 hours/day) = 182.40
Total daily cost = **$219.36**

DECISION POINT

The labor cost for robot repair is only 20 percent of the idle cost of the robots. Management might consider having a second repair person on call in the event two or more robots are waiting for repair at the same time.

Waiting Lines and Simulation

For each of the problems we analyzed with the waiting-line models, the arrivals had a Poisson distribution (or exponential interarrival times), the service times had an exponential distribution, the service facilities had a simple arrangement, the waiting line was unlimited, and the priority discipline was first-come, first-served. Waiting-line theory has been used to develop other models in which these criteria are not met, but these models are complex. For example, POM for Windows includes a finite system-size model in which limits can be placed on the size of the system (waiting line and server capacity). It also has several models that relax assumptions on the service time distribution. Nonetheless, many times the nature of the customer population, the constraints on the line, the priority rule, the service-time distribution, and the arrangement of the facilities are such that waiting-line theory is no longer useful. In these cases, simulation is often used. Online Supplement E, "Simulation," discusses simulation programming languages and powerful PC-based packages. Here we illustrate process simulation with the SimQuick software (also available online).



Vicki Beaver/Alamy Stock Photo

Passengers go through a TSA security checkpoint screening at Logan International Airport, Boston, Massachusetts. The airport security process is a multi-channel, multiphase system.

SimQuick

SimQuick is an easy-to-use package that is simply an Excel spreadsheet with some macros. Models can be created for a variety of simple processes, such as waiting lines, inventory control, and projects. Here, we consider the passenger security process at one terminal of a medium-sized airport between the hours of 8 A.M. and 10 A.M. The process works as follows. Passengers arriving at the security area immediately enter a single line. After waiting in line, each passenger goes through one of two inspection stations, which involves walking through a metal detector and running any carry-on baggage through a scanner. After completing this inspection, 10 percent of the passengers are randomly selected for an additional inspection, which involves a pat-down and a more thorough search of the person's carry-on baggage. Two stations handle this additional inspection, and selected passengers go through only one of them. Management is interested in examining the effect of increasing the percentage of passengers who undergo the second inspection. In particular, they want to compare the waiting times for the second inspection when 10 percent, then 15 percent, and then 20 percent of the passengers are randomly selected for this inspection. Management also

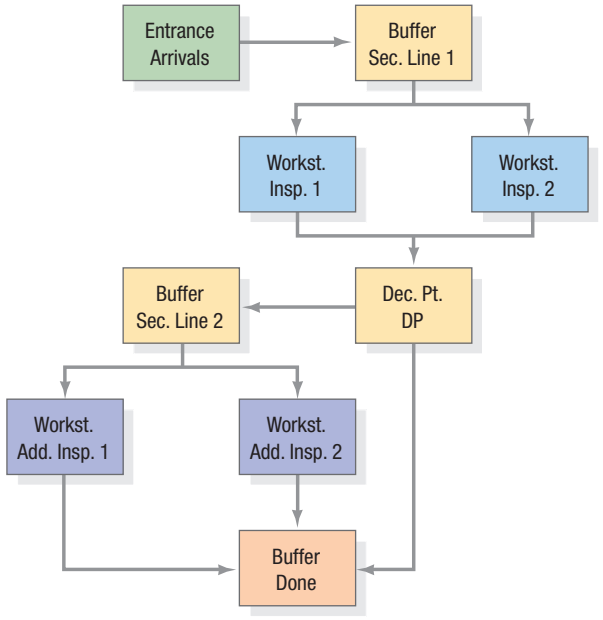
wants to know how opening a third station for the second inspection would affect these waiting times.

A first step in simulating this process with SimQuick is to draw a flowchart of the process using SimQuick's building blocks. SimQuick has five building blocks that can be combined in a wide variety of ways. Four of these types are used to model this process. An *entrance* is used to model the arrival of passengers at the security process. A *buffer* is used to model each of the two waiting lines, one before each type of inspection, as well as the passengers that have finished the process. Each of the four inspection stations is modeled with a *workstation*. Finally, the random selection of passengers for the second inspection is modeled with a *decision point*. Figure B.7 shows the flowchart.

Information describing each building block is entered into SimQuick tables. In this model, three key types of information are entered: (1) when people arrive at the entrance, (2) how long inspections take at the four stations, and (3) what percentage of passengers are randomly selected for the additional inspection. All of this information must be entered into SimQuick in the form of statistical distributions. The first two types of information are determined by observing the real process from 8 A.M. and 10 A.M. The third type of information is a policy decision (10 percent, 15 percent, or 20 percent).

The original model is run 30 times, simulating the arrival of passengers during the hours from 8 A.M. to 10 A.M. Statistics are collected by SimQuick and summarized. Figure B.8 provides some key results for the model of the present process as output by SimQuick (many other statistics are collected, but not displayed here).

The numbers shown are averages across the 30 simulations. The number 237.23 is the average number of passengers that enter line 1 during the simulated 2 hours. The two mean inventory statistics tell us, on average, 5.97 simulated passengers were standing in line 1 and 0.10 standing in line 2. The two statistics on *cycle time*, interpreted here as the time a passenger spends in one or more SimQuick building blocks, tell us that the simulated passengers in line 1 waited an average of 3.12 minutes, while those in line 2 waited 0.53 minute. The final inventory statistic tells us that, on average, 224.57 simulated passengers passed through the security process in the simulated 2 hours. The next step is to change the percentage of simulated passengers selected for the second inspection to 15 percent, and then to 20 percent, and rerun the model. Of course, these process changes will increase the average waiting time for the second inspection, but by how much? The final step is to rerun these simulations with one more workstation and see its effect on the waiting time for the second inspection. All the details for this model (as well as many others) appear in the book *SimQuick: Process Simulation with Excel*, which is included, along with the SimQuick software, available online.



▲ **FIGURE B.7**
Flowchart of Passenger Security Process

Element Types	Element Names	Statistics	Overall Means
Entrance(s)	Door	Objects entering process	237.23
Buffer(s)	Line 1	Mean inventory	5.97
		Mean cycle time	3.12
	Line 2	Mean inventory	0.10
		Mean cycle time	0.53
	Done	Final inventory	224.57

▲ **FIGURE B.8**
Simulation Results of Passenger Security Process

Decision Areas for Management

After analyzing a waiting-line problem, management can improve the service system by making changes in one or more of the following areas.

1. *Arrival Rates.* Management often can affect the rate of customer arrivals, λ, through advertising, special promotions, or differential pricing. For example, hotels in the Caribbean will reduce their room rates during the hot, rainy season to attract more customers and increase their utilization.
2. *Number of Service Facilities.* By increasing the number of service facilities, such as tool cribs, toll booths, or bank tellers, or by dedicating some facilities in a phase to a unique set of services, management can increase system capacity.
3. *Number of Phases.* Managers can decide to allocate service tasks to sequential phases if they determine that two sequential service facilities may be more efficient than one. For instance, in assembly lines a decision concerns the number of phases or workers needed along the assembly line. Determining the number of workers needed on the line also involves assigning a certain set of work elements to each one. Changing the facility arrangement can increase the service rate, μ, of each facility and the capacity of the system.
4. *Number of Servers per Facility.* Managers can influence the service rate by assigning more than one person to a service facility.

5. *Server Efficiency.* By adjusting the capital-to-labor ratio, devising improved work methods, or instituting incentive programs, management can increase the efficiency of servers assigned to a service facility. Such changes are reflected in μ.
6. *Priority Rule.* Managers set the priority rule to be used, decide whether to have a different priority rule for each service facility, and decide whether to allow preemption (and, if so, under what conditions). Such decisions affect the waiting times of the customers and the utilization of the servers.
7. *Line Arrangement.* Managers can influence customer waiting times and server utilization by deciding whether to have a single line or a line for each facility in a given phase of service.

Obviously, these factors are interrelated. An adjustment in the customer arrival rate might have to be accompanied by an increase in the service rate, λ, in some way. Decisions about the number of facilities, the number of phases, and waiting-line arrangements also are related.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
B.1 Identify the structure of waiting lines in real situations.	The section "Structure of Waiting-Line Problems" defines the four elements of every waiting-line problem. Figures B.1, B.2, and B.3 depict these elements and various service facility arrangements.	
B.2 Use the single-server, multiple-server, and finite-source models to analyze operations and estimate the operating characteristics of a process.	See the section "Using Waiting-Line Models to Analyze Operations" for a description and demonstration of these three models. Examples B.3, B.4, and the Solved Problem at the end of the supplement apply the single-server model. Example B.5 shows the multiple-server model and Example B.6 applies the finite-source model. In addition, Examples B.3 through B.6 show how to obtain estimates for the important operating characteristics of processes using waiting-line models.	**Active Model Exercises:** B.1: Single-Server Waiting-Line Model; B.2: Multi-Server Model with Costs; B.3: Finite Source Model with Costs **OM Explorer Solvers:** Single-Server Waiting-Line Model; Multi-Server Model; Finite Source Model **OM Explorer Tutors:** B.1: Single-Server Waiting-Line Model; B.2: Multi-Server Model; B.3: Finite Source Model **POM for Windows:** B.1: Single-Server Waiting-Line Model; B.2: Multi-Server Model with Costs; B.3: Finite Source Model with Costs; B.4: Finite System-Size Model
B.3 Describe the situations where simulation should be used for waiting-line analysis and the nature of the information that can be obtained.	The section "Waiting Lines and Simulation" explains when simulation must be used and discusses an example that demonstrates the nature of the managerial information that can be obtained from that analysis.	**Online Text:** SimQuick: Process Simulation with Excel, 2e
B.4 Explain how waiting-line models can be used to make managerial decisions.	The section "Decision Areas for Management" describes seven decision areas that can be analyzed with waiting-line models.	

Key Equations

Structure of Waiting-Line Problems

1. Customer arrival Poisson distribution:

$$P_n = \frac{(\lambda T)^n}{n!} e^{-\lambda T}$$

2. Service time exponential distribution:

$$P(t \leq T) = 1 - e^{-\mu T}$$

Using Waiting-Line Models to Analyze Operations

3. Average utilization of the system:

$$\rho = \frac{\lambda}{\mu}$$

4. Probability that n customers are in the system:

$$P_n = (1 - \rho)\rho^n$$

5. Probability that zero customers are in the system:

$$P_0 = 1 - \rho$$

6. Average number of customers in the service system:

$$L = \frac{\lambda}{\mu - \lambda}$$

7. Average number of customers in the waiting line:

$$L_q = \rho L$$

8. Average time spent in the system, including service:

$$W = \frac{1}{\mu - \lambda}$$

9. Average waiting time in line:

$$W_q = \rho W$$

10. Little's law:

$$L = \lambda W$$

Key Terms

channel 223
customer population 222
interarrival times 225
Little's law 230
phase 223
preemptive discipline 225
priority rule 222
service facility 222
service system 222
waiting line 221

Solved Problem

A photographer takes passport pictures at an average rate of 20 pictures per hour. The photographer must wait until the customer smiles, so the time to take a picture is exponentially distributed. Customers arrive at a Poisson-distributed average rate of 19 customers per hour.

a. What is the utilization of the photographer?

b. How much time will the average customer spend with the photographer?

SOLUTION

a. The assumptions in the problem statement are consistent with a single-server model. Utilization is

$$\rho = \frac{\lambda}{\mu} = \frac{19}{20} = \mathbf{0.95}$$

b. The average customer time spent with the photographer is

$$W = \frac{1}{\mu - \lambda} = \frac{1}{20 - 19} = \mathbf{1} \text{ hour}$$

Problems

The OM Explorer, POM for Windows, and Active Model software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations.

Structure of Waiting-Line Problems

1. Wingard Credit Union is redesigning the entryway into its bank of ATM machines. Management is trying to conceptually understand the interarrival of individuals, which has been described to them as following a Poisson distribution. If, on average, two customers arrive per minute randomly during busy times, calculate the probability that during a specific minute, no customers arrive. Calculate the probability that between one and four customers arrive.

2. Wingard Credit Union (from Problem 1) is also interested in understanding how long customers spend in front of the ATMs. Customer service times follow an exponential distribution, with an average customer taking 1.5 minutes to complete a transaction. Calculate the probability that a customer will take less than half a minute. Additionally, calculate the probability that a customer will take more than 3 minutes.

Using Waiting-Line Models to Analyze Operations

3. The Solomon, Smith, and Samson law firm produces many legal documents that must be word processed for clients and the firm. Requests average eight pages of documents per hour, and they arrive according to a Poisson distribution. The secretary can word process 10 pages per hour on average according to an exponential distribution.
   - **a.** What is the average utilization rate of the secretary?
   - **b.** What is the probability that more than four pages are waiting or being word processed?
   - **c.** What is the average number of pages waiting to be word processed?

4. Benny's Arcade has six video game machines. The average time between machine failures is 50 hours. Jimmy, the maintenance engineer, can repair a machine in 15 hours on average. The machines have an exponential failure distribution, and Jimmy has an exponential service-time distribution.
   - **a.** What is Jimmy's utilization?
   - **b.** What is the average number of machines out of service, that is, waiting to be repaired or being repaired?
   - **c.** What is the average time a machine is out of service?

5. Moore, Aiken, and Payne is a critical care dental clinic serving the emergency needs of the general public on a first-come, first-served basis. The clinic has five dental chairs, three of which are currently staffed by a dentist. Patients in distress arrive at the rate of five per hour, according to a Poisson distribution, and do not balk or renege. The average time required for an emergency treatment is 30 minutes, according to an exponential distribution. Use POM for Windows or OM Explorer to answer the following questions:
   - **a.** If the clinic manager would like to ensure that patients do not spend more than 15 minutes on average waiting to see the dentist, are three dentists on staff adequate? If not, how many more dentists are required?
   - **b.** From the current state of three dentists on staff, what is the change in each of the following operating characteristics when a fourth dentist is placed on staff:
     - Average utilization
     - Average number of customers in line
     - Average number of customers in the system
   - **c.** From the current state of three dentists on staff, what is the change in each of the following operating characteristics when a fifth dentist is placed on staff:
     - Average utilization
     - Average number of customers in line
     - Average number of customers in the system

6. Fantastic Styling Salon is run by three stylists, Jenny Perez, Jill Sloan, and Jerry Tiller, each capable of serving four customers per hour, on average. Use POM for Windows or OM Explorer to answer the following questions:

   During busy periods of the day, when nine customers on average arrive per hour, all three stylists are on staff.
   - **a.** If all customers wait in a common line for the next available stylist, how long would a customer wait in line, on average, before being served?
   - **b.** Suppose that each customer wants to be served by a specific stylist, 1/3 want Perez, 1/3 want Sloan, 1/3 want Tiller. How long would a customer wait in line, on average, before being served?

     During less busy periods of the day, when six customers on average arrive per hour, only Perez and Sloan are on staff.
   - **c.** If all customers wait in a common line for the next available stylist, how long would a customer wait in line, on average, before being served?

d. Suppose that each customer wants to be served by a specific stylist; 60 percent want Perez and 40 percent want Sloan. How long would a customer wait in line, on average, before being served by Perez? By Sloan? Overall?

7. You are the manager of a local bank where three tellers provide services to customers. On average, each teller takes 3 minutes to serve a customer. Customers arrive, on average, at a rate of 50 per hour. Having recently received complaints from some customers that they waited a long time before being served, your boss asks you to evaluate the service system. Specifically, you must provide answers to the following questions:

a. What is the average utilization of the three-teller service system?

b. What is the probability that no customers are being served by a teller or are waiting in line?

c. What is the average number of customers waiting in line?

d. On average, how long does a customer wait in line before being served?

e. On average, how many customers would be at a teller's station and in line?

8. Pasquist Water Company (PWC) operates a 24-hour facility designed to efficiently fill water-hauling tanker trucks. Trucks arrive randomly to the facility and wait in line to access a wellhead pump. Since trucks vary in size and the filling operation is manually performed by the truck driver, the time to fill a truck is also random.

a. If the manager of PWC uses the multiple-server model to calculate the operating characteristics of the facility's waiting line, list three assumptions she must make regarding the behavior of waiting trucks and the truck arrival process.

b. Suppose an average of 336 trucks arrive each day, there are four wellhead pumps, and each pump can serve an average of four trucks per hour.

- What is the probability that exactly 10 trucks will arrive between 1:00 P.M. and 2:00 P.M. on any given day?
- How likely is it that once a truck is in position at a wellhead, the filling time will be less than 15 minutes?

c. Contrast and comment on the performance differences between:

- One waiting line feeding all four stations.
- One waiting line feeding two wellhead pumps and a second waiting line feeding two other wellhead pumps. Assume that drivers cannot see each line and must choose randomly between them. Further, assume that once a choice is made, the driver cannot back out of the line.

9. The supervisor at the Precision Machine Shop wants to determine the staffing policy that minimizes total operating costs. The average arrival rate at the tool crib, where tools are dispensed to the workers, is eight machinists per hour. Each machinist's pay is $20 per hour. The supervisor can staff the crib either with a junior attendant who is paid $5 per hour and can process 10 arrivals per hour or with a senior attendant who is paid $12 per hour and can process 16 arrivals per hour. Which attendant should be selected, and what would be the total estimated hourly cost?

10. The daughter of the owner of a local hamburger restaurant is preparing to open a new fast-food restaurant called Hasty Burgers. Based on the arrival rates at her father's outlets, she expects customers to arrive at the drive-up window according to a Poisson distribution, with a mean of 20 customers per hour. The service rate is flexible; however, the service times are expected to follow an exponential distribution. The drive-in window is a single-server operation.

a. What service rate is needed to keep the average number of customers in the service system (waiting line and being served) to four?

b. For the service rate in part (a), what is the probability that more than four customers are in line and being served?

c. For the service rate in part (a), what is the average waiting time in line for each customer? Does this average seem satisfactory for a fast-food business?

11. The manager of a branch office of Banco Mexicali observed that during peak hours an average of 20 customers arrives per hour and that there is an average of four customers in the branch office at any time. How long does the average customer spend waiting in line and being serviced?

12. Paula Caplin is manager of a major electronics repair facility owned by Fisher Electronics. Recently, top management expressed concern over the growth in the number of repair jobs in process at the facility. The average arrival rate is 120 jobs per day. The average job spends 4 days at the facility.

a. What is the current work-in-process level at the facility?

b. Suppose that top management has put a limit of one-half the current level of work in process. What goal must Paula establish, and how might she accomplish it?

13. Failsafe Textiles employs three highly skilled maintenance workers who are responsible for repairing the numerous industrial robots used in its manufacturing process. A worker can fix one robot every 8 hours on average, with an exponential distribution. An average of one robot fails every 3 hours, according to a Poisson distribution. Each down robot costs the company $100.00 per hour in lost production. A new maintenance worker costs the company $80.00 per hour in salary, benefits, and equipment. Should the manager hire any new personnel? If so, how many people? What would you recommend to the manager, based on your analysis?

14. The College of Business and Public Administration at Benton University has a copy machine on each floor for faculty use. Heavy use of the five copy machines causes frequent failures. Maintenance records show that a machine fails every 2.5 days (or $\lambda = 0.40$ failure/day). The college has a maintenance contract with the authorized dealer of the copy machines. Because the copy machines fail so frequently, the dealer has assigned one person to the college to repair them. The person can repair an average of 2.5 machines per day. Using the finite-source model, answer the following questions:

a. What is the average utilization of the maintenance person?

b. On average, how many copy machines are being repaired or waiting to be repaired?

c. What is the average time spent by a copy machine in the repair system (waiting and being repaired)?

15. The manager of Vintage Time Video Machine Parlor is responsible for ensuring that all six of his machines are in good condition. Machines frequently need attention but can normally be returned to service quickly. On average, each machine requires attention five times each hour. The manager averages 4 minutes per repair.

a. What percentage of each hour is the manager fixing machines?

b. On average, how many machines are broken down and waiting for repair?

c. On average, how many minutes in an hour are machines waiting for repair or being repaired?

16. Two nurses at Northwood Hospital's Cardiac Care Unit are assigned to care for eight patients. Nurses are responsible for administering medication, taking vital signs, and responding to frequent calls for assistance that can come either from the patient or from the equipment monitoring the patient's current condition. On average, each patient requires attention three times each hour. Nurses average 6 minutes per patient visit.

a. What is the average utilization of the nursing staff?

b. On average, how many patients are waiting for a nurse?

c. By how much would adding a third nurse reduce the patient waiting time?

17. You are in charge of a quarry that supplies sand and stone aggregates to your company's construction sites. Empty trucks from construction sites arrive at the quarry's huge piles of sand and stone aggregates and wait in line to enter the station, which can load either sand or aggregate. At the station, they are filled with material, weighed, checked out, and proceed to a construction site. Currently, nine empty trucks arrive per hour, on average. Once a truck has entered a loading station, it takes 6 minutes for it to be filled, weighed, and checked out. Concerned that trucks are spending too much time waiting and being filled, you are evaluating two alternatives to reduce the average time the trucks spend in the system. The first alternative is to add side boards to the trucks (so that more material could be loaded) and to add a helper at the loading station (so that filling time could be reduced) at a total cost of $50,000. The arrival rate of trucks would change to six per hour, and the filling time would be reduced to 4 minutes. The second alternative is to add another loading station identical to the current one at a cost of $80,000. The trucks would wait in a common line and the truck at the front of the line would move to the next available station.

Which alternative would you recommend if you want to reduce the current average time the trucks spend in the system, including service?

6

CONSTRAINT MANAGEMENT

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

6.1 Explain the theory of constraints.

6.2 Identify and manage bottlenecks in service processes.

6.3 Identify and manage bottlenecks in manufacturing processes.

6.4 Apply the theory of constraints to product mix decisions.

6.5 Describe how to manage constraints in line processes and balance assembly lines.

Microsoft Corporation



Bloomberg/Getty Images

Attendees work in the coding competition booth at the Microsoft Developers Build Conference in San Francisco, California, United States, on Thursday, March 31, 2016.

Microsoft Corporation is a diversified technology company that develops, manufactures, and supports computer software and consumer electronic products. Founded in Redmond, Washington, in 1975, it is one of the largest software development companies in the world, with its 286,556 employees generating 2019 revenues of more than $125 billion. Within software development, XIT Sustained Engineering is one of Microsoft's eight IT groups that maintains over 80 applications used internally at Microsoft. The XIT process consisted of Estimation, which produced a rough time estimate to produce the requested change; Development, which produced the change; and Testing, which ran

multiple tests on the software to make sure everything was working as planned. Of the 85 change requests per quarter coming on an average into XIT, half were rejected in the Estimation process for unacceptable cost or time. The remaining 43 or so requests were funneled to Development, where a team of three developers could each process only 6.5 requests per quarter, for a throughput of about 20 requests per quarter. The input exceeded the output, which resulted in backlogs that were five times its capacity during the first quarter of 2005. Also, four of its major internal customer groups were dissatisfied with the service quality. Clearly, the developers were a bottleneck for this team due to lack of sufficient capacity to handle the change orders. Through an extensive application of the theory of constraints (TOC), a scientific approach to improve productivity and throughput, this team became one of the best performers in the company within 9 months. How, exactly, did such a dramatic change and turnaround occur?

The theory of constraints in the context of software engineering tells us to maximize throughput while controlling for customer feature/change requirements and eliminating waste processes that take away productive capacity from scarce resources, such as software engineers. By applying TOC, three main improvement suggestions were made by a process improvement task team at Microsoft. First, the team added an eight-slot queue system before the development process. This queue system would limit the change request from flowing directly into the bottleneck. Each change request would be assigned one of eight positions in the queue, depending on the scope of what had to be done. This was a way to synchronize the material release, pace the bottleneck, and balance the task flows of work within XIT. Second, the team eliminated the process for providing detailed time estimates. Not only was this time-consuming, but it was also not providing useful estimates. Instead, every change was assumed to take an average of 5 days, with slight variation for some cases that may require additional setup time or downtime due to scheduled maintenance. The eight-slot buffer allowed the developers to work at a steady pace with minimal loss in production time. Third, one person was reassigned from testing to the preceding development process. This reallocation of resources helped XIT to balance the capacity and workflows between the development and testing process, and thus reduced the congestion that would often occur at the development phase. Finally, the team relieved the bottleneck by hiring more developers. By increasing the bottleneck capacity, total throughput increased from 20 requests per quarter to 56. Backlog decreased from 80 requests to under 10, and the average cost per request fell from $7,500 to $2,900. The lead time was reduced from 5 months to 2 weeks, along with an increase in on-time service delivery rate from near zero to over 90 percent. Overall, productivity grew by 155 percent.

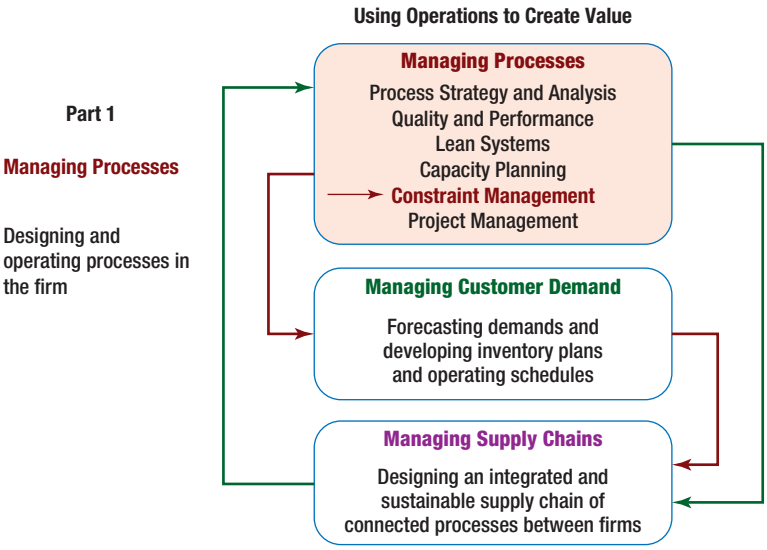
By applying the theory of constraints, the XIT team at Microsoft Corporation could reclaim customer trust and satisfaction.[1]

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[1] *Sources:* D. J. Anderson, *Agile Management for Software Engineering: Applying the Theory of Constraints for Business Results*, Prentice Hall (2003); T. Forte, "Theory of Constraints 105: Drum-Buffer-Rope at Microsoft," Forte Labs (2016), https://praxis.fortelabs.co/theory-of-constraints-105-drum-buffer-rope-at-microsoft-fda187c6d1d9#.pii2wsi3r; J. A. Ricketts, *Reaching the Goal: How Managers Improve a Services Business Using Goldratt's Theory of Constraints*, IBM Press (2007); S. Tendon, "Theory of Constraints and Software Engineering," http://chronologist.com/blog/2012-07-27/theory-of-constraints-and-software-engineering/ (2012); https://en.wikipedia.org/wiki/Microsoft (July 3, 2020).

We will learn more in this chapter about the theory of constraints (TOC), its main principles, and how it can be used to enhance organizational performance. Thinking beyond Microsoft Corporation, the case of the XIT team shows that the application of TOC and constraint management is not limited to manufacturing processes alone, but can also be used to improve the productivity of all types of knowledge work by balancing the planning, scheduling, and queueing of work and resources. Failing to do so results in creation of constraints that lead to high costs and low customer satisfaction. A **constraint** is any factor that limits the performance of a system and restricts its output, while *capacity* is the maximum rate of output of a process or a system. When constraints exist at any step, as they did for software developers at Microsoft Corporation, capacity can become imbalanced—too high in some areas and too low in others. As a result, the overall performance of the system suffers.

Constraints can occur up or down the supply chain, with either the firm's suppliers or customers or within one of the firm's processes like service or product development or order fulfillment. Three kinds of constraints can generally be identified: physical (usually machine, labor, or workstation capacity or material shortages, but could be space or quality), market (demand is less than capacity), or managerial (policy, metrics, or mindsets that create constraints that impede work flow). A **bottleneck**[2] is a special type of a constraint that relates to the capacity shortage of a process and is defined as any resource whose available capacity limits the organization's ability to meet the service or product volume, product mix, or fluctuating requirements demanded by the marketplace. A business system or a process would have at least one constraint or a bottleneck; otherwise, its output would be limited only by market demand, as seen in the Managerial Challenge at Schmidt Industries.





Aerial Archives/Alamy Stock Photo

George Washington bridge toll plazas on New Jersey side create bottlenecks in traffic flow.

MANAGERIAL CHALLENGE Marketing

Schmidt Industries, incorporated in 1988, is a supplier of standard winches, 4wd hubs and axel assemblies, and plow systems for trucks and SUVs. Schmidt has 500 employees and generates $150 M in revenue per year in a competitive industry. While the 4wd hub and axel assembly product line was holding a 65 percent market share, and the plow systems product line had a 42 percent market share, the winches were not doing so well. At only 17 percent share, the sentiment at the top levels of the company was that improvement was necessary. Sales of the winch were on the decline, while sales of the trucks and SUVs that use them were on the rise.

The executive committee, consisting of the CEO, finance manager, marketing manager, human resources manager, and production manager, met to discuss the problem. Madeline Stuart, the production manager, reported that the production process for the winches was running smoothly: raw materials were readily available, no machines were experiencing breakdowns, and no employee shortages were occurring due to sickness. Madeline said that she will have to shut down the third shift to avoid building excessive inventory.

constraint

Any factor that limits the performance of a system and restricts its output. In linear programming, a limitation that restricts the permissible choices for the decision variables.

bottleneck

A capacity constraint resource (CCR) whose available capacity limits the organization's ability to meet the product volume, product mix, or demand fluctuation required by the marketplace.

[2]Under certain conditions, a bottleneck is also called a *capacity constrained resource* (CCR). The process with the least capacity is called a bottleneck if its output is less than the market demand, or called a CCR if it is the least capable resource in the system but still has higher capacity than the market demand.

The focus shifted to Malik Brown, manager of marketing. Malik explained that bulk of the sales came from vehicle manufacturers. The sales process had three major segments: lead generation, lead management, and opportunity management. The lead generation segment identifies leads from trade shows, advertising, or on-site visits to vehicle manufacturers. The lead management segment, undertaken by sales reps, amounts to working the lead, following up the initial contact, assessing the lead's current financial situation, estimating the potential size of the order, and identifying the main competitor. If the lead qualifies, it becomes an opportunity and is turned over to an account executive for the final stage of the sales process, the opportunity management segment. Here the lead's interest in concluding a sale is confirmed, any objections are handled, a final price is negotiated, and, it is hoped, the sale is won.

Malik realized that the sales process was a bottleneck. There definitely was enough production capacity and product to sell; however, demand was declining. Apparently, quality and design were not an issue, as the winch has consistently received favorable reviews in the trade journals. What could the problem be? Lack of effective training? Lack of effective sales enablement tools and content? Poor internal collaboration? Not enough personnel? Where was the weakest link in the process?

Firms must manage their constraints and make appropriate capacity choices at the individual-process level as well as at the organization level. Hence, this process involves interfunctional cooperation. Detailed decisions and choices made within each of these levels affect where resource constraints or bottlenecks show up, both within and across departmental lines. Relieving a bottleneck in one part of an organization might not have the desired effect unless a bottleneck in another part of the organization is also addressed. A bottleneck could be the sales department not getting enough sales or the loan department not processing loans fast enough. The constraint could be a lack of capital or equipment, or it could be planning and scheduling.

The experience of Microsoft and other firms in the health care, banking, and manufacturing industries demonstrates how important managing constraints can be to an organization's future. Therefore, managers throughout the organization must understand how to identify and manage bottlenecks in all types of processes, how to relate the capacity and performance measures of one process to another, and how to use that information to determine the firm's best service or product mix. This chapter explains how managers can best make these decisions.

The Theory of Constraints

theory of constraints (TOC)
A systematic management approach that focuses on actively managing those constraints that impede a firm's progress toward its goal.

The **theory of constraints (TOC)** is a systematic management approach that focuses on actively managing those constraints that impede a firm's progress toward its goal of maximizing profits and effectively using its resources. The theory was developed nearly three decades ago by Eli Goldratt, a well-known business systems analyst. It outlines a deliberate process for identifying and overcoming constraints. The process focuses not just on the efficiency of individual processes but also on the bottlenecks that constrain the system as a whole. The process improvement team in the opening vignette followed this theory to improve Microsoft's operations.

TOC methods increase the firm's profits more effectively by focusing on making materials flow rapidly through the entire system. They help firms look at the big picture—how processes can be improved to increase overall work flows, and how inventory and workforce levels can be reduced while still effectively utilizing critical resources. To do this, it is important to understand the relevant performance and capacity measures at the operational level, as well as their relationship to the more broadly understood financial measures at the firm level. These measures and relationships, so critical in successfully applying the principles of the TOC, are defined in Table 6.1.

According to the TOC view, every capital investment in the system, including machines and work-in-process materials, represents inventory because they could all potentially be sold to make money. Producing a product or a service that does not lead to a sale will not increase a firm's throughput, but will increase its inventory and operating expenses. It is always best to manage the system so that utilization at the bottleneck resource is maximized to maximize throughput.

TABLE 6.1 HOW THE FIRM'S OPERATIONAL MEASURES RELATE TO ITS FINANCIAL MEASURES

Operational Measures	TOC View	Relationship to Financial Measures
Inventory (I)	All the money invested in a system in purchasing things that it intends to sell	A decrease in I leads to an increase in net profit, ROI, and cash flows.
Throughput (T)	Rate at which a system generates money through sales	An increase in T leads to an increase in net profit, ROI, and cash flows.
Operating Expense (OE)	All the money a system spends to turn inventory into throughput	A decrease in OE leads to an increase in net profit, ROI, and cash flows.
Utilization (U)	The degree to which equipment, space, or workforce is currently being used; it is measured as the ratio of average output rate to maximum capacity, expressed as a percentage	An increase in U at the bottleneck leads to an increase in net profit, ROI, and cash flows.

Key Principles of the TOC

The chief concept behind the TOC is that the bottlenecks should be scheduled to maximize their throughput of services or products while adhering to promised completion dates. The underlying assumption is that demand is greater or equal to the capacity of the process that produces the service or product; otherwise instead of internal changes, marketing must work toward promoting increasing demand. For example, manufacturing a garden rake involves attaching a bow to the rake's head. Rake heads must be processed on the blanking press, welded to the bow, cleaned, and attached to the handle to make the rake, which is packaged and finally shipped to Sears, Home Depot, or Walmart, according to a specific delivery schedule. Suppose that the delivery commitments for all styles of rakes for the next month indicate that the welding station is loaded at 105 percent of its capacity, but that the other processes will be used at only 75 percent of their capacities. According to the TOC, the welding station is the bottleneck resource, whereas the blanking, cleaning, handle attaching, packaging, and shipping processes are non-bottleneck resources. Any idle time at the welding station must be eliminated to maximize throughput. Managers should therefore focus on the welding schedule.

Seven key principles of the TOC that revolve around the efficient use and scheduling of bottlenecks and improving flow and throughput are summarized in Table 6.2.

Practical application of the TOC involves the implementation of the following steps.

1. *Identify the System Bottleneck(s).* For the rake example, the bottleneck is the welding station because it is restricting the firm's ability to meet the shipping schedule and, hence, total value-added funds. Other ways of identifying the bottleneck will be looked at in more detail a little later in this chapter.

TABLE 6.2 SEVEN KEY PRINCIPLES OF THE THEORY OF CONSTRAINTS

1. The focus should be on balancing flow, not on balancing capacity.
2. Maximizing the output and efficiency of every resource may not maximize the throughput of the entire system.
3. An hour lost at a bottleneck or a constrained resource is an hour lost for the whole system. In contrast, an hour saved at a non-bottleneck resource is a mirage, because it does not make the whole system more productive.
4. Inventory is needed only in front of the bottlenecks to prevent them from sitting idle and in front of assembly and shipping points to protect customer schedules. Building inventories elsewhere should be avoided.
5. Work, which can be materials, information to be processed, documents, or customers, should be released into the system only as frequently as the bottlenecks need it. Bottleneck flows should be equal to the market demand. Pacing everything to the slowest resource minimizes inventory and operating expenses.
6. Activating a non-bottleneck resource (using it for improved efficiency that does not increase throughput) is not the same as utilizing a bottleneck resource (that does lead to increased throughput). Activation of non-bottleneck resources cannot increase throughput, nor promote better performance on financial measures outlined in Table 6.1.
7. Every capital investment must be viewed from the perspective of its global impact on overall throughput (T), inventory (I), and operating expense (OE).

2. *Exploit the Bottleneck(s).* Create schedules that maximize the throughput of the bottleneck(s). For the rake example, schedule the welding station to maximize its utilization while meeting the shipping commitments to the extent possible. Also make sure that only good-quality parts are passed on to the bottleneck.
3. *Subordinate All Other Decisions to Step 2.* Non-bottleneck resources should be scheduled to support the schedule of the bottleneck and not produce more than the bottleneck can handle. That is, the blanking press should not produce more than the welding station can handle, and the activities of the cleaning and subsequent operations should be based on the output rate of the welding station.
4. *Elevate the Bottleneck(s).* After the scheduling improvements in steps 1 through 3 have been exhausted, and the bottleneck is still a constraint to throughput, management should consider increasing the capacity of the bottleneck. For example, if the welding station is still a constraint after exhausting schedule improvements, consider increasing its capacity by adding another shift or another welding machine. Other mechanisms are also available for increasing bottleneck capacity, and we address them a little later.
5. *Do Not Let Inertia Set In.* Actions taken in steps 3 and 4 will improve the welder throughput and may alter the loads on other processes. Consequently, the system constraint(s) may shift. Then, the practical application of steps 1 through 4 must be repeated to identify and manage the new set of constraints.

Because of its potential for improving performance dramatically, many manufacturers have applied the principles of the TOC. All manufacturers implementing TOC principles can also dramatically change the mindset of employees and managers. Instead of focusing solely on their own functions, they can see the "big picture" and where other improvements in the system might lie. A study shows that more than one-third of winners and finalists of *Industry Week's* best manufacturing plants have extensively implemented TOC, while up to 80 percent make some use of it.

Managing Bottlenecks in Service Processes

throughput time
Total elapsed time from the start to the finish of a job or a customer being processed at one or more work centers.

Bottlenecks can be both internal and external to the firm, and typically represent a process, a step, or a workstation with the lowest capacity. **Throughput time** is the total elapsed time from the start to the finish of a job or a customer being processed at one or more work centers. Where a bottleneck lies in a given service or manufacturing process can be identified in two ways. A workstation in a process is a bottleneck if (1) it has the highest total time per unit processed, or (2) it has the highest average utilization and total workload.

Example 6.1 illustrates how a bottleneck step or activity can be identified for a car wash process at a local neighborhood business.

A front-office process with high customer contact and divergence does not enjoy the simple line flows shown in Example 6.1. Its operations may serve many different customer types, and the demands on any one operation could vary considerably from one day to the next. Computing the average utilization of each operation can still identify bottlenecks. However, the variability in workload also creates *floating bottlenecks*. One week the mix of work may make operation 1 a bottleneck, and the next week it may make operation 3 the bottleneck. This type of variability increases the complexity of day-to-day scheduling. In this situation, management prefers lower utilization rates, which allow greater slack to absorb unexpected surges in demand.

EXAMPLE 6.1 Identifying the Bottleneck in a Service Process

Keith's Car Wash offers two types of washes: Standard and Deluxe. The process flow for both types of customers is shown in Figure 6.1. Both wash types are first processed through Steps A1 and A2. The Standard wash then goes through Steps A3 and A4 while the Deluxe is processed through Steps A5, A6, and A7. Both offerings finish at the drying station (A8). The numbers in parentheses indicate the minutes it takes for that activity to process a customer.

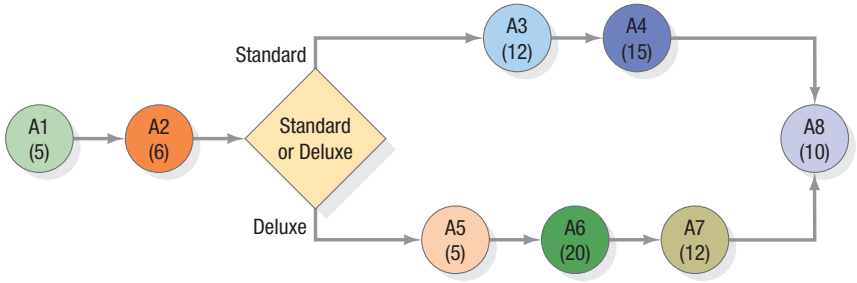


FIGURE 6.1 ▶
Process Flow for Keith's Car Wash

a. Which step is the bottleneck for the Standard car wash process? For the Deluxe car wash process?

b. What is the capacity (measured as customers served per hour) of Keith's Car Wash to process Standard and Deluxe customers? Assume that no customers are waiting at Step A1, A2, or A8.

c. If 60 percent of the customers are Standard and 40 percent are Deluxe, what is the average capacity of the car wash in customers per hour?

d. Where would you expect Standard wash customers to experience waiting lines, assuming that new customers are always entering the shop and that no Deluxe customers are in the shop? Where would the Deluxe customers have to wait, assuming no Standard customers?

SOLUTION

a. Step A4 is the bottleneck for the Standard car wash process, and Step A6 is the bottleneck for the Deluxe car wash process, because these steps take the longest time in the flow.

b. The capacity for Standard washes is four customers per hour because the bottleneck Step A4 can process one customer every 15 minutes (60/15). The capacity for Deluxe car washes is three customers per hour (60/20). These capacities are derived by translating the "minutes per customer" of each bottleneck activity to "customers per hour."

c. The average capacity of the car wash is $(0.60 \times 4) + (0.40 \times 3) = \mathbf{3.6}$ customers per hour.

d. Standard wash customers would wait before Steps A1, A2, A3, and A4 because the activities that immediately precede them have a higher rate of output (i.e., smaller processing times). Deluxe wash customers would experience a wait in front of Steps A1, A2, and A6 for the same reasons. A1 is included for both types of washes because the arrival rate of customers could always exceed the capacity of A1.

DECISION POINT

Due to the processing times at the bottleneck, the standard car wash process is capable of serving four customers per hour, while the deluxe car wash process can serve three customers per hour. There may be a waiting line in front of the bottleneck processes, and all preceding processes where the processing time is longer than their preceding processes. If the car wash manager wishes to increase the throughput, he could do so by adding more capacity at processes A4 and A6.

TOC principles outlined here are fairly broad and widely applicable to many types of processes. They can be useful for evaluating individual processes as well as large systems for both manufacturers and service providers. Service organizations, such as Delta Airlines, United Airlines, and major hospitals across the United States, including the U.S. Air Force health care system, use the TOC to their advantage.

Managing Bottlenecks in Manufacturing Processes

Bottlenecks can exist in all types of manufacturing processes, including the job process, batch process, line process, and continuous process. Since these processes differ in their design, strategic intent, and allocation of resources (see Chapter 2, "Process Strategy and Analysis," for additional details), identification and management of bottlenecks will also differ accordingly with process type. We first discuss in this section issues surrounding management of bottlenecks in job and batch processes, while relegating constraint management in line processes to a later section.



Medical-R/Shutterstock

Due to constrained resources like doctors, nurses, and equipment, patients wait for medical care in a crowded waiting room at South Central Family Health Center in Los Angeles, California.

Identifying Bottlenecks

Manufacturing processes often pose some complexities when identifying bottlenecks. If multiple services or products are involved, extra setup time at a workstation is usually needed to change over from one service or product to the next, which in turn increases the overload at the workstation being changed over. *Setup times* and their associated costs affect the size of the lots traveling through the job or batch processes. Management tries to reduce setup times because they represent unproductive time for workers or machines and thereby allow for smaller, more economic, batches. Nonetheless, whether setup times are significant or not, one way to identify a bottleneck operation is by its utilization. Example 6.2 illustrates how a bottleneck can be identified in a manufacturing setting where setups are negligible.

EXAMPLE 6.2 Identifying the Bottleneck in a Batch Process

Diablo Electronics manufactures four unique products (A, B, C, and D) that are fabricated and assembled in five different workstations (V, W, X, Y, and Z) using a small batch process. Each workstation is staffed by a worker who is dedicated to work a single shift per day at an assigned workstation. Batch setup times have been reduced to such an extent that they can be considered negligible. A flowchart denotes the path each product follows through the manufacturing process, as shown in Figure 6.2, where each product's price, demand per week, and processing times per unit are indicated as well. Inverted triangles represent purchased parts and raw materials consumed per unit at different workstations. Diablo can make and sell up to the limit of its demand per week, and no penalties are incurred for not being able to meet all the demand.

Which of the five workstations (V, W, X, Y, or Z) has the highest utilization, and thus serves as the bottleneck for Diablo Electronics?

SOLUTION

Because the denominator in the utilization ratio is the same for every workstation, with one worker per machine at each step in the process, we can simply identify the bottleneck by computing aggregate workloads at each workstation.

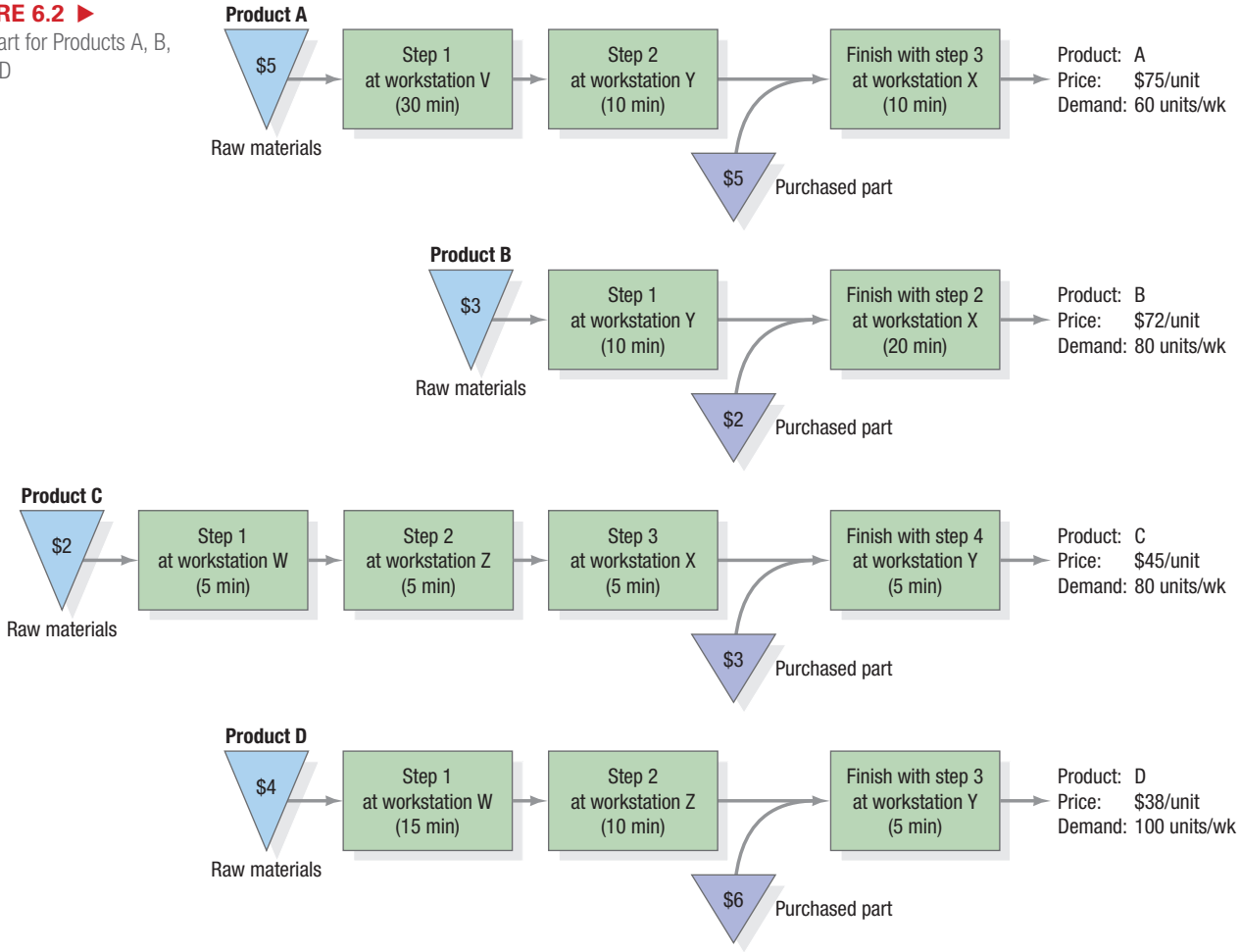


FIGURE 6.2 ▶ Flowchart for Products A, B, C, and D

The firm wants to satisfy as much of the product demand in a week as it can. Each week consists of 2,400 minutes of available production time. Multiplying the processing time at each station for a given product by the number of units demanded per week yields the workload represented by that product. These loads are summed across all products going through a workstation to arrive at the total load for the workstation, which is then compared with the others and the existing capacity of 2,400 minutes.

Workstation	Load from Product A	Load from Product B	Load from Product C	Load from Product D	Total Load (min)
V	60 × 30 = 1800	0	0	0	1,800
W	0	0	80 × 5 = 400	100 × 15 = 1,500	1,900
X	60 × 10 = 600	80 × 20 = 1,600	80 × 5 = 400	0	**2,600**
Y	60 × 10 = 600	80 × 10 = 800	80 × 5 = 400	100 × 5 = 500	2,300
Z	0	0	80 × 5 = 400	100 × 10 = 1,000	1,400

DECISION POINT

Workstation X is the bottleneck for Diablo Electronics because the aggregate workload at X is larger than the aggregate workloads of workstations V, W, Y, and Z and the maximum available capacity of 2,400 minutes per week.

Identifying the bottlenecks becomes considerably harder when setup times are lengthy and the degree of divergence in the process is greater than that shown in Example 6.2. When the setup time is large, the operation with the highest total time per unit processed would typically tend to be the bottleneck. Variability in the workloads will again likely create floating bottlenecks, especially if most processes involve multiple operations, and often their capacities are not identical. In practice, these bottlenecks can also be determined by asking workers and supervisors in the plant where the bottlenecks might lie, and looking for piled-up material in front of different workstations.

Relieving Bottlenecks

The key to preserving bottleneck capacity is to carefully monitor short-term schedules and keep bottleneck resource as busy as is practical. Managers should minimize idle time at the bottlenecks caused by delays elsewhere in the system and make sure that the bottleneck has all the resources it needs to stay busy. When a changeover or setup is made at a bottleneck, the number of units or customers processed before the next changeover should be large compared to the number processed at less critical operations. Maximizing the number of units processed per setup means fewer setups per year and, thus, less total time lost to setups. The number of setups also depends on the required product variety; more variety necessitates more frequent changeovers.

The long-term capacity of bottleneck operations can be expanded in various ways. Investments can be made in new equipment and in brick-and-mortar facility expansions. The bottleneck's capacity also can be expanded by operating it more hours per week, such as by hiring more employees and going from a one-shift operation to multiple shifts, or by hiring more employees and operating the plant 6 or 7 days per week versus 5 days per week. Managers also might relieve the bottleneck by redesigning the process, either through *process reengineering* or *process improvement*, or by purchasing additional machines that can handle more capacity.

drum-buffer-rope (DBR)

A planning and control system that regulates the flow of work-in-process materials at the bottleneck or the capacity constrained resource (CCR) in a productive system.

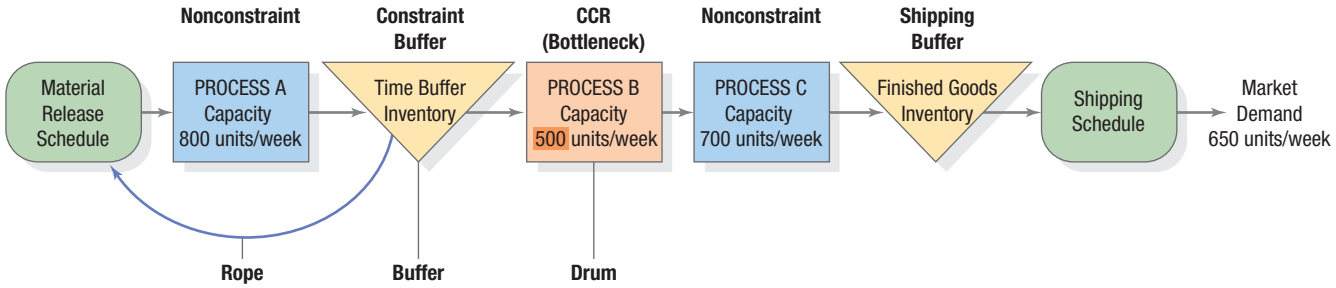
Drum-Buffer-Rope Systems **Drum-buffer-rope (DBR)** is a planning and control system based on the TOC that is often used in manufacturing firms to plan and schedule production. It works by regulating the flow of work-in-process materials at the bottleneck or the capacity constrained resource (CCR). The bottleneck schedule is the *drum* because it sets the beat or the production rate for the entire plant and is linked to the market demand. The *buffer* is a time buffer that plans early flows to the bottleneck and thus protects it from disruption. It also ensures that the bottleneck is never starved for work. A finished-goods inventory buffer can also be placed in front of the shipping point to protect customer shipping schedules. Finally, the *rope* represents the tying of material release to the drumbeat, which is the rate at which the bottleneck controls the throughput of the entire plant. It is thus a communication device to ensure that raw material is not introduced into the system at a rate faster than what the bottleneck can handle. Completing the loop, *buffer management* constantly monitors the execution of incoming bottleneck work. Working together, the drum, the buffer, and the rope can help managers create a production schedule that reduces lead times and inventories while simultaneously increasing throughput and on-time delivery.

To better understand the DBR system, consider the schematic layout shown in Figure 6.3. Process B, with a capacity of only 500 units per week, is the bottleneck because the upstream Process A and downstream Process C have capacities of 800 units per week and 700 units per week, respectively, and

the market demand is 650 units per week, on average. In this case, because the capacity at Process B is less than the market demand, it is the bottleneck. A constraint time buffer, which can be in the form of materials arriving earlier than needed, is placed right in front of the bottleneck (Process B). A shipping buffer, in the form of finished goods inventory, can also be placed prior to the shipping schedule to protect customer orders that are firm. Finally, a rope ties the material release schedule to match the schedule, or drumbeat, at the bottleneck. The material flow is pulled forward by the drumbeat prior to the bottleneck, while it is pushed downstream toward the customer subsequent to the bottleneck.

DBR specifically strives to improve throughput by better utilizing the bottleneck resource and protecting it from disruption through the time buffer and protective buffer capacity elsewhere. So while the process batch in the DBR is any size that minimizes setups and improves utilization at the bottleneck, at nonconstrained resources the process batches are equal to what is needed for production at that time. The material can consequently be released in small batches known as transfer batches at the release point, which then combine at the constraint buffer to make a full process batch at the bottleneck. Transfer batches can be as small as one unit each, to allow a downstream workstation to start work on a batch before it is completely finished at the prior process. Using transfer batches typically facilitates a reduction in overall lead time.

FIGURE 6.3 ▼
Drum-Buffer-Rope System



DBR can be an effective system to use when the product the firm produces is relatively simple and the production process has more line flows. Planning is greatly simplified in this case and primarily revolves around scheduling the constrained resource and triggering other points to meet that bottleneck's schedule. Effectively implementing a DBR system requires an understanding of the TOC principles. However, such a system can be utilized in many different kinds of manufacturing and service organizations, either by itself or in conjunction with other planning and control systems. Managerial Practice 6.1 shows how a small steel manufacturing company in the United Kingdom successfully applied the TOC principles to design a simple and effective DBR system and grow rapidly within a decade.

MANAGERIAL PRACTICE 6.1 Theory of Constraints (TOC) and Drum-Buffer-Rope (DBR) at Steelo Limited

Steelo Limited is a structural steel fabrication company located in West London near Heathrow International Airport. With sales of £4 million and 30 employees, delivering high-quality products that fit right every time and that meet tight project deadlines is critical to success. Developing such a manufacturing capability has allowed its founder, Michael Krajewski, who immigrated to the United Kingdom from Poland, to grow Steelo from its humble origins in 2009 to become the industry leader in the fabrication and distribution of high-quality structural steel. Most of his customers are in the residential construction industry and require lead times as short as 1 day, with delivery-to-site occurring in a 2-hour window. Customers pay in advance for their orders.

To increase throughput and reduce inventory in its semi-automated plant, Steelo applied the principles of the theory of constraints to identify where bottlenecks may lie. Initial conjecture was that the welding bay may be constraining output. However, further analysis revealed that shipping is the bottleneck, since deliveries could be done only between the hours of 8 A.M. and 5 P.M. according to the local Council restrictions. Working overtime could alleviate capacity shortages elsewhere in the plant, but not in extending the delivery into the evenings if an order was delayed for completion beyond 5 P.M. So every material flow in the plant has to be coordinated and tied to the delivery schedule, which essentially sets the rhythm for plant operation and serves as the drum in its DBR implementation of the TOC. The staff in the plant are cross-trained, and



Roman Zaiets/Shutterstock

Structural steel fabrication and welding on the shop floor.

can move from one area to another when production glitches develop. Only 2 or 3 days of steel stock inventory are kept on hand to support production, which is synchronized with customer orders. The focus is on creating product flow as opposed to keeping large inventories at every station. Accordingly, the plant

operates in a very lean fashion to process between 10 and 15 orders every day, which translates to an output of about 200 tons of steel a month. A customized information technology (IT) system prioritizes tasks and rejects those short-term customer orders that cannot be completed on time due to capacity limitations. This order rejection is similar to tying the rope by only introducing materials into the shop floor at the rate at which they can be shipped to the customers.

With the success of its core operations, Steelo and Michael Krajewski are now moving into exploring innovations such as 3D printing, using artificial intelligence to configure orders, and full automation. The workforce is approximately 60 percent Polish, and despite the upcoming Brexit, Michael expects most of his workers to stay on because they like being part of a thriving and innovative firm such as Steelo.[3]

Applying the Theory of Constraints to Product Mix Decisions

Managers might be tempted to produce the products with the highest contribution margins or unit sales. *Contribution margin* is the amount each product contributes to profits and overhead; no fixed costs are considered when making the product mix decision. We call this approach the *traditional method*, which is often used by nonmanufacturing processes such as the accounting and sales groups within a firm. The problem with this approach is that the firm's actual throughput and overall profitability depend more upon the contribution margin generated at the bottleneck than by the contribution margin of each individual product produced. We call this latter approach the *bottleneck method*. Example 6.3 illustrates both of these methods.

Linear programming (see Supplement D) could also be used to find the best product mix in Example 6.3. It must be noted, however, that the problem in Example 6.3 does not involve significant setup times. Otherwise, they must be taken into consideration for not only identifying the bottleneck but also in determining the product mix. The experiential learning exercise of Min-Yo Garment Company at the end of this chapter provides an interesting illustration of how the product mix can be determined when setup times are significant. In this way, the principles behind the TOC can be exploited for making better decisions about a firm's most profitable product mix.

EXAMPLE 6.3 Determining the Product Mix Using Contribution Margin

The senior management at Diablo Electronics (see Example 6.2) wants to improve profitability by accepting the right set of orders, and so collected some additional financial data. Variable overhead costs are $8,500 per week. Each worker is paid $18 per hour and is paid for an entire week, regardless of how much the worker is used. Consequently, labor costs are fixed expenses. The plant operates one 8-hour shift per day, or 40 hours each week. Currently, decisions are made using the traditional method, which is to accept as much of the highest contribution margin product as possible (up to the limit of its demand), followed by the next highest contribution margin product, and so on until no more capacity is available. Pedro Rodriguez, the newly hired production supervisor, is knowledgeable about the TOC and bottleneck-based scheduling. He believes that profitability can indeed be improved if bottleneck resources were exploited to determine the product mix. What is the change in profits if, instead of the traditional method used by Diablo Electronics, the bottleneck method advocated by Pedro is used to select the product mix?

SOLUTION

Decision Rule 1: Traditional Method

Select the best product mix according to the highest overall contribution margin of each product.

Step 1. Calculate the contribution margin per unit of each product as shown here.

	A	B	C	D
Price	$75.00	$72.00	$45.00	$38.00
Raw material and purchased parts	−10.00	−5.00	−5.00	−10.00
= Contribution margin	$65.00	$67.00	$40.00	$28.00

When ordered from highest to lowest, the contribution margin per unit sequence of these products is B, A, C, D.

Step 2. Allocate resources V, W, X, Y, and Z to the products in the order decided in Step 1. Satisfy each demand until the bottleneck resource (workstation X) is encountered. Subtract minutes away from 2,400 minutes available for each week at each stage.

[3] *Sources:* https://www.linkedin.com/company/steelo-ltd (July 12, 2020); "Poles Apart," *Construction Index Magazine*, March 2019; https://www.theconstructionindex.co.uk/news/view/poles-apart (July 12, 2020).

Work Center	Minutes at the Start	Minutes Left After Making 80 B	Minutes Left After Making 60 A	Can Only Make 40 C	Can Still Make 100 D
V	2,400	2,400	600	600	600
W	2,400	2,400	2,400	2,200	700
X	2,400	800	200	0	0
Y	2,400	1,600	1,000	800	300
Z	2,400	2,400	2,400	2,200	1,200

The best product mix according to this traditional approach is, then, 60 A, 80 B, 40 C, and 100 D.

Step 3. Compute profitability for the selected product mix.

	Profits	
Revenue	(60 × $75) + (80 × $72) + (40 × $45) + (100 × $38)	= $15,860
Materials	(60 × $10) + (80 × $5) + (40 × $5) + (100 × $10)	= −$2,200
Labor	(5 workers) × (8 hours/day) × (5 days/week) × (18/hour)	= −$3,600
Overhead		= −$8,500
Profit		= $1,560

Manufacturing the product mix of 60 A, 80 B, 40 C, and 100 D will yield a profit of **$1,560** per week.

Decision Rule 2: Bottleneck Method

Select the best product mix according to the dollar contribution margin per minute of processing time at the bottleneck workstation X. This method would take advantage of the principles outlined in the TOC and get the most dollar benefit from the bottleneck.

Step 1. Calculate the contribution margin/minute of processing time at bottleneck workstation X:

	Product A	Product B	Product C	Product D
Contribution margin	$65.00	$67.00	$40.00	$28.00
Time at bottleneck	10 minutes	20 minutes	5 minutes	0 minutes
Contribution margin per minute	$6.50	$3.35	$8.00	Not defined

When ordered from highest to lowest contribution margin/minute at the bottleneck, the manufacturing sequence of these products is D, C, A, B, which is the reverse of the earlier order. Product D is scheduled first because it does not consume any resources at the bottleneck.

Step 2. Allocate resources V, W, X, Y, and Z to the products in the order decided in Step 1. Satisfy each demand until the bottleneck resource (workstation X) is encountered. Subtract minutes away from 2,400 minutes available for each week at each stage.

Work Center	Minutes at the Start	Minutes Left After Making 100 D	Minutes Left After Making 80 C	Minutes Left After Making 60 A	Can Only Make 70 B
V	2,400	2,400	2,400	600	600
W	2,400	900	500	500	500
X	2,400	2,400	2,000	1,400	0
Y	2,400	1,900	1,500	900	200
Z	2,400	1,400	1,000	1,000	1,000

The best product mix according to this bottleneck-based approach is, then, 60 A, 70 B, 80 C, and 100 D.

Step 3. Compute profitability for the selected product mix.

	Profits	
Revenue	(60 × $75) + (70 × $72) + (80 × $45) + (100 × $38)	= $16,940
Materials	(60 × $10) + (70 × $5) + (80 × $5) + (100 × $10)	= −$2,350
Labor	(5 workers) × (8 hours/day) × (5 days/week) × (18/hour)	= −$3,600
Overhead		= −$8,500
Profit		= $2,490

Manufacturing the product mix of 60 A, 70 B, 80 C, and 100 D will yield a profit of **$2,490** per week.

DECISION POINT

By focusing on the bottleneck resources in accepting customer orders and determining the product mix, the sequence in which products are selected for production is reversed from **B, A, C, D** to **D, C, A, B**. Consequently, the product mix is changed from 60 A, 80 B, 40 C, and 100 D to 60 A, 70 B, 80 C, and 100 D. The increase in profits by using the bottleneck method is **$930** ($2,490 − $1,560), or almost 60 percent over the traditional approach.

Managing Constraints in Line Processes

As noted in Chapter 2, "Process Strategy and Analysis," products created by a line process include the assembly of computers, automobiles, appliances, and toys. Such assembly lines can exist in providing services as well. For instance, putting together a standardized hamburger with a fixed sequence of steps is akin to operating an assembly line. In this section, we explain in greater detail how constraints can be managed for line processes.



andresr/Getty Images

A man making shoes at an assembly line in a factory.

Line Balancing

Line balancing is the assignment of work to stations in a line process so as to achieve the desired output rate with the smallest number of workstations. Normally, one worker is assigned to a station. Thus, the line that produces at the desired pace with the fewest workers is the most efficient one. Achieving this goal is much like the TOC, because both approaches are concerned about bottlenecks. Line balancing differs in how it addresses bottlenecks. Rather than (1) taking on new customer orders to best use bottleneck capacity or (2) scheduling so that bottleneck resources are conserved, line balancing takes a third approach. It (3) creates workstations with workloads as evenly balanced as possible. It seeks to create workstations so that the capacity utilization for the bottleneck is not much higher than for the other workstations in the line. Another difference is that line balancing applies only to line processes that do assembly work, or to work that can be bundled in many ways to create the jobs for each workstation in the line. The latter situation can be found both in manufacturing and service settings.

The goal of line balancing is to obtain workstations with well-balanced workloads (e.g., every station takes roughly 3 minutes per customer in a cafeteria line with different food stations). The analyst begins by separating the work into **work elements**, which are the smallest units of work that can be performed independently. The analyst then obtains the time standard for each element and identifies the work elements, called **immediate predecessors**, which must be done before the next element can begin.

line balancing
The assignment of work to stations in a line process so as to achieve the desired output rate with the smallest number of workstations.

work elements
The smallest units of work that can be performed independently.

immediate predecessors
Work elements that must be done before the next element can begin.

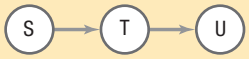
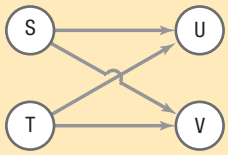
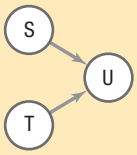
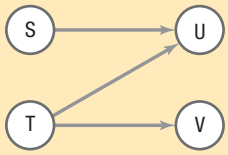
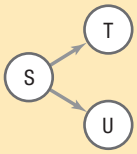
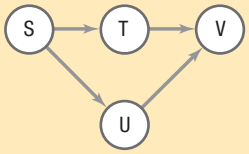
precedence diagram
A diagram that allows one to visualize immediate predecessors better; work elements are denoted by circles, with the time required to perform the work shown below each circle.

Precedence Diagram Most lines must satisfy some technological precedence requirements; that is, certain work elements must be done before the next can begin. However, most lines also allow for some latitude and more than one sequence of operations. To help you better visualize immediate predecessors, let us run through the construction of a **precedence diagram**. The diagramming approach we use in this text is referred to as the **activity-on-node (AON) network**, in which nodes represent activities and arcs represent the precedence relationships between them. More specifically,

activity-on-node (AON) network
An approach used to create a network diagram, in which nodes represent activities and arcs represent the precedence relationships between them.

we denote the work elements by nodes or circles, with the time required to perform the work shown below each circle. Arrows or arcs lead from immediate predecessors to the next work element. Some diagramming conventions must be used for AON networks. In cases of multiple activities with no predecessors, it is usual to show them emanating from a common node called *start*. For multiple activities with no successors, it is usual to show them connected to a node called *finish*. Figure 6.4 shows how to diagram several commonly encountered activity relationships.

FIGURE 6.4 ▼
Diagramming Activity Relationships

AON	Activity Relationships	AON	Activity Relationships
	S precedes T, which precedes U.		U and V cannot begin until both S and T have been completed.
	S and T must be completed before U can be started.		U cannot begin until both S and T have been completed; V cannot begin until T has been completed.
	T and U cannot begin until S has been completed.		T and U cannot begin until S has been completed and V cannot begin until both T and U have been completed.

Example 6.4 illustrates a manufacturing process, but a back-office line-flow process in a service setting can be approached similarly.

EXAMPLE 6.4 Constructing a Precedence Diagram

Green Grass, Inc., a manufacturer of lawn and garden equipment, is designing an assembly line to produce a new fertilizer spreader, the Big Broadcaster. Using the following information on the production process, construct a precedence diagram for the Big Broadcaster.

Work Element	Description	Time (sec)	Immediate Predecessor(s)
A	Bolt leg frame to hopper	40	None
B	Insert impeller shaft	30	A
C	Attach axle	50	A
D	Attach agitator	40	B
E	Attach drive wheel	6	B
F	Attach free wheel	25	C
G	Mount lower post	15	C
H	Attach controls	20	D, E
I	Mount nameplate	18	F, G
		Total 244	

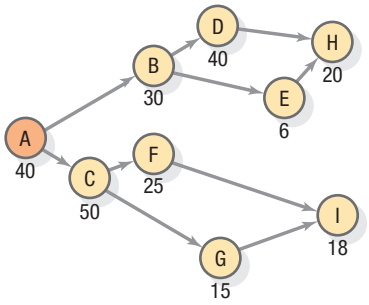
SOLUTION

Figure 6.5 shows the complete diagram. We begin with work element A, which has no immediate predecessors. Next, we add elements B and C, for which element A is the only immediate predecessor. After entering time standards and arrows showing precedence, we add elements D and E, and so on. The diagram simplifies interpretation. Work element F, for example, can be done anywhere on the line after element C is completed. However, element I must await completion of elements F and G.

DECISION POINT

Management now has enough information to develop a line-flow layout that clusters work elements to form workstations, with a goal being to balance the workloads and, in the process, minimize the number of workstations required.

▼ **FIGURE 6.5**
Precedence Diagram for Assembling the Big Broadcaster



Desired Output Rate The goal of line balancing is to match the output rate to the staffing or production plan. For example, if the plan calls for 4,800 units or customers per week and the line operates 80 hours per week, the desired output rate ideally would be 60 units or customers (4,800/80) per hour. Matching output to the plan ensures on-time delivery and prevents buildup of unwanted inventory or customer delays. However, managers should avoid rebalancing a line too frequently because each time a line is rebalanced many workers' jobs on the line must be redesigned, temporarily hurting productivity and sometimes even requiring a new detailed layout for some stations.

Cycle Time After determining the desired output rate for a line, the analyst can calculate the line's cycle time. A line's **cycle time** is the maximum time allowed for work on a unit at each station.[4] If the time required for work elements at a station exceeds the line's cycle time, the station will be a bottleneck, preventing the line from reaching its desired output rate. The target cycle time is the reciprocal of the desired hourly output rate:

cycle time
The maximum time allowed for work on a unit at each station.

$$c = \frac{1}{r}$$

where

c = cycle time in hours per unit
r = desired output rate in units per hour

For example, if the line's desired output rate is 60 units per hour, the cycle time is $c = 1/60$ hour per unit, or 1 minute.

Theoretical Minimum To achieve the desired output rate, managers use line balancing to assign every work element to a station, making sure to satisfy all precedence requirements and to minimize the number of stations, n, formed. If each station is operated by a different worker, minimizing n also maximizes worker productivity. Perfect balance is achieved when the sum of the work-element times at each station equals the cycle time, c, and no station has any idle time. For example, if the sum of each station's work-element times is 1 minute, which is also the cycle time, the line achieves perfect balance. Although perfect balance usually is unachievable in practice, owing to the unevenness of work-element times and the inflexibility of precedence requirements, it sets a benchmark, or goal, for the smallest number of stations possible. The **theoretical minimum (TM)** for the number of stations is

theoretical minimum (TM)
A benchmark or goal for the smallest number of stations possible, where the total time required to assemble each unit (the sum of all work-element standard times) is divided by the cycle time.

$$\text{TM} = \frac{\Sigma t}{c}$$

where

Σt = total time required to assemble each unit (the sum of all work-element standard times)
c = cycle time

For example, if the sum of the work-element times is 15 minutes and the cycle time is 1 minute, TM = 15/1, or 15 stations. Any fractional values obtained for TM are rounded up because fractional stations are impossible.

[4]Except in the context of line balancing, *cycle time* has a different meaning. It is the elapsed time between starting and completing a job. Some researchers and practitioners prefer the term *lead time* in these non-line-balancing applications.

Idle Time, Efficiency, and Balance Delay Minimizing n automatically ensures (1) minimal idle time, (2) maximal efficiency, and (3) minimal balance delay. Idle time is the total unproductive time for all stations in the assembly of each unit:

$$\text{Idle time} = nc - \Sigma t$$

where

n = number of stations
c = cycle time
Σt = total standard time required to assemble each unit

Efficiency is the ratio of productive time to total time, expressed as a percent:

$$\text{Efficiency (\%)} = \frac{\Sigma t}{nc}(100)$$

balance delay
The amount by which efficiency falls short of 100 percent.

Balance delay is the amount by which efficiency falls short of 100 percent:

$$\text{Balance delay (\%)} = 100 - \text{Efficiency}$$

As long as c is fixed, we can optimize all three goals by minimizing n.

EXAMPLE 6.5 Calculating the Cycle Time, Theoretical Minimum, and Efficiency

Online Resource
Tutor 6.1 in OM Explorer provides another example to calculate these line-balancing measures.

Green Grass's plant manager just received marketing's latest forecasts of Big Broadcaster sales for the next year. She wants its production line to be designed to make 2,400 spreaders per week for at least the next 3 months. The plant will operate 40 hours per week.

a. What should be the line's cycle time?

b. What is the smallest number of workstations that she could hope for in designing the line for this cycle time?

c. Suppose she finds a solution that requires only five stations. What would be the line's efficiency?

SOLUTION

a. First, convert the desired output rate (2,400 units per week) to an hourly rate by dividing the weekly output rate by 40 hours per week to get $r = 60$ units per hour. Then, the cycle time is

$$c = 1/r = 1/60 \text{ (hour/unit)} = 1 \text{ minute/unit} = \mathbf{60} \text{ seconds/unit}$$

b. Now, calculate the theoretical minimum for the number of stations by dividing the total time, Σt, by the cycle time, $c = 60$ seconds. Assuming perfect balance, we have

$$\text{TM} = \frac{\Sigma t}{c} = \frac{244 \text{ seconds}}{60 \text{ seconds}} = 4.067 \text{ or } \mathbf{5} \text{ stations}$$

c. Now, calculate the efficiency of a five-station solution, assuming for now that one can be found:

$$\text{Efficiency (\%)} = \frac{\Sigma t}{nc}(100) = \frac{244}{5(60)}(100) = \mathbf{81.3\%}$$

DECISION POINT

If the manager finds a solution with five stations that satisfies all precedence constraints, then that is the optimal solution; it has the minimum number of stations possible. However, the efficiency (sometimes called the *theoretical maximum efficiency*) will be only 81.3 percent. Perhaps the line should be operated less than 40 hours per week (thereby adjusting the cycle time) and the employees transferred to other kinds of work when the line does not operate.

Finding a Solution Often, many assembly-line solutions are possible, even for such simple problems as Green Grass's. The goal is to cluster the work elements into workstations so that (1) the number of workstations required is minimized, and (2) the precedence and cycle-time requirements are not violated. The idea is to assign work elements to workstations subject to the precedence requirements so that the work content for the station is equal to (or nearly so, but less than) the cycle time for the line. In this way, the number of workstations will be minimized.

Here we use the trial-and-error method to find a solution, although commercial software packages are also available. Most of these packages use different decision rules in picking which work element to assign next to a workstation being created. The ones used by POM for Windows are described in Table 6.3. The solutions can be examined for improvement, because there is no guarantee that they are optimal or even feasible. Some work elements cannot be assigned to the same station, some changes can be made to reduce the number of stations, or some shifts can provide better balance between stations.

Figure 6.6 shows a solution that creates just five workstations. We know that five is the minimum possible, because five is the theoretical minimum found in Example 6.5. All of the precedence and cycle-time requirements are also satisfied. Consequently, the solution is optimal for this problem. Each worker at each station must perform the work elements in the proper sequence. For example, workstation **S5** consists of one worker who will perform work elements E, H, and I on each unit that comes along the assembly line. The processing time per unit is 44 seconds (6 + 20 + 18) which does not exceed the cycle time of 60 seconds (see Example 6.5). Furthermore, the immediate predecessors of these three work elements are assigned to this workstation or upstream workstations, so their precedence requirements are satisfied. The worker at workstation S5 can do element I at any time but will not start element H until element E is finished.

TABLE 6.3 HEURISTIC DECISION RULES IN ASSIGNING THE NEXT WORK ELEMENT TO A WORKSTATION BEING CREATED

Create one station at a time. For the station now being created, identify the unassigned work elements that qualify for assignment. They are candidates if:

1. All of their predecessors have been assigned to this station or stations already created.

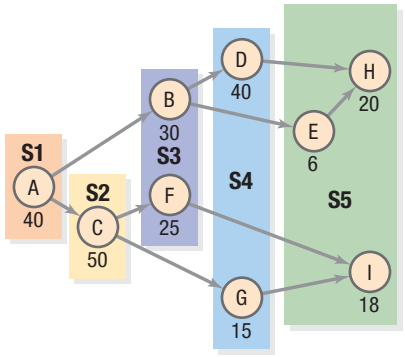
2. Adding them to the workstation being created will not create a workload that exceeds the cycle time.

Decision Rule	Logic
Longest work element	Picking the candidate with the longest time to complete is an effort to fit in the most difficult elements first, leaving the ones with short times to "fill out" the station.
Shortest work element	This rule is the opposite of the longest work element rule because it gives preference in work-station assignments to those work elements that are quicker. It can be tried because no single rule guarantees the best solution. It might provide another solution for the planner to consider.
Most followers	When picking the next work element to assign to a station being created, choose the element that has the most *followers* (due to precedence requirements). In Figure 6.5, item C has three followers (F, G, and I) whereas item D has only one follower (H). This rule seeks to maintain flexibility so that good choices remain for creating the last few workstations at the end of the line.
Fewest followers	Picking the candidate with the fewest followers is the opposite of the most followers rule.

Rebalancing the Assembly Line

While the product mix or demand volumes do not change as rapidly for line processes as for job or batch processes, the load can shift between work centers in a line as the end product being assembled is changed from one product to another, or when the total output rate of the line is altered. Constraints arising out of such actions can be managed by either rebalancing the line or by shifting workers across different lines in the manufacturing plant to reduce waste and create a more balanced allocation of workloads and available worker capacity. This approach is best illustrated by Chrysler Corporation, which is especially well known for its industry-leading pioneering design of minivans. The corporation was interested in reducing costs and improving efficiency through a better balancing of its assembly lines in the trim, chassis, and final (TCF) center at one of its manufacturing plants in Windsor, Ontario, which builds the popular minivan models. Instead of actually stopping the lines and experimenting with new ideas, the improvement team felt that it would be best to build simulation models that can identify system bottlenecks and evaluate the impact of line design and scheduling decisions associated with different cycle times, mean time to repair, and mean time between failures. With the use of different scenarios, it was determined that slowing down the best performing lines would not adversely affect the system throughput, which in turn would allow some workers to be not needed. The plant reduced two people a shift on one line. So, with three shifts, Chrysler effectively reduced manpower costs by six on that line, saving them $600,000 per year. This idea of using a simulation tool for slowing down the best performing lines to improve efficiency has now been rolled out to eight other

▼ **FIGURE 6.6**
Big Broadcaster Precedence Diagram Solution





Jim West/Alamy Stock Photo

A Chrysler auto worker uses an ergo-arm to load the seats into Chrysler minivans during the production launch of the new 2011 Dodge Grand Caravan's and Chrysler Town & Country minivans at the Windsor Assembly Plant in Windsor, Ontario.

Chrysler assembly plants, with cumulative savings projected to be around $5 million.[5]

Understanding the impact of bottlenecks, cycle times, repair times, and product mix on the efficiency and throughputs of assembly lines can really pay off in managing line processes.

Managerial Considerations

In addition to balancing a line for a given cycle time, managers have four other considerations: (1) pacing, (2) behavioral factors, (3) number of models produced, and (4) different cycle times.

Pacing The movement of product from one station to the next as soon as the cycle time has elapsed is called **pacing**. Pacing manufacturing processes allows materials handling to be automated and requires less inventory storage area. However, it is less flexible in handling unexpected delays that require either slowing down the entire line or pulling the unfinished work off the line to be completed later.

Behavioral Factors The most controversial aspect of line-flow layouts is behavioral response. Studies show that installing production lines increases absenteeism, turnover, and grievances. Paced production and high specialization (say, cycle times of less than 2 minutes) lower job satisfaction. Workers generally favor inventory buffers as a means of avoiding mechanical pacing. One study even showed that productivity increased on unpaced lines.

pacing
The movement of product from one station to the next as soon as the cycle time has elapsed.

mixed-model line
A production line that produces several items belonging to the same family.

Number of Models Produced A line that produces several items belonging to the same family is called a **mixed-model line**. In contrast, a single-model line produces one model with no variations. Mixed-model production enables a plant to achieve both high-volume production *and* product variety. However, it complicates scheduling and increases the need for good communication about the specific parts to be produced at each station.

Cycle Times A line's cycle time depends on the desired output rate (or sometimes on the maximum number of workstations allowed). In turn, the maximum line efficiency varies considerably with the cycle time selected. Thus, exploring a range of cycle times makes sense. A manager might go with a particularly efficient solution even if it does not match the desired output rate. The manager can compensate for the mismatch by varying the number of hours the line operates through overtime, extending shifts, or adding shifts. Multiple lines might even be the answer.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
6.1 Explain the theory of constraints.	The section "The Theory of Constraints" explains that constraints or bottlenecks can exist in the form of internal resources or market demand in both manufacturing and service organizations, and in turn play an important role in determining system performance. Review the opening vignette on Microsoft Corporation for an application of TOC in a nonmanufacturing setting and Table 6.2 for its key principles.	
6.2 Identify and manage bottlenecks in service processes.	The section "Managing Bottlenecks in Service Processes" shows you how to identify bottlenecks in manufacturing firms. Review Solved Problem 1 for an illustration of this approach.	
6.3 Identify and manage bottlenecks in manufacturing processes.	The section "Managing Bottlenecks in Manufacturing Processes" shows you how to identify and relieve bottlenecks in manufacturing firms, and links them to a planning and control system known as drum-buffer-rope.	
6.4 Applying the theory of constraints to product mix decisions.	The section "Applying the Theory of Constraints to Product Mix Decisions" helps you understand how using a bottleneck-based method for allocating resources and determining the product mix leads to greater profits. The experiential learning exercise involving Min-Yo Garment Company illustrates how product mix can be determined when setup times are significant.	**OM Explorer Solver:** Min-Yo Garment Company spreadsheet

[5] *Sources:* http://en.wikipedia.org/wiki/Windsor_Assembly; http://www.simul8.com/our_customers/case_studies/Chrysler_line_balancing_case_study.pdf (July 29, 2014); https://en.wikipedia.org/wiki/Chrysler (March 24, 2017).

Learning Objective	Guidelines for Review	Online Resources
6.5 Describe how to manage constraints in line processes and balance assembly lines.	The section "Managing Constraints in Line Processes" shows you how to balance assembly lines and create workstations. It also positions assembly-line balancing as a special form of a constraint in managing a line process within both manufacturing and services, and it can also be an effective mechanism for matching output to a plan and running such processes more efficiently. Review Solved Problem 2 for an application of line-balancing principles.	**OM Explorer Tutor:** 6.1: Calculate Line-Balancing Measures **POM for Windows:** Line Balancing

Key Equations

Managing Constraints in Line Processes

1. Cycle time: $c = \frac{1}{r}$
2. Theoretical minimum number of workstations: $\text{TM} = \frac{\Sigma t}{c}$
3. Idle time: $nc - \Sigma t$
4. Efficiency (%): $\frac{\Sigma t}{nc}(100)$
5. Balance delay (%): 100 − Efficiency

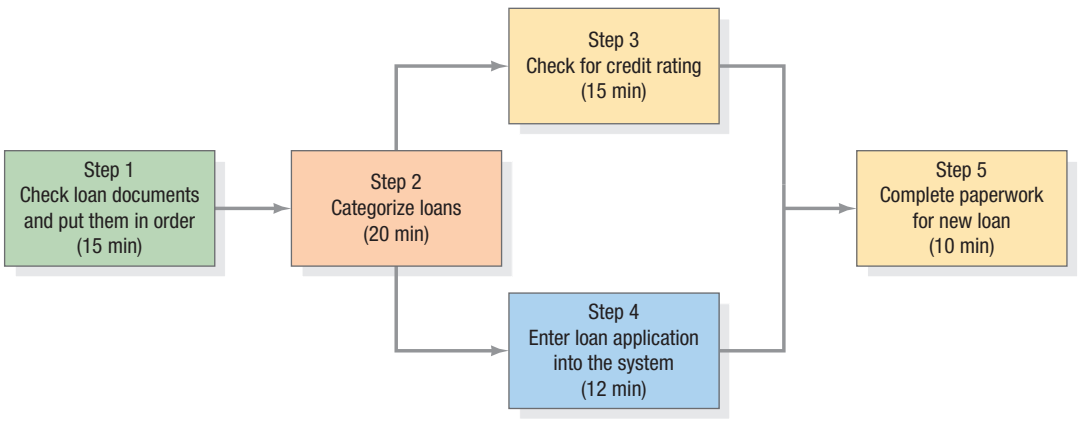
Key Terms

activity-on-node (AON) network 251
balance delay 254
bottleneck 241
constraint 241
cycle time 253
drum-buffer-rope (DBR) 247
immediate predecessors 251
line balancing 251
mixed-model line 256
pacing 256
precedence diagram 251
theoretical minimum (TM) 253
theory of constraints (TOC) 242
throughput time 244
work elements 251

Solved Problem 1

Managers at the First Community Bank are attempting to shorten the time it takes customers with approved loan applications to get their paperwork processed. The flowchart for this process, consisting of several different activities, each performed by a different bank employee, is shown in Figure 6.7. Approved loan applications first arrive at activity or Step 1, where they are checked for completeness and put in order. At Step 2, the loans are categorized into different classes according to the loan amount and whether they are being requested for personal or commercial reasons. While credit checking commences at Step 3, loan application data are entered in parallel into the information system for record-keeping purposes at Step 4 by two different data entry clerks with different levels of training and experience. Finally, all paperwork for setting up the new loan is finished at Step 5. The time taken in minutes is given in parentheses.

Which single step is the bottleneck, assuming that market demand for loan applications exceeds the capacity of the process? The management is also interested in knowing the maximum number of approved loans this system can process in a 5-hour workday.



◀ **FIGURE 6.7**
Processing Credit Loan Applications at First Community Bank

SOLUTION

The capacity for loan completions is derived by translating the "minutes per customer" at any step to "customers per hour." Step 1 can process 4 (60/15) customers per hour, Step 2 can process 3 (60/20) customers per hour, Step 3 can process 4 (60/15) customers per hour, and Step 5 can process 6 (60/10) customers per hour. Step 4 has two data entry clerks working in parallel, with Clerk 1 being able to process 3 (60/20) customers per hour, and Clerk 2 being able to process only 2 (60/30) customers per hour. So the cumulative capacity of Step 4 is 5 (3 + 2) customers per hour, which represents an aggregate processing time for Step 4 of 12 (60/5) minutes.

The throughput time to complete an approved loan application is 15 + 20 + max (15, 12) + 10 = **60** minutes. Although we assume no waiting time in front of any step, in practice such a smooth process flow is not always the case. So the actual time taken for completing an approved loan will be longer than 60 minutes due to nonuniform arrival of applications, variations in actual processing times, and the related factors.

DECISION POINT

At First Community Bank, Step 2 is the bottleneck constraint, as it has the highest time per loan processed. The bank will be able to complete a maximum of only three loan applications per hour, or 15 in a 5-hour day. Management can increase the flow of loan applications by increasing the capacity of Step 2 up to the point where another step becomes the bottleneck.

Solved Problem 2

A company is setting up an assembly line to produce 192 units per 8-hour shift. The following table identifies the work elements, times, and immediate predecessors:

Work Element	Time (Sec)	Immediate Predecessor(s)
A	40	None
B	80	A
C	30	D, E, F
D	25	B
E	20	B
F	15	B
G	120	A
H	145	G
I	130	H
J	115	C, I
	Total 720	

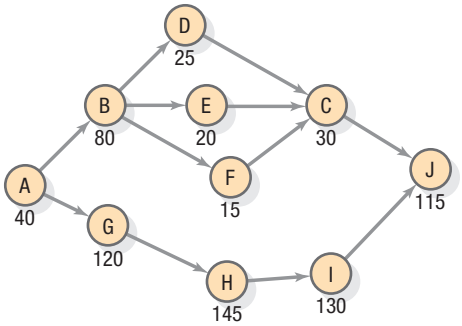
a. What is the desired cycle time (in seconds)?

b. What is the theoretical minimum number of stations?

c. Use trial and error to work out a solution, and show your solution on a precedence diagram.

d. What are the efficiency and balance delay of the solution found?

▼ **FIGURE 6.8**
Precedence Diagram



SOLUTION

a. Substituting in the cycle-time formula, we get

$$c = \frac{1}{r} = \frac{8 \text{ hours}}{192 \text{ units}}(3{,}600 \text{ seconds/hour}) = \mathbf{150} \text{ seconds/unit}$$

b. The sum of the work-element times is 720 seconds, so

$$\text{TM} = \frac{\Sigma t}{c} = \frac{720 \text{ seconds/unit}}{150 \text{ seconds/unit-station}} = 4.8 \text{ or } \mathbf{5} \text{ stations}$$

which may not be achievable.

c. The precedence diagram is shown in Figure 6.8. Each row in the following table shows work elements assigned to each of the five workstations in the proposed solution.

d. Calculating the efficiency, we get

$$\text{Efficiency} = \frac{\Sigma t}{nc}(100) = \frac{720 \text{ seconds/unit}}{5[150 \text{ seconds/unit}]}(100) = \mathbf{96\%}$$

Thus, the balance delay is only 4 percent (100 − 96).

Station	Candidate(s)	Choice	Work-Element Time (Sec)	Cumulative Time (Sec)	Idle Time (c = 150 Sec)
S1	A	A	40	40	110
	B	B	80	120	30
	D, E, F	D	25	145	5
S2	E, F, G	G	120	120	30
	E, F	E	20	140	10
S3	F, H	H	145	145	5
S4	F, I	I	130	130	20
	F	F	15	145	5
S5	C	C	30	30	120
	J	J	115	145	5

Discussion Questions

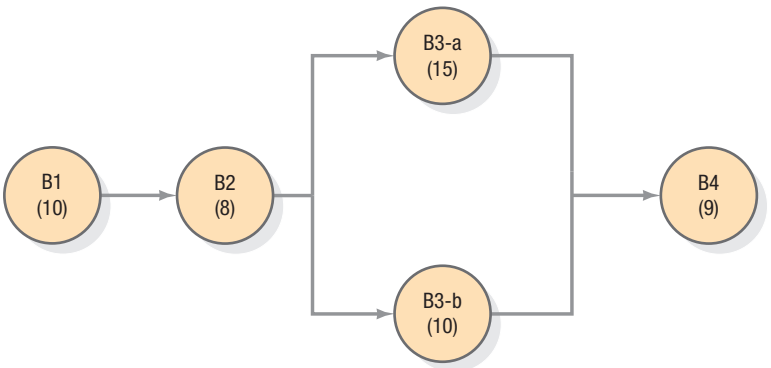
1. Identify potential bottlenecks in the following activities:
   - **a.** Driving to your university
   - **b.** Shopping in a supermarket
   - **c.** Joyrides in an amusement park
   - **d.** Check-in process at an airport
   - **e.** Sale offers in e-commerce websites
2. Using the same process as in question 1, identify the main reason for the bottleneck?
3. What actions can be undertaken to minimize the impact of bottleneck?

Problems

The OM Explorer, POM for Windows, and Active Model software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations.

Managing Bottlenecks in Service Processes

1. Bill's Barbershop has two barbers available to cut customers' hair. Both barbers provide roughly the same experience and skill, but one is just a little bit slower than the other. The process flow in Figure 6.9 shows that all customers go through Steps B1 and B2 and then can be served at either of the two barbers at Step B3. The process ends for all customers at Step B4. The numbers in parentheses indicate the minutes it takes that activity to process a customer.
   - **a.** How long does it take a customer to complete this process?
   - **b.** What single activity is the bottleneck for the entire process?
   - **c.** How many customers can this process serve in an hour?



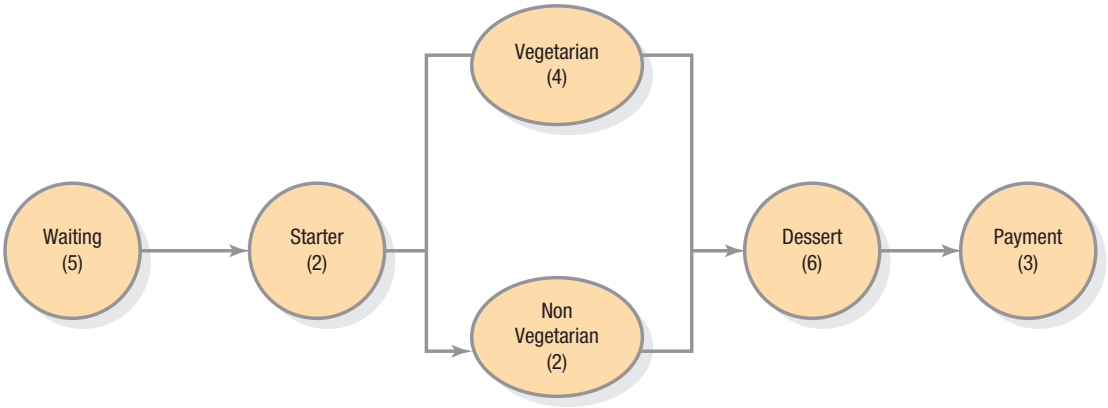
◀ **FIGURE 6.9**
Process Flow for Bill's Barbershop

2. Khushi's Kitchen offers both vegetarian and nonvegetarian lunch for office workers. The peak period for the business is between 12:15 P.M. and 14:15 P.M. Due to limited space, customers form a queue, pick the food they want, and pay at the end. They start with a single line for starters and then fork out for the main course and fall in line again for the dessert. Since Khushi offers more vegetarian options than nonvegetarian, it takes a little longer for the vegetarian queue. The process flow diagram in Figure 6.10 shows how customers pick up their food during the peak lunch hour and the associated duration of each element in minutes.

a. How long does it take a customer to complete the entire process of buying food from Khushi's Kitchen?

b. What single activity is the bottleneck for the entire process?

c. How many customers can Khushi serve in an hour?



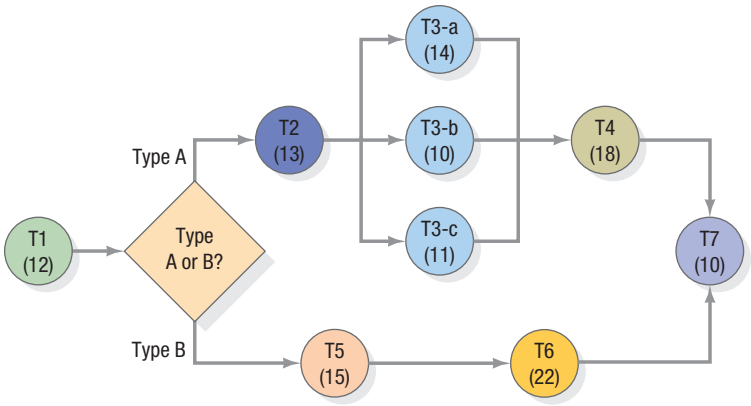
▲ **FIGURE 6.10**
Process Flow for Khushi's Kitchen

3. Figure 6.11 details the process flow for two types of customers who enter Barbara's Boutique shop for customized dress alterations. After Step T1, Type A customers proceed to Step T2 and then to any of the three workstations at T3, followed by Steps T4 and T7. After Step T1, Type B customers proceed to Step T5 and then Steps T6 and T7. The numbers in parentheses are the minutes it takes to process a customer.

a. What is the capacity of Barbara's shop in terms of the numbers of Type A customers who can be served in an hour? Assume no customers are waiting at Steps T1 or T7.

b. If 30 percent of the customers are Type A customers and 70 percent are Type B customers, what is the average capacity of Barbara's shop in customers per hour?

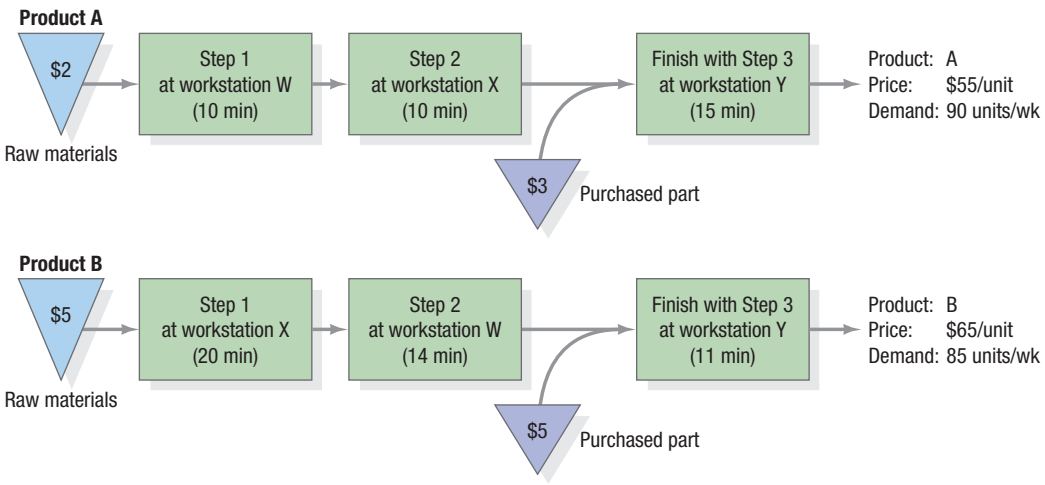
c. Assuming that the arrival rate is greater than five customers per hour, when would you expect Type A customers to experience waiting lines, assuming no Type B customers in the shop? Where would the Type B customers have to wait, assuming no Type A customers?



◀ **FIGURE 6.11**
Process Flow for Barbara's Boutique Customers

Managing Bottlenecks in Manufacturing Processes

4. Canine Kernels Company (CKC) manufactures two different types of dog chew toys (A and B, sold in 1,000-count boxes) that are manufactured and assembled on three different workstations (W, X, and Y) using a small-batch process (Figure 6.12). Batch setup times are negligible. The flowchart denotes the path each product follows through the manufacturing process, and each product's price, demand per week, and processing times per unit are indicated as well. Purchased parts and raw materials consumed during production are represented by inverted triangles. CKC can make and sell up to the limit of its demand per week; no penalties are incurred for not being able to meet all the demand. Each workstation is staffed by a worker who is dedicated to work on that workstation alone, and is paid $6 per hour. Total labor costs per week are fixed. Variable overhead costs are $3,500/week. The plant operates one 8-hour shift per day, or 40 hours/week. Which of the three workstations, W, X, or Y, has the highest aggregate workload, and thus serves as the bottleneck for CKC?



◀ FIGURE 6.12
Flowchart for Canine Kernels Company (CKC)

5. A garment tailoring company in Shanghai specializes in four types of shirts, namely formal shirts, polo shirts, printed shirts, and T-shirts. The following table shows how long it takes to process each shirt through each required activity. Note that all times are in minutes. The factory is open 8 hours a day, 6 days a week.

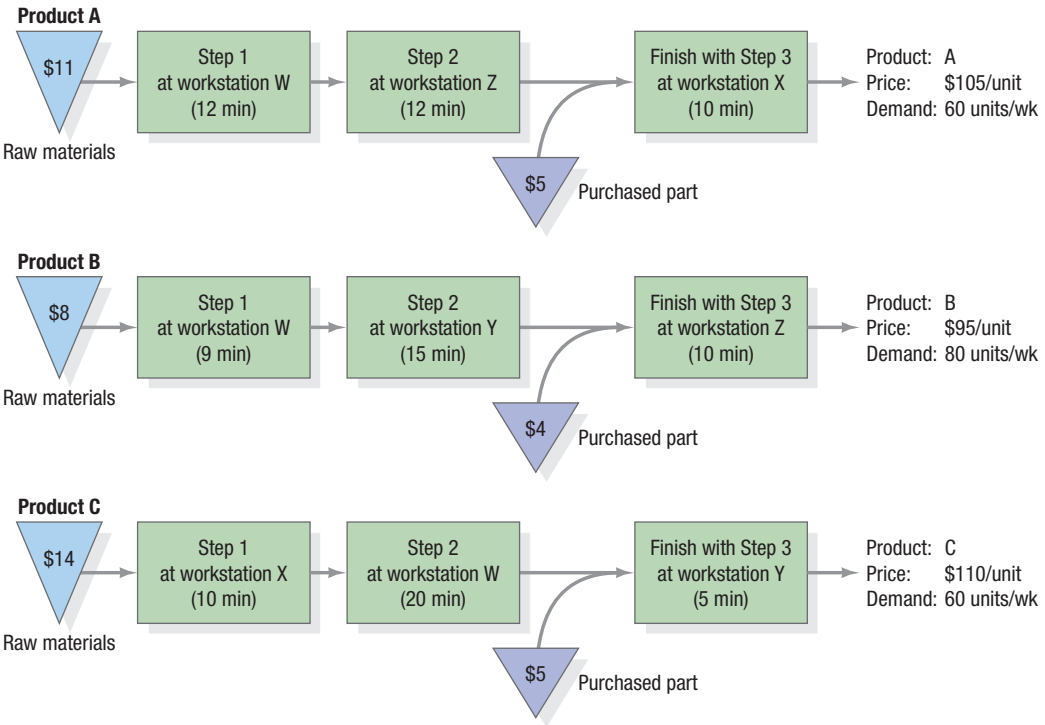
	Formal Shirt (full sleeves)	Polo Shirt	Printed Shirt	T-Shirt
Fabric cutting	30	15	17	20
Sewing and printing if applicable	40	30	50	15
Inspection	30	8	15	0
Finishing and packing	20	7	8	5

If the factory makes only T-shirts during summer to meet high demand, what would be its production capacity?

If weekly demand for the four shirts is formal shirt = 20 units, polo shirt = 15 units, printed shirt = 10 units, and T-shirt = 72 units, which activity is the bottleneck, and is it capable of producing all the shirts demanded?

6. Returning to Problem 5, if weekly demand for the four shirts is formal shirt = 5 units, polo shirt = 25 units, printed shirt = 10 units, and T-shirt = 82 units, which activity is the bottleneck now, and is the factory capable of producing all the shirts demanded? How many additional number of T-shirts will the factory be able to produce? Will there be any change in the bottleneck?

7. Yost-Perry Industries (YPI) manufactures a mix of affordable guitars (A, B, C) that are fabricated and assembled at four different processing stations (W, X, Y, Z). The operation is a batch process with small setup times that can be considered negligible. The product information (price,



◀ FIGURE 6.13
Flowchart for Yost-Perry Industries (YPI)

weekly demand, and processing times) and process sequences are shown in Figure 6.13. Raw materials and purchased parts (shown as a per-unit consumption rate) are represented by inverted triangles. YPI is able to make and sell up to the limit of its demand per week with no penalties incurred for not meeting the full demand. Each workstation is staffed by one highly skilled worker who is dedicated to work on that workstation alone and is paid $15 per hour. The plant operates one 8-hour shift per day and operates on a 5-day workweek (i.e., 40 hours of production per person per week). Overhead costs are $9,000/week. Which of the four workstations, W, X, Y, or Z, has the highest aggregate workload, and thus serves as the bottleneck for YPI?

Applying the Theory of Constraints to Product Mix Decisions

8. The senior management at Canine Kernels Company (CKC) mentioned in Problem 4 is concerned with the existing capacity limitation, so senior management wants to accept the mix of orders that maximizes the company's profits. Traditionally, CKC has utilized a method whereby decisions are made to produce as much of the product with the highest contribution margin as possible (up to the limit of its demand), followed by the next highest contribution margin product, and so on until no more capacity is available. Because capacity is limited, choosing the proper product mix is crucial. Troy Hendrix, the newly hired production supervisor, is an avid follower of the TOC philosophy and the bottleneck method for scheduling. He believes that profitability can indeed be approved if bottleneck resources are exploited to determine the product mix.

- **a.** What is the profit if the traditional contribution margin method is used for determining CKC's product mix?
- **b.** What is the profit if the bottleneck method advocated by Troy is used for selecting the product mix?
- **c.** Calculate the profit gain, both in absolute dollars and in terms of percentage gains, by using TOC principles for determining product mix.

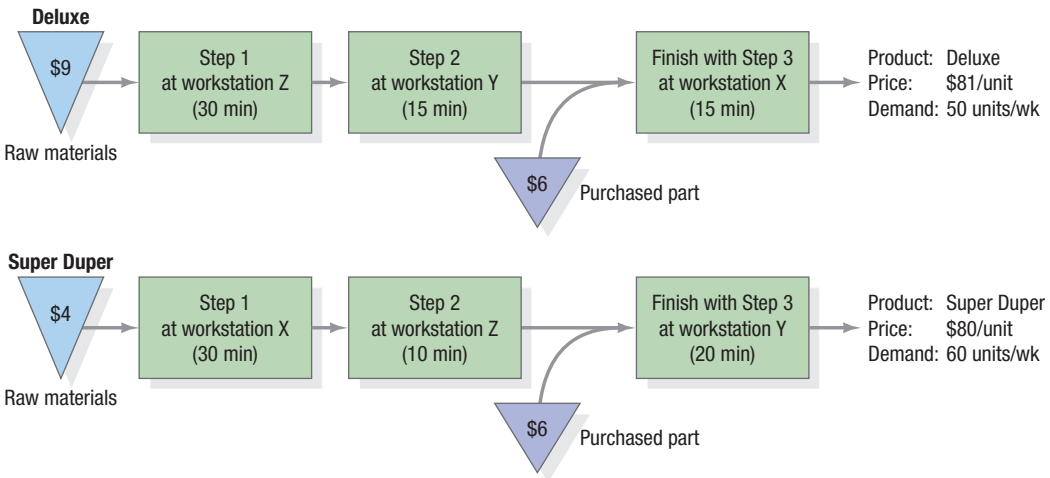
9. The Yost-Perry Industries (YPI) senior management team wants to improve the profitability of the firm by accepting the right set of orders. Currently, decisions are made using the traditional method, which is to accept as much of the highest contribution margin product as possible (up to the limit of its demand), followed by the next highest contribution margin product, and so on until all available capacity is utilized. Because the firm cannot satisfy all the demand, the product mix must be chosen carefully. Jay Perry, the newly promoted production supervisor, is knowledgeable about the TOC and the bottleneck-based method for scheduling. He believes that profitability can indeed be improved if bottleneck resources are exploited to determine the product mix. What is the change in profits if, instead of the traditional method that YPI has used thus far, the bottleneck method advocated by Jay is used for selecting the product mix?

10. A.J.'s Wildlife Emporium manufactures two unique birdfeeders (Deluxe and Super Duper) that are manufactured and assembled in up to three different workstations (X, Y, Z) using a small batch process. Each of the products is produced according to the flowchart in Figure 6.14. Additionally, the flowchart indicates each product's price, weekly demand, and processing times per unit. Batch setup times are negligible. A.J. can make and sell up to the limit of its weekly demand and there are no penalties for not being able to meet all of the demand. Each workstation is staffed by a worker who is dedicated to work on that workstation alone and is paid $16 per hour. The plant operates 40 hours per week, with no overtime. Overhead costs are $2,000 per week. Based on the information provided, as well as the information contained in the flowchart, answer the following questions.

- **a.** Using the traditional method, which bases decisions solely on a product's contribution to profits and overhead, what is the optimal product mix and what is the overall profitability?
- **b.** Using the bottleneck-based method, what is the optimal product mix and what is the overall profitability?

11. Cooper River Glass Works (CRGW) produces four different models of desk lamps as shown in Figure 6.15. The operations manager knows that total monthly demand exceeds the capacity available for production. Thus, she is interested in determining the product mix that will maximize profits. Each model's price, routing, processing times, and material cost are provided in Figure 6.15. Demand next month is estimated to be 200 units of model Alpha, 250 units of model Bravo, 150 units of model Charlie, and 225 units of model Delta. CRGW operates

FIGURE 6.14 ▶
A.J.'s Wildlife Emporium Flowchart



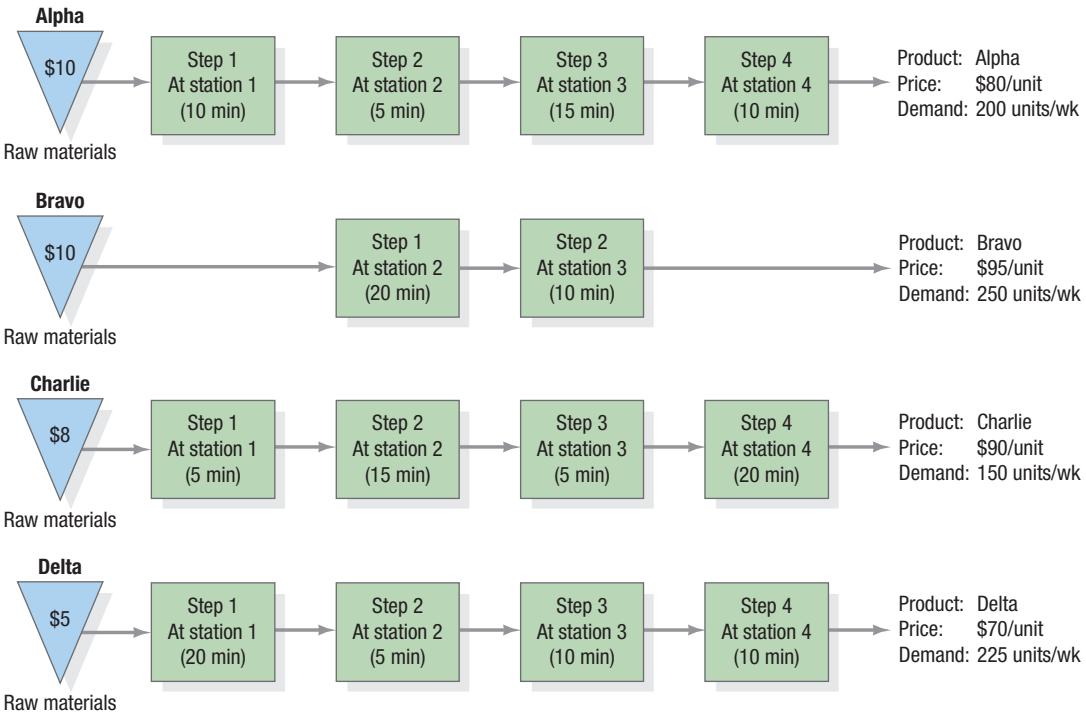


FIGURE 6.15
Cooper River Glass Works Flowchart

only one 8-hour shift per day and is scheduled to work 20 days next month (no overtime). Further, each station requires a 10 percent capacity cushion.

a. Which station is the bottleneck?

b. Using the traditional method, which bases decisions solely on a product's contribution to profits and overhead, what is the optimal product mix and what is the overall profitability?

c. Using the bottleneck-based method, what is the optimal product mix and what is the overall profitability?

12. Fabulous Ice-cream Limited manufactures and distributes ice-creams to various retail outlets in India. The company manufactures a wide variety of flavors and the product mix is determined by giving resource priority to the highest contribution margin ice-cream. The ice-cream manufacturing process is completed in four workstations. Fabulous Ice-cream employs 25 workers; each worker is paid 100 Indian rupees (INR) per hour and works 40 hours per week. Overhead costs are 12,500 INR per week. Labor is considered a fixed expense because workers are paid for their time regardless of their utilization. The plant operates 16 hours per day and 6 days per week. The production manager has identified workstation 1 as the bottleneck. Detailed production information is provided in the table.

	Vanilla	Strawberry	Chocolate
Price (INR)	1,345	1,200	1,895
Material cost (INR)	400	550	700
Weekly demand	100	75	40
Processing time station 1	54 min	0 min	27 min
Processing time station 2	0 min	0 min	54 min
Processing time station 3	8 min	54 min	0 min
Processing time station 4	18 min	27 min	36 min

a. Using the traditional method, which bases decisions solely on a product's contribution to profits and overhead, what is the product mix that yields the highest total profit for Fabulous Ice-cream? What is the resulting profit?

b. Using the bottleneck-based method, what is the product mix that yields the highest total profit? What is the resulting profit?

Managing Constraints in Line Processes

13. Quick Stop Pharmacy is a small family-owned, drug-compounding business in Portland, Oregon, that is trying to perfect its customer service operations. The owner, John Suleiman, wants to maximize the productivity of his staff as well as serve customers well. One area of concern is the drive-thru operation during the 7:30–8:30 morning rush hour. The process of fulfilling an order is as follows:

	Work Element	Time (Sec.)	Immediate Predecessor(s)
(A)	Greet patient and take prescription	40	—
(B)	Check patient information on system	45	A
(C)	Gather compounding materials	55	A

	Work Element	Time (Sec.)	Immediate Predecessor(s)
(D)	Perform compounding	55	C
(E)	Package and label	65	D
(F)	Instruct patient on use	40	B
(G)	Collect payment	25	B

a. If all the steps are handled by one employee, how many patients could be served per hour?

b. If John wants to process 30 patients per hour, how many employees will he need?

c. How many stations are required using the longest work element decision rule?

d. Using the solution developed in part (c), which station is the bottleneck and how large is its capacity cushion?

14. Use the longest work element rule to balance the assembly line described in the following table and Figure 6.16 so that it will produce 40 units per hour.

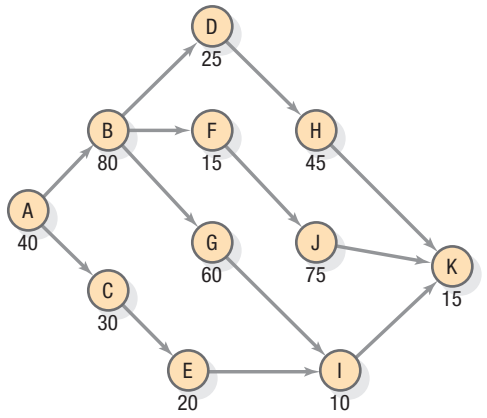
a. What is the cycle time?

b. What is the theoretical minimum number of workstations?

c. Which work elements are assigned to each workstation?

d. What are the resulting efficiency and balance delay percentages?

e. Use the shortest work element rule to balance the assembly line. Do you note any changes in solution?



▲ **FIGURE 6.16**
Precedence Diagram

Work Element	Time (Sec)	Immediate Predecessor(s)
A	40	None
B	80	A
C	30	A
D	25	B
E	20	C
F	15	B
G	60	B
H	45	D
I	10	E, G
J	75	F
K	15	H, I, J
	Total 415	

15. Johnson Cogs wants to set up a line to serve 60 customers per hour. The work elements and their precedence relationships are shown in the following table.

a. What is the theoretical minimum number of stations?

b. How many stations are required using the longest work element decision rule?

c. Suppose that a solution requiring five stations is obtained. What is its efficiency?

Work Element	Time (Sec)	Immediate Predecessor(s)
A	40	None
B	30	A
C	50	A
D	40	B
E	6	B
F	25	C
G	15	C
H	20	D, E
I	18	F, G
J	30	H, I
	Total 274	

16. The *trim line* at PW is a small subassembly line that, along with other such lines, feeds into the final chassis line. The entire assembly line, which consists of more than 900 workstations, is to make PW's new E cars. The trim line itself involves only 13 work elements and must handle 20 cars per hour. Work-element data are as follows:

Work Element	Time (Sec)	Immediate Predecessor(s)
A	1.8	None
B	0.4	None
C	1.6	None
D	1.5	A
E	0.7	A
F	0.5	E
G	0.8	B
H	1.4	C

Work Element	Time (Sec)	Immediate Predecessor(s)
I	1.4	D
J	1.4	F, G
K	0.5	H
L	1.0	J
M	0.8	I, K, L

a. Draw a precedence diagram.

b. What cycle time (in minutes) results in the desired output rate?

c. What is the theoretical minimum number of stations?

d. Use the longest work element decision rule to balance the line and calculate the efficiency of your solution.

e. Use the most followers work element decision rule to balance the line and calculate the efficiency of your solution.

17. Refer back to Problem 16. Suppose that in addition to the usual precedence constraints, there are two zoning constraints within the trim line. First, work elements K and L should be assigned to the same station; both use a common component, and assigning them to the same station conserves storage space. Second, work elements H and J cannot be performed at the same station.

a. Using trial and error, balance the line as best you can.

b. What is the efficiency of your solution?

18. A bespoke furniture manufacturer requires a production line to manufacture 25 chairs with engravings per week, while operating only 40 hours per week. There are only four steps required to produce a single engraved chair with respective processing times of 10 minutes for cutting the wood, 10 minutes for sanding, 90 minutes for engraving and assembly, and 30 minutes for painting.

a. What is the manufacturer's cycle time?

b. What is the minimum number of workstations the manufacturer could hope for in designing the line considering this cycle time?

c. If customers are not interested in painted chairs, the manufacturer can eliminate the last step. Will there be any change in the number of workstations?

d. Suppose the manufacturer finds a solution that requires only three stations. What would be the efficiency of this line?

19. A paced assembly line has been devised to manufacture calculators, as the following data show:

Station	Work Element Assigned	Work Element Time (min)
S1	A	2.7
S2	D, E	0.6, 0.9
S3	C	3.0
S4	B, F, G	0.7, 0.7, 0.9
S5	H, I, J	0.7, 0.3, 1.2
S6	K	2.4

a. What is the maximum hourly output rate from this line? (*Hint:* The line can go only as fast as its slowest workstation.)

b. What cycle time corresponds to this maximum output rate?

c. If a worker is at each station and the line operates at this maximum output rate, how much idle time is lost during each 10-hour shift?

d. What is the line's efficiency?

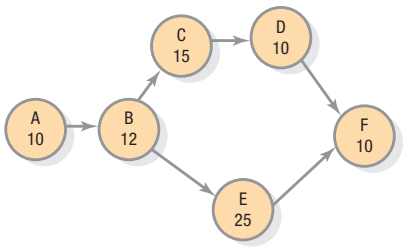
20. Remarkable and Co. manufactures and assembles bicycles using six distinct work elements. Each workstation is managed by one employee. Remarkable would like to assemble eight bikes in each 10-hour shift. Figure 6.17 details each work element and its associated durations in minutes as well as their precedence relationships.

a. What cycle time is required to satisfy the required output rate?

b. What is the minimum number of workstations required to maintain the output?

c. If Remarkable identifies a five-station solution, what is the associated efficiency and balance delay?

d. If the cycle time is increased by 100 percent, would the minimum number of workstations required also increase by 100 percent?



◀ **FIGURE 6.17**
Precedence Diagram for Assembling Bicycles

21. Greg Davis, a business major at the University of South Carolina (USC), has opened Six Points Saco (SPS), a specialty subs–taco restaurant, at the rim of the USC campus. SPS has grown in popularity over the first year that it has been in operation, and Greg is trying to perfect the business model before making it into a franchise. He wants to maximize the productivity of his staff, as well as serve customers well in a timely fashion. One area of concern is the drive-thru operation during the 11:30 A.M. to 12:30 P.M. lunch hour.

The process of fulfilling an order involves fulfilling the tasks listed in the table.

Greg is interested in getting a better understanding of the staffing patterns that will be needed to operate his restaurant. After taking a course in operations management at the university, he knows that fulfilling a customer order at SPS is very similar to operating an assembly line. He has also used the POM for Windows software before, and wants to apply it for examining different demand scenarios for serving his customers.

a. If all seven tasks are handled by one employee, how many customers could be served per hour?

b. If Greg wants to process 45 customers per hour, how many employees will he need during the peak period?

c. With the number of employees determined in part (b), what is the maximum number of customers who could be served every hour (i.e., what is the maximum output capacity)?

d. Assuming that no task is assigned to more than one employee, what is the maximum output capacity from this assembly line? How many employees will be needed to actually accomplish this maximum output capacity?

e. Beyond the output accomplished in part (d), if Greg decides to add one additional worker to help out with a bottleneck task, where should he add that worker? With that addition, would he be able to process more customers per hour? If so, what is the new maximum output capacity for the drive-thru?

Task	Time (Seconds)	Immediate Predecessors
A. Take an order at the booth. Most orders are for a taco and a sub.	25	
B. Collect money at the window.	20	A
C. Gather drinks.	35	B
D. Assemble taco order.	32	B
E. Assemble sub order.	30	B
F. Put drinks, taco, and sub in a bag.	25	C, D, E
G. Give the bag to the customer.	10	F

EXPERIENTIAL LEARNING 6.1 Min-Yo Garment Company

The Min-Yo Garment Company is a small firm in Taiwan that produces sportswear for sale in the wholesale and retail markets. Min-Yo's garments are unique because they offer fine embroidery and fabrics with a variety of striped and solid patterns. Over the 20 years of its existence, the Min-Yo Garment Company has become known as a quality producer of sports shirts with dependable deliveries. However, during that same period, the nature of the apparel industry has undergone change. In the past, firms could be successful producing standardized shirts in high volumes with few pattern or color choices and long production lead times. Currently, with the advent of regionalized merchandising and intense competition at the retail level, buyers of the shirts are looking for shorter lead times and much more variety in patterns and colors. Consequently, many more business opportunities are available today than ever before to a respected company such as Min-Yo.

Even though the opportunity for business success seemed bright, the management meeting last week was gloomy. Min-Yo Lee, president and owner of Min-Yo Garment, expressed concerns over the performance of the company: "We are facing strong competition for our products. Large apparel firms are driving prices down on high-volume licensed brands. Each day more firms enter the customized shirt business. Our profits are lower than expected, and delivery performance is deteriorating. We must reexamine our capabilities and decide what we can do best."

Products

Min-Yo has divided its product line into three categories: licensed brands, subcontracted brands, and special garments.

Licensed Brands

Licensed brands are brands that are owned by one company but, through a licensing agreement, are produced by another firm that also markets the brand in a specific geographic region. The licenser may have licensees all over the world. The licensee pays the licenser a fee for the privilege of marketing the brand in its region, and the licenser agrees to provide some advertising for the product, typically through media outlets that have international exposure. A key aspect of the licensing agreement is that the licensee must agree to provide sufficient quantities of product at the retail level. Running out of stock hurts the image of the brand name.

Currently, only one licensed brand is manufactured by Min-Yo. The brand, called the Muscle Shirt, is owned by a large "virtual corporation" in Italy that has no manufacturing facilities of its own. Min-Yo has been licensed to manufacture Muscle Shirts and sell them to large retail chains in Taiwan. The retail chains require prompt shipments at the end of each week. Because of competitive pressures from other licensed brands, low prices are important. Min-Yo sells each Muscle Shirt to retail chains for $6.

The demand for Muscle Shirts averages 900 shirts per week. The demand for Muscle Shirts shown below has been forecasted for the next 12 weeks.

Min-Yo's forecasts of Muscle Shirts are typically accurate to within ±200 shirts per week. If demand exceeds supply in any week, the excess demand is lost. No backorders are taken, and Min-Yo incurs no cost penalty for lost sales.

Subcontracted Brands

Manufacturers in the apparel industry often face uncertain demand. To maintain level production at their plants, many manufacturers seek subcontractors to produce their brands. Min-Yo is often considered a subcontractor because of its reputation in the industry. Although price is a consideration, the owners of subcontracted brands emphasize dependable delivery and the ability of the subcontractor to adjust order quantities on short notice.

Week	Demand	Week	Demand
1*	700	7	1,100
2	800	8	1,100
3	900	9	900
4	900	10	900
5	1,000	11	800
6	1,100	12	700

*In other words, the company expects to sell 700 Muscle Shirts at the end of week 1.

Currently, Min-Yo manufactures only one subcontracted brand, called the Thunder Shirt because of its bright colors. Thunder Shirts are manufactured to order for a company in Singapore. Min-Yo's price to this company is $7 per shirt. When orders are placed, usually twice a month, the customer specifies the delivery of certain quantities in each of the next 2 weeks. The last order the customer placed is overdue, forcing Min-Yo to pay a penalty charge. To avoid another penalty, 200 shirts must be shipped in week 1. The Singapore company is expected to specify the quantities it requires for weeks 2 and 3 at the beginning of week 1. The delivery schedule containing the orders for weeks 4 and 5 is expected to arrive at the beginning of week 3, and so on. The customer has estimated its average weekly needs for the year to be 200 shirts per week, although its estimates are frequently inaccurate.

Because of the importance of this large customer to Min-Yo and the lengthy negotiations of the sales department to get the business, management always tries to satisfy its needs. Management believes that if Min-Yo Garment ever refuses to accept an order from this customer, Min-Yo will lose the Thunder Shirt business. Under the terms of the sales contract, Min-Yo agreed to pay this customer $1 for every shirt not shipped on time for each week the shipment of the shirt is delinquent. Delinquent shipments must be made up.

Special Garments

Special garments are made only to customer order because of their low volume and specialized nature. Customers come to Min-Yo Garment to manufacture shirts for special promotions or special company occasions. Min-Yo's special garments are known as Dragon Shirts because of the elaborate embroidery and unique flair of the designs. Because each shirt is made to a particular customer's specifications and requires a separate setup, special garments cannot be produced in advance of a firm customer order.

Although price is not a major concern for the customers of special garments, Min-Yo sells Dragon Shirts for $8 a shirt to ward off other companies seeking to enter the custom shirt market. Its customers come to Min-Yo because the company can produce almost any design with high quality and deliver an entire order on time. When placing an order for a Dragon Shirt, a customer specifies the design of the shirt (or chooses from Min-Yo's catalog), supplies specific designs for logos, and specifies the quantity of the order and the delivery date. In the past, management checked to see whether such an order would fit into the schedule, and then either accepted or rejected it on that basis. If Min-Yo accepts an order for delivery at the *end* of a certain week and fails to meet this commitment, it pays a penalty of $2 per shirt for each week delivery is delayed. This penalty is incurred weekly until the delinquent order is delivered. The company tried to forecast demand for specific designs of Dragon Shirts but has given up. Last week, Min-Yo had four Dragon Shirt opportunities of 50, 75, 200, and 60 units but chose not to accept any of the orders. Dragon Shirt orders in the past ranged from 50 units to 300 units with varying lead times.

Figure 6.18, Min-Yo's current open-order file, shows that in some prior week Min-Yo accepted an order of 400 Thunder Shirts for delivery last week. The open-order file is important because it contains the commitment management made to customers. Commitments are for a certain quantity and a date of delivery. As customer orders are accepted, management enters the quantity in the cell representing the week that they are due. Because Dragon Shirts are unique unto themselves, they each have their own order number for future use. No Dragon Shirt orders appear in the open-order file because Min-Yo has not committed to any in the past several weeks.

MIN-YO GARMENT COMPANY

Open Order File (Record of commitments)

	Week Order is Due									
Product	1	2	3	4	5	6	7	8	9	10
Thunder Orders	400									
Dragon Order 1										
Dragon Order 2										
Dragon Order 3										
Dragon Order 4										
Dragon Order 5										
Dragon Order 6										
Dragon Order 7										
Dragon Order 8										
Dragon Order 9										
Dragon Order 10										
Dragon Order 11										
Dragon Order 12										
Dragon Order 13										
Dragon Order 14										
Dragon Order 15										

Intro | Open Order File | Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 | Week 7 | Week 8 | Week 9 | Week 10

▲ **FIGURE 6.18**
Min-Yo's Open-Order File

Note: All orders are to be delivered at the end of the week indicated, after production for the week has been completed and before next week's production is started.

Manufacturing Process

The Min-Yo Garment Company has the latest process technology in the industry—a machine, called a garment maker, that is run by one operator on each of three shifts. This single machine process can make every garment Min-Yo produces; however, the changeover times consume a substantial amount of capacity. Company policy is to run the machine three shifts a day, five days a week. If business is insufficient to keep the machine busy, the workers are idle because Min-Yo is committed to never fire or lay off a worker. By the same token, the firm has a policy of never working on weekends. Thus, the capacity of the process is 5 days $\times$ 24 hours $=$ 120 hours per week. The hourly wage is \$10 per hour, so the firm is committed to a fixed labor cost of \$10 $\times$ 120 $=$ \$1,200 per week. Once the machine has been set up to make a particular type of garment, it can produce that garment at the rate of 10 garments per hour, regardless of type. The cost of the material in each garment, regardless of type, is \$4. Raw materials are never a problem and can be obtained overnight.

Scheduling the Garment Maker

Scheduling at Min-Yo is done once each week, after production for the week has been completed and shipped, after new orders from customers have arrived, and before production for the next week has started. Scheduling results in two documents.

The first is a production schedule, shown in Figure 6.19. The schedule shows what management wants the garment maker process to produce in a given week. Two spreadsheet entries are required for each product that is to be produced in a given week. They are in the cells under the Changeover and Quantity headings. The first is the production quantity. In Figure 6.19, the schedule shows that Min-Yo produced quantities of 800 units for Muscle and 200 units for Thunder last week. The second input is a "1" if the machine is to be set up for a given product or a "blank" if no changeover is required. Figure 6.19 shows that last week changeovers were required for the Muscle and Thunder production runs. The changeover information is important because, at the end of a week, the garment maker process will be set up for the last product produced. If the same product is to be produced first the following week, no new changeover will be required. Management must keep track of the sequence of production each week to take advantage of this savings. The only exception to this rule is Dragon Shirts, which are unique orders that always require a changeover. In week 0, Min-Yo did not produce any Dragon Shirts; however, it did produce 800 Muscle Shirts, followed by 200 Thunder Shirts. Finally, the spreadsheet calculates the hours required for the proposed schedule. Changeover times for Muscle, Thunder, and Dragon Shirts are 8, 10, and 25 hours, respectively. Because the garment maker process produces 10 garments per hour regardless of type, the number of production hours required for Muscle Shirts is $8 + 800/10 = 88$ hours, and the number of production hours for Thunder Shirts is $10 + 200/10 = 30$ hours, as shown in Figure 6.19. The total time spent on the garment maker process on all products in a week cannot exceed 120 hours. The spreadsheet will not allow you to proceed if this constraint is violated.

The second document is a weekly profit and loss (P&L) statement that factors in sales and production costs, including penalty charges and inventory carrying costs, as shown in Figure 6.20. The inventory carrying cost for *any type of product* is \$0.10 per shirt per week left in inventory after shipments for the week have been made. The spreadsheet automatically calculates the P&L statement, which links to the open-order file and the production schedule, after the demand for Muscle Shirts is known. Figure 6.20 shows that the actual demand for Muscle Shirts last week was 750 shirts.

MIN-YO GARMENT COMPANY

PRODUCTION SCHEDULE

The two inputs to the Production Schedule table are:
1. The quantity you decide to produce this time period
2. Whether there is a setup/changeover required (1 or 0)

PRODUCT		
	Changeover	Quantity
Muscle	1	800
Hours		88
Thunder	1	200
Hours		30

	Changeover	Quantity		Changeover	Quantity		Changeover	Quantity
Dragon Order 1			Dragon Order 11			Dragon Order 21		
Dragon Order 2			Dragon Order 12			Dragon Order 22		
Dragon Order 3			Dragon Order 13			Dragon Order 23		
Dragon Order 4			Dragon Order 14			Dragon Order 24		
Dragon Order 5			Dragon Order 15			Dragon Order 25		
Dragon Order 6			Dragon Order 16			Dragon Order 26		
Dragon Order 7			Dragon Order 17			Dragon Order 27		
Dragon Order 8			Dragon Order 18			Dragon Order 28		
Dragon Order 9			Dragon Order 19			Dragon Order 29		
Dragon Order 10			Dragon Order 20			Dragon Order 30		
Total Dragon Hours		0						
Total Dragon Production		0						

Total Hours scheduled		118

Is production within capacity? Yes

▲ **FIGURE 6.19**
Min-Yo's Production Schedule

P&L STATEMENT

Product	Price	Beg Inv	Production	Available	Demand	Sales	End Inv	Inv/Past due costs
Muscle	$6	550	800	1350	750	4500	600	60
Thunder	$7		200	200	400	1400	-200	200
Dragon Orders	$8		0	0	0	0	0	0
Totals			1000			5900		260

		Current	Cumulative
Sales Total		$5,900	$5,900
Labor	$1,200		
Materials	$4,000		
Inv/Past due	$260		
Total Cost		$5,460	
Profit Contribution		$440	$440

▲ **FIGURE 6.20**
Min-Yo's P&L Schedule

Notes

- The past due quantity of shirts is the number of shirts not shipped as promised, and this appears as a negative number in the "End Inv" column.
- Available = Beginning inventory + Production
- Sales = Demand × Production < available; Available × Price, otherwise
- Inventory cost = $0.10 times number of shirts in inventory. Past due cost equals past due quantity times the penalty ($1 for Thunder Shirts; $2 for Dragon Shirts). These costs are combined in the "Inv/Past Due Costs" column.

The Simulation

At Min-Yo Garment Company,[6] the executive committee meets weekly to discuss the new order possibilities and the load on the garment maker process. The executive committee consists of top management representatives from finance, marketing, and operations. You will be asked to participate on a team and play the role of a member of the executive committee in class. During this exercise, you must decide how far into the future to plan. Some decisions, such as the markets you want to exploit, are long term in nature. Before class, you may want to think about the markets and their implications for manufacturing. Other decisions are short term and have an impact on the firm's ability to meet its commitments. In class, the simulation will proceed as follows.

1. Use the Min-Yo Tables spreadsheet in OM Explorer available online. It is found in the Solver menu, under Constraint Management. You will start by specifying the production schedule for week 1, based on the forecasts for week 1 in the case narrative for Muscle Shirts and additional information on new and existing orders for the customized shirts from your instructor. *You may assume that your managerial predecessors left the garment machine set up for Thunder Shirts.* The production schedule decision is to be made in collaboration with your executive committee colleagues in class.
2. When all the teams have finalized their production plans for week 1, the instructor will supply the actual demands for Muscle Shirts in week 1. Enter that quantity in the P&L statement in the spreadsheet for week 1.
3. After the P&L statement for week 1 is completed, the instructor will announce the new order requests for Thunder Shirts and Dragon Shirts to be shipped in week 2 and the weeks beyond.
4. You should look at your order requests, accept those that you want, and reject the rest. Add those that you accept for delivery in future periods to your open-order file. Enter the quantity in the cell representing the week the order is due. You are then irrevocably committed to them and their consequences.
5. You should then make out a new production schedule, specifying what you want your garment maker process to do in the next week (it will be for week 2 at that time).
6. The instructor will impose a time limit for each period of the simulation. When the time limit for one period has been reached, the simulation will proceed to the next week. Each week the spreadsheet will automatically update your production and financial information in the Summary Sheet.

[6] *Source:* Min-Yo Lee, president and owner of Min-Yo Garment.

VIDEO CASE

Managing Constraints for Caregivers and Patients at Cleveland Clinic During COVID-19

Beginning in January of 2020, the United States faced an unprecedented health crisis of epic and global proportions. The COVID-19 coronavirus, originating in China, quickly spread around the globe, causing hundreds of thousands of deaths and impacting the lives of millions everywhere. In the United States, one of the country's leading healthcare organizations, Cleveland Clinic, realized that this virus was here for the foreseeable future and would touch every aspect of healthcare delivery. Demand for COVID-19 care very rapidly exceeded the demand for other types of patient services. In addition, Cleveland Clinic had to effectively respond to a historic supply bottleneck where demand for personal protective equipment (PPE) was rapidly increasing between 300% to 1000%, but supply chain production for existing PPE and related supplies could only increase up to 50% of that demand. As Cleveland Clinic supply chain managers readily identified, most of the PPE used in its facilities were sourced off-shore in China, and those supply lines quickly dried up as the pandemic escalated.

Under normal operating conditions, Cleveland Clinic's PPE that came from suppliers and distributors was stored in distribution warehouses after arriving on-shore. This warehouse inventory served as buffers from which the healthcare system could pull needed PPE on a defined schedule based on its historic demand patterns. With the dramatic increase in demand caused by COVID-19, the pull of PPE quickly depleted stored supplies.

To prepare for the impact of an impending PPE bottleneck on its operations, Cleveland Clinic's facilities across the country flexed and repurposed physical space to accommodate emergency room, intensive care, and general nursing care capacities and staff. Elective surgical procedures and spaces were converted to caring for victims of the COVID-19 virus. Cross-functional team collaboration between Supply Chain, Philanthropy, Innovations, Surgical Operations, Quality and Patient Safety, and the Clinical Institutes took top priority in addressing the looming constraints. These departments rapidly devised a new holistic supply response team that approached the challenges of the pandemic from six distinct work stream strategies:

- BUY as much PPE as the available market offered
- MAKE PPE components that could not be sourced from suppliers
- SEEK DONATIONS to help the hospital offset the increased cost of sourcing outside normal contracts
- DISINFECT and reuse some PPE items to recycle into workflows
- MANAGE USE of PPE to minimize waste and assure supplies were properly deployed
- MONITOR DATA ANALYTICS to get a better sense of what was occurring in the PPE management process

The shift towards caring for infected COVID-19 patients meant the organization needed to quickly assess its supply chain to determine where bottlenecks existed in procuring ventilator equipment and personal protective equipment (PPE) such as respirator face masks, isolation gowns, gloves, hand sanitizer, and other materials essential to the safety of each and every patient and healthcare worker. Cleveland Clinic's Objectives and Key Results (OKRs) are centered around patient safety, highest-quality patient care, and delivery of an optimal patient experience. Everyone knew that understanding and addressing these immediate needs became paramount, and that having the right PPE in the right places at the right time was needed.



Photo courtesy of Cleveland Clinic/Russell Lee

The Ohio Department of Health, in response to the COVID-19 pandemic, on March 18th, 2020, suspended all non-essential or elective surgeries and procedures that utilized personal protective equipment (PPE) so that essential surgeries could proceed. Here Cleveland Clinic cardiothoracic surgeon, Edward Soltez, MD, MPH, leads a team performing open-heart surgery.

From the theory of constraints perspective as shown in Table 6.2, Cleveland Clinic shifted its focus to the following principles:

1. Balancing flow of resources—material, people, and physical space to accommodate increased demand
2. Recognizing that the sudden shift to managing the throughput of a completely new care protocol might mean loss of efficiency in the short run
3. Identifying where bottlenecks would cause a loss of efficiency, such as in the inability to procure PPE in a timely manner
4. Front-loading PPE and other required materials in anticipation of a spike in demand in the coming weeks and months
5. Assuring both upstream and downstream personnel, processes, and materials were realigned to enhance the flow of work in the system to avoid future bottlenecks and unnecessary inventory build-up and operating expense
6. Redirecting non-bottleneck resources from other clinical activities and non-emergency services to address constraints in impacted areas of operations
7. Tracking capital investments in new equipment and flexed facilities to be sure that the overall impact of these measures did not negatively affect patient care and safety outcomes, materials inventories, and operating expense.

Realizing that the task of global sourcing was beyond the scope of supply chain procurement alone, clinic staff in Philanthropy, Innovations, and Surgical Operations joined forces for an integrated team approach to managing the crisis. Every healthcare provider around the globe was clamoring for the same finite set of PPE resources, which meant there would not be enough supply to meet worldwide demand. The Chief Executive Officer and President of Cleveland Clinic, Dr. Tom Mihaljevic's motto of "A team of teams" was visible everywhere in the health system. This approach allowed people at every

level to contribute ideas on how to improve processes and procedures and create a climate of teamwork and shared responsibility to work around the PPE bottleneck.

Buy

Under the direction of Simrit Sandhu, Chief Supply Chain and Patient Support Services Officer, the Supply Chain team quickly formed a Command Center to assess the BUY work stream of Cleveland Clinic's response. An email inbox was created as a clearinghouse for every possible lead in regard to obtaining PPE. These opportunities were triaged and vetted by one of the work streams listed above. As noted earlier, the Supply Chain team saw demand increases on PPE products escalate 300% to 1000% with only a 50% production increase at the overseas suppliers. This left a large product gap and required the Supply Chain team to leverage relationships to obtain as much product as possible.

Supply Chain caregivers working in the Service Center manually picked and processed an average of 300 PPE orders daily. A standard PPE package consists of over 70 items ordered on a regular basis. A record high was set on July 23, 2020 with 832 orders filled. This product and equipment are stored at six different Northeast Ohio warehouse locations and totals over 2,500 pallets trucked in daily across the system.

Donate

For the Donate work stream, the Philanthropy department coordinated and advertised a program called *Make a Mask* and reached out to surrounding communities asking for help in creating cloth masks and getting donations. There were four drop-off sites spread out across Northeast Ohio which were staffed by volunteers from Philanthropy for 6 weeks (150 shifts totaling 600 volunteer hours). Caregivers in the Service Center managed the thousands of donations that were acquired by Philanthropy from the Donate work stream. This program, in accordance with other coordinated donations from large companies like Procter & Gamble, Nike, Lubrizol, Sherwin-Williams, Avery Dennison, Etsy, and Fanatics, produced the following results:

- Close to 40,000 N95 masks
- 250,000+ surgical/ear loop masks
- 250,000+ face shields
- 250,000+ gloves
- 5,000 homemade masks

Make

Knowing that buying increased levels of PPE from its current suppliers and relying on financial and material donations to quickly acquire resources may not be enough to meet anticipated demand, Cleveland Clinic prepared to produce its own product should the day come when it was unable to externally source them. Caregivers on the Innovations team got specifications from the Supply Chain team on standard products and went to work designing and making its own products while partnering with local manufacturers to bring those items into the enterprise.

The most beneficial partnership took place with Procter and Gamble (P&G) in manufacturing face shields. P&G used an injection molding process to manufacture a custom-designed face shield from Cleveland Clinic specifications, which subsequently became the "best practice" for P&G's broader production. Through a licensing partnership, Cleveland Clinic-designed face shields are now being sold nationwide, including to the government for the national stockpile.

Another design licensing partnership came from Microbrush as caregivers worked to create a new swab that is also now available for purchase nationwide. In a matter of weeks, the Make team brought into the enterprise new products and designs including:

- 350,000 face shields (with an additional 60,000 shields)
- 573,000 cotton masks
- 63,000 swabs
- 43,000 isolation gowns
- 500 stems and 30,000 cradles for high-line IV
- 100 intubation bags
- 200 multiplex vent pieces

This team, with the help of physician input, also made a prototype N95 respirator mask, where the final design is being tested for future use. This **Make** step was tantamount to adding extra capacity to a constrained process.

Disinfect

One of the largest concerns of the Disinfect team was developing alternative strategies in case the Clinic's health system was unable to procure product at any level. The team started asking, "Would it be possible to disinfect and reuse certain items?" Over the course of nine days, Supply Chain, Surgical Operations, and Buildings & Properties worked together to build an offsite reprocessing center and create a strategy to disinfect PPE. All three teams collaborated on design plans as well as logistical workflows to ensure that the regulatory requirements were met. In-house construction crews worked around the clock installing drywall, electric, lights, and painting in a building repurposed for the new disinfection process.

The disinfection process also included colleagues at the Cleveland Clinic laundry facility, which is staffed by a third-party vendor, Evergreen Co-Op. PPE was collected after use in orange bags and transported by Environmental Service workers to the laundry pick-up locations at its facilities. Evergreen laundry trucks then transported these bags back to the laundry facility where they were handed off to the Sterile Processing Department staff who sorted the N95 masks from the rest of plastic PPE parts like goggles and face shields.

N95 masks were then put through an intensive process to disinfect them before placement in sealed containers to be transported back to the Clinic's Service Center. There, supply chain workers distributed the masks back into the PPE supply network for deployment as needed. The total number of items to go through this process in just a six-month period included 71,353 N95 Masks, 35,970 goggles, and 15,369 face shields.

This process continues as new items are collected daily, reprocessed, and stored in the Service Center. As the enterprise continues to reopen and PPE guidelines continue to change, Cleveland Clinic is examining the possibility of increasing the daily staffing at the reprocessing center to maintain this process into the future.

Manage Use

Under normal patient care protocols, PPE gets discarded after each patient encounter, generating a huge volume of disposable goods. The teams revisited the necessity and safety surrounding such disposal practices and developed a new standard that permitted re-use of certain PPE components that would not adversely impact patient safety. This managed use contributed significantly to reducing the pull of PPE from the supply warehouses.

Monitor Data Analytics

Underpinning all these work streams was a robust Data Analytics team that aggregated all pertinent supply volumes, calculated usage rates, and informed

Quality and Patient Safety and Clinical Institutes via dashboards of demand patterns so adjustments could be made before demand reached critical levels.

Focused Approach to Managing Constraints

These concerted and coordinated actions across the six work streams illustrate how Cleveland Clinic leveraged its strong Purchasing capability to buy product from alternative suppliers while the Philanthropy team set up a process for soliciting and receiving donations. To alleviate a critical constraint, new capabilities to make its own PPE supplies were added, as well as figuring out how to get multiple uses out of certain protective items through a new disinfection protocol. Along the entire continuum, this response team used data analytics and dashboards to guide decisions and inform usage guidelines. The collaboration between everyone involved in these teams ensured that the Cleveland Clinic inventory on PPE never dropped below 45 days on hand across the enterprise, delivering on the Cleveland Clinic mission to provide "Care for our Patients, Care for our Caregivers, Care for our Community and Care for our Organization."

Going forward, Cleveland Clinic is focusing on moving its supply chain back on-shore so that they will never again face the shortages of PPE experienced early in the COVID-19 crisis. Existing vendors are being asked to move PPE production back to the United States, and new domestic supplier partnerships and procurement processes are being refined to manage PPE demand. The new goal is to always have at least 45 days' PPE inventory on hand. The pandemic taught all healthcare providers that critical PPE needs to be available in-country at all times should such a crisis ever occur in the future. This plan is further underscored by the strong preference by the President that America increase its production of essential medical supplies to cut down its reliance on foreign producers.

QUESTIONS

1. Consider the six work stream strategies that Cleveland Clinic activated to meet the sudden increase in demand for its services. Going forward, which of those strategies is most sustainable? Why?
2. In which way did Cleveland Clinic achieve a global optimum in managing its COVID-19 constraints instead of just focusing on local solutions? Could it have been equally effective without such a holistic approach?
3. What future bottlenecks might Cleveland Clinic avoid by continuing to monitor its PPE activity through its data analytics and dashboard reporting systems?

7

PROJECT MANAGEMENT

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

- **7.1** Explain the major activities associated with defining and organizing a project.
- **7.2** Describe the procedure for constructing a project network.
- **7.3** Develop the schedule of a project.
- **7.4** Analyze cost–time trade-offs in a project network.
- **7.5** Assess the risk of missing a project deadline.
- **7.6** Identify the options available to monitor and control projects.

Burj Khalifa



robertharding/Alamy Stock Photo

The Burj Khalifa in Dubai, UAE, was the tallest man-made structure in the world as of 2020.

What has concrete equivalent to the weight of 100,000 elephants; aluminum equivalent to the weight of that used in five A380 aircraft; 15 million gallons of water sustainably collected a year; the longest single running elevator, which travels at 33 feet per second, and reaches 140 floors and required 22 million labor hours to build? The answer is the Burj Khalifa, presently the tallest building in the world at 2,722 feet. Located in the heart of downtown Dubai, United Arab Emirates (UAE), it incorporates a 304-room Armani hotel in the first 15 floors and has the world's highest nightclub, restaurant, swimming pool, and observation deck. At the peak of construction, the project employed more than 12,000 workers from 100 countries. Even with this short description, it is clear that constructing the Burj Khalifa was a complex affair. Let's take a peek at how that project was designed and executed.

Every project has a life cycle that consists of four major phases: (1) definition and organization, (2) planning, (3) execution, and (4) closeout. In the case of the Burj Khalifa, that cycle took 6 years.

Definition and Organization

The decision to build the Burj Khalifa was made by the Dubai government to make Dubai a hub for finance, trade, and tourism in the Middle East. From the get-go, the structure had to be the tallest building in the world. It was to contain residential apartments, offices, a hotel, restaurants, and observation decks, and be the centerpiece of a large-scale, mixed-use development that included homes, hotels, parks, shopping malls, and an artificial lake. Emaar Properties, the developer of the project, wanted the development to be strikingly modern while maintaining the culture of its surroundings. The design of the tower itself incorporates cultural and historical elements particular to the region, such as a spiral minaret, which grows slender as it rises. The start date for excavation was set for January 2004, with the finish date 48 months later. At the start of the project, the budget was $876 million for a tower 2,388 feet tall.

Planning

Planning for the Burj Khalifa not only entailed assembling a schedule of activities properly sequenced for technical reasons but also involved addressing a number of engineering challenges because of the uniqueness of the project. The planning, too, involved design-test-redesign cycles for many key structural elements to enhance their effectiveness and safety in light of the environment the Burj Khalifa finds itself in. Here are two examples of the engineering challenges.

Wind The winds in the UAE average 8 mph but can have gusts as high as 80 mph. You can imagine the forces against a building a half-mile tall. After many wind tunnel tests, the engineers developed a Y-shaped design that not only afforded aesthetic advantages and breathtaking views from all rooms, but also provided a buttress against wind from any direction. The structural system enables the building to support itself laterally and keeps it from twisting. Even so, at its tallest point, the building sways 4.9 feet.

Concrete Given the high temperatures in the UAE and the weight of the building, many tests of the various concrete mixes were required. These tests included durability, compressive strength, creep and shrinkage, water penetration, and pump simulations, which had to certify that the concrete could be pumped up to 2,000 feet—a world record. The project required 431,000 cubic yards of concrete and 61,000 tons of steel rebar.

Execution

The execution phase of any project is the time frame over which most of the project's resources will be expended and progress toward the target completion date will be measured. Maintaining the project schedule of individual tasks was paramount toward completing the Burj Khalifa project on time. To that end, a 3-day cycle was established. Tasks were sequenced in a repetitive way, and the latest technologies employed, so that one story was raised every 3 days. However, as in any project, things happen to disrupt the schedule. For example, the most common reason for schedule delays and cost overruns in any project is scope creep. Emaar Properties decided in 2008 to change the final height of the building, making it 334 feet taller than the original plan. Further, it said that the luxury finishes for the apartments and offices that were decided on in 2004, when the tower was originally conceived, would be replaced by upgraded finishes to make them more aesthetically attractive and functionally superior. These changes, in conjunction with a 4-month delay because of economic conditions in Dubai, increased costs and added to the duration of the project. All told, the project's cost was $624 million over budget and took 9 months longer than planned.

Closeout

The closeout phase of a project involves writing final reports and assessing the performance of the management team regarding three critical goals of any project: to complete the project on time or better (*time*), to stay within budget (*cost*), and to meet the specifications to the satisfaction of the customer (*quality*). Regarding the Burj Khalifa, we have seen that both the budget and the target completion date were exceeded, largely due to economic conditions and scope creep. The quality of the tower can be judged by the materials and technology used in its construction, its functionality, and its achievement of the strategic objectives of its owners. The materials and technology used in the construction of the tower were the best available at the time. Mixed reinforced concrete, tested many times, and the latest technologies for pumping the concrete are just two examples of the quality of construction. The project's functionality objectives had been met, with the launching of the Armani hotel, offices, apartments, restaurants, observation decks, and nightclub. As for the strategic objectives, the tower certainly is a world phenomenon. It holds many awards, such as the building with the highest occupied floor, highest outdoor observation deck, highest restaurant, highest nightclub, longest travel distance for elevators, and highest vertical pumping of concrete for a building, among many other achievements. It draws international tourists to Dubai just to see the structure and enjoy its amenities. However, the record for being the world's tallest building may be short lived. The Jeddah Tower, in Saudi Arabia, was scheduled for completion in 2020 at a height of 3,280 feet. However, at present no end is in sight for this ambitious project. And the beat goes on.[1]

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[1] *Sources:* Jennifer Dombrowski, "10 Fun Facts About the Burj Khali-fa, http://luxeadventuretraveler.com (accessed September 29, 2016); S. E. Ahmad Abdelrazaq, Kyung Jun Kim, and Jae Ho Kim, "Brief on the Construction Planning of the Burj Dubai Project, Dubai, UAE, *CTBUH 8th World Congress 2008*; https://en.wikipedia.org/wiki/Burj_Khalifa (accessed September 29, 2016); http://www.turnerconstruction.com/experience/project/28/burj-khalifa; Essays, UK. (November 2018). Analysis of the Burj Khalifa Tower Project. Retrieved from https://www.ukessays.com/esays/economics/analysis-of-the-burj-khalifa-tower-project-economics-essay.php (March 23, 2015); Renee McKeown, "Jeddah Tower Progress: What Happened to the World's Largest Tower?" The Urban Developer (March 4, 2020).

project
An interrelated set of activities with a definite starting and ending point, which results in a unique outcome for a specific allocation of resources.

Companies such as Turner Construction and Samsung Engineering & Construction, project manager and primary construction contractor, respectively, for the Burj Khalifa project, are experts at managing large projects. They master the ability to schedule activities and monitor progress within strict time, cost, and performance guidelines. A **project** can be defined as an interrelated set of activities with a definite starting and ending point, which results in a unique outcome for a specific allocation of resources.

Projects are common in everyday life as well as in business. Planning weddings, remodeling bathrooms, writing term papers, and organizing surprise parties are examples of small projects in everyday life. Conducting company audits, planning mergers, creating advertising campaigns, reengineering processes, developing new services or products, and establishing a strategic alliance are examples of large projects in business.

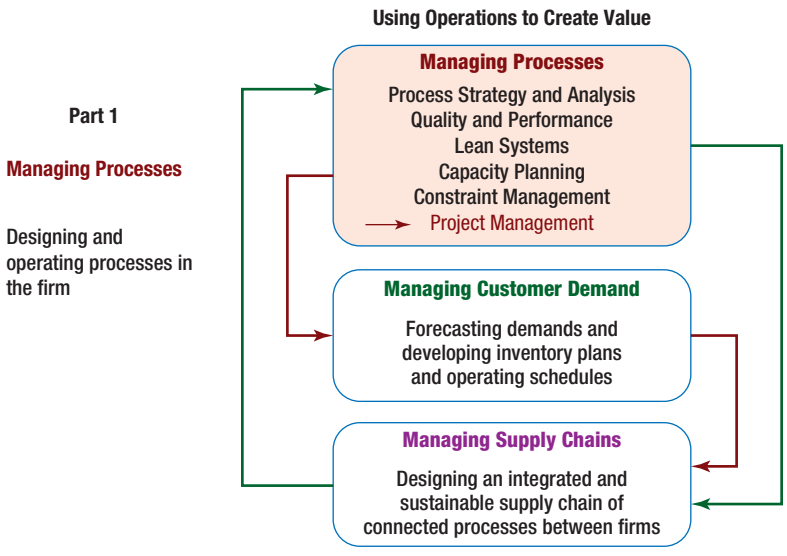
Recall from the opening vignette, the three main goals of any project are (1) to complete the project on time or earlier, (2) to stay within budget, and (3) to meet the specifications to the satisfaction of the customer; these three goals are often referred to as the *iron triangle*. When we must undertake projects with some uncertainty involved, it helps to have flexibility with respect to resource availability, deadlines, and budgets. Consequently, projects can be complex and challenging to manage. **Project management**—a systemized, phased approach to defining, organizing, planning, monitoring, and controlling projects—is one way to overcome that challenge.

project management
A systemized, phased approach to defining, organizing, planning, monitoring, and controlling projects.

Projects often cut across organizational lines because they require the skills of multiple professions and organizations. Furthermore, each project is unique, even if it is routine, requiring new combinations of skills and resources in the project process. For example, projects for adding a new branch office, installing new computers in a department, or developing a sales promotion may be initiated several times a year. Each project may have been done many times before; however, differences arise with each replication. Uncertainties, such as the advent of new technologies or the activities of competitors, can change the character of projects and require responsive countermeasures. Finally, projects are temporary because personnel, materials, and facilities are organized to complete them within a specified time frame and then are disbanded.

Projects, and the application of project management, facilitate the implementation of operations strategy and enable the fruition of all the changes and improvements to the processes discussed in Part 1. However, the power of this approach goes beyond the focus on any one project. Operations strategy initiatives often require the coordination of many interdependent projects. Such a collection of projects is called a **program**, which is an interdependent set of projects with a common strategic purpose. As new project proposals come forward, management must assess their fit to the current operations strategy and ongoing initiatives and have a means to prioritize them, because funds for projects are often limited. Projects also can be used to implement changes to processes and supply chains. For example, projects involving the implementation of major information technologies may affect all of a firm's core processes and supporting processes as well as some of its suppliers' and customers' processes. As such, projects are a useful tool for improving processes and supply chains.

program
An interdependent set of projects that have a common strategic purpose.



Defining and Organizing Projects

A clear understanding of a project's organization and how personnel are going to work together to complete the project are keys to success. In this section, we will address (1) defining the scope and objectives, (2) selecting the project manager and team, and (3) recognizing the organizational structure.

Defining the Scope and Objectives of a Project

A thorough statement of a project's scope, time frame, and allocated resources is essential to managing the project. This statement is often referred to as the *project objective statement*. The scope provides a succinct statement of project objectives and captures the essence of the desired project outcomes in the form of major deliverables, which are

concrete outcomes of the project. Changes to the scope of a project inevitably increase costs and delay completion. Collectively, changes to scope are called *scope creep* and, in sufficient quantity, are primary causes of failed projects. The time frame for a project should be as specific as possible, as in "the project should be completed by January 1, 2024." Finally, although specifying an allocation of resources to a project may be difficult during the early stages of planning, it is important for managing the project. The allocation should be expressed as a dollar figure or as full-time equivalents of personnel time. A specific statement of allocated resources makes it possible to make adjustments to the scope of the project as it proceeds.

Selecting the Project Manager and Team

Once the project is selected, a project manager must be chosen. The qualities of a good project manager should be well aligned with the roles a project manager must play.

- *Facilitator.* The project manager often must resolve conflicts between individuals or departments to ensure that the project has the appropriate resources for the job to be completed. Successful project managers have good leadership skills and a *systems view*, which encompasses the interaction of the project, its resources, and its deliverables with the firm as a whole.
- *Communicator.* Project progress and requests for additional resources must be clearly communicated to senior management and other stakeholders in a project. The project manager must also frequently communicate with the project team to get the best performance.
- *Decision Maker.* Good project managers will be sensitive to the way the team performs best and be ready to make tough decisions, if necessary. The project manager must organize the team meetings, specify how the team will make decisions, and determine the nature and timing of reports to senior management.

Selecting the project team is just as important as the selection of the project manager. Several characteristics should be considered.

- *Technical Competence.* Team members should have the technical competence required for the tasks to which they will be assigned.
- *Sensitivity.* All team members should be sensitive to interpersonal conflicts that may arise. Senior team members should be politically sensitive to help mitigate problems with upper-level management.
- *Dedication.* Team members should feel comfortable solving project problems that may spill over into areas outside their immediate expertise. They should also be dedicated to getting the project done.

Recognizing Organizational Structure

The relationship of the project manager to the project team is determined by the firm's organizational structure. Each of the three types of organizational structure described here has its own implications for project management.

- *Functional.* The project is housed in a specific department or functional area, presumably the one with the most interest in the project. Assistance from personnel in other functional areas must be negotiated by the project manager. In such cases, the project manager has less control over project timing than if the entire scope of the project fell within the purview of the department.
- *Pure Project.* The team members work exclusively for the project manager on a particular project. This structure simplifies the lines of authority and is particularly effective for large projects that consist of enough work for each team member to work full time. For small projects, it could result in significant duplication of resources across functional areas.
- *Matrix.* The matrix structure is a compromise between the functional and pure project structures. The project managers of the firm's projects all report to a program manager who coordinates resource and technological needs across the functional boundaries. The matrix structure allows each functional area to maintain control over who works on a project and the technology that is used. However, team members, in effect, have two bosses: the project manager and the department manager. Resolving these line-of-authority conflicts requires a strong project manager.

Managers of all disciplines can find themselves managing a project, as we see in the following Managerial Challenge.

MANAGERIAL CHALLENGE Marketing

Martha Connors is the head of the marketing department of a large financial services company. The department is responsible for messaging to customers and potential clients. Each year the department is deluged with thousands of requests for creative ads, innovative communications, printed brochures, new web content, and continual sales support from units all over the company. There is no well-defined process for handling all these requests, and as such, delays have been common. As head of the marketing department, Martha has been requested by her firm's CEO to design a fully functional messaging-request process, capable of processing 50 requests per week. This project must be completed in 1 month. The organizational structure of the project will be functional, totally within the marketing department. That left one more important detail: selecting the project manager. She decided on Vijay Sarkar, who was recruited several years ago from a local university. Vijay struck Martha as being a good communicator and facilitator, and as possessing good decision-making skills. Most of all, the employees in the department liked him.

Vijay realized that he had to organize all the tasks that had to be done and assign people to them. Some major activities had to take place. For example, the present layout of the department was not conducive to efficient processing of the requests. Personnel involved in creating the content of ads were on a different floor from the personnel who would create the artwork. Workstations had to be moved, and computers upgraded to the latest technology. In some cases, new personnel had to be hired and trained. It became obvious to Vijay that some tasks had to be done before others; for example, the technical specifications for the new equipment and the design plan for the new layout had to be completed before the workstations could be moved. The software, computers, and printers for the brochure proofs had to be ordered and installed before the workstation for printing brochures could be operational. However, some activities could be done simultaneously, such as ordering the software, computers, and printers at the same time as ordering new desks and workstations. Hiring could begin, but training could not be done until the layout and equipment were in place. Vijay had time estimates for all the activities: What can he tell Martha about the completion date of the project? Which activities will determine the length of the project, and therefore are most deserving of his attention? How can he monitor the progress of the project and the amount of resources expended? The details of this chapter will be helpful to him.

Constructing Project Networks

After the project is defined and organized, the team must formulize the specific work to be accomplished and the relationships between the activities in the project. Constructing a project network involves two steps: (1) defining the work breakdown structure and (2) diagramming the network.

Defining the Work Breakdown Structure

work breakdown structure (WBS)
A statement of all work that has to be completed.

activity
The smallest unit of work effort consuming both time and resources that the project manager can schedule and control.

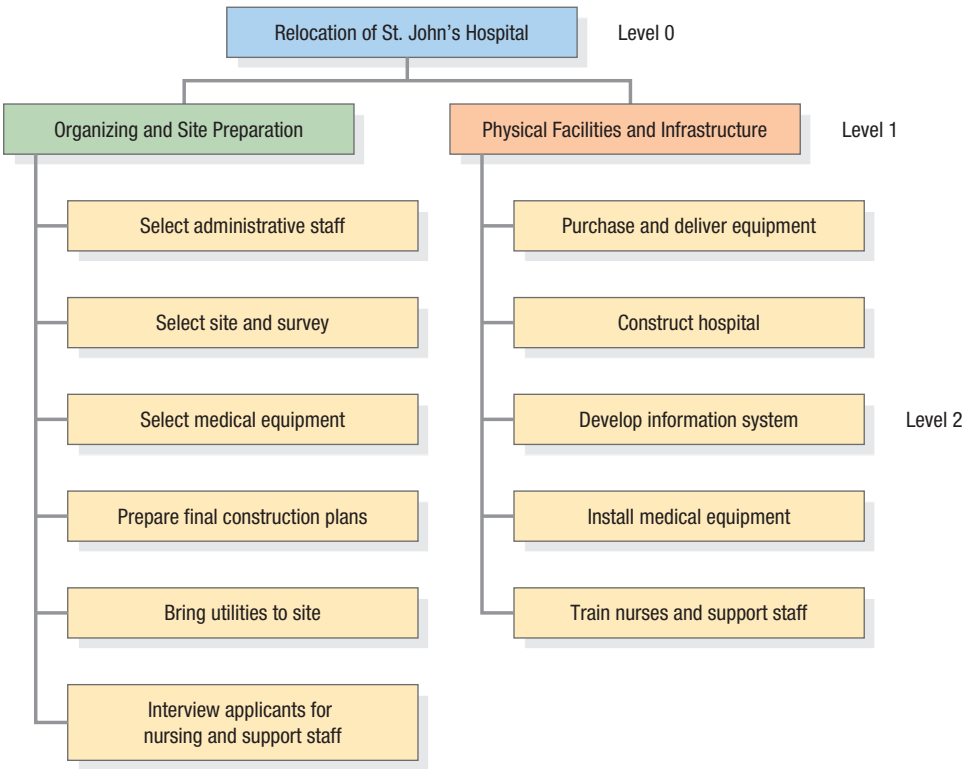
The **work breakdown structure (WBS)** is a statement of all work that has to be completed. Perhaps the single most important contributor to delay is the omission of work that is germane to the successful completion of the project. The project manager must work closely with the team to identify all activities. An **activity** is the smallest unit of work effort consuming both time and resources that the project manager can schedule and control. Typically, in the process of accumulating activities, the team generates a hierarchy to the work breakdown. Major work components are broken down to smaller tasks that ultimately are broken down to activities that are assigned to individuals. Figure 7.1 shows a WBS for a major project involving the relocation of a hospital. In the interest of better serving the surrounding community, the board of St. John's Hospital has decided to move to a new location. The project involves constructing a new hospital and making it operational. The work components at level 1 in the WBS can be broken down into smaller units of work in level 2 that could be further divided at level 3, until the project manager gets to activities at a level of detail that can be scheduled and controlled. For example, "Organizing and Site Preparation" has been divided into six activities at level 2 in Figure 7.1. We have kept our example simple so that the concept of the WBS can be easily understood. If our activities in the example are divided into even smaller units of work, it is easy to see that the total WBS for a project of this size may include many more than 100 activities. Regardless of the project, care must be taken to include all important activities in the WBS to avoid project delays. Often overlooked are the activities required to plan the project, get management approval at various stages, run pilot tests of new services or products, and prepare final reports.



Simon Turner/Alamy Stock Photo

The view of the construction site of the Papworth Hospital in Cambridge, UK shows the extent of the activities that must take place simultaneously. Projects such as this have complex work breakdown structures and network diagrams.

Each activity in the WBS must have an "owner" who is responsible for doing the work. *Activity ownership* avoids confusion in the execution of activities and assigns responsibility for timely completion. The team should have a defined procedure for assigning activities to team members, which can be democratic (consensus of the team) or autocratic (assigned by the project manager).



◀ **FIGURE 7.1**
Work Breakdown Structure for the St. John's Hospital Project

Diagramming the Network

network diagram
A visual display, designed to depict the relationships between activities, that consists of nodes (circles) and arcs (arrows).

program evaluation and review technique (PERT)
A network planning method created for the U.S. Navy's Polaris missile project in the 1950s, which involved 3,000 separate contractors and suppliers.

critical path method (CPM)
A network planning method developed in the 1950s as a means of scheduling maintenance shutdowns at chemical-processing plants.

Network planning methods can help managers monitor and control projects. These methods treat a project as a set of interrelated activities that can be visually displayed in a **network diagram**, which consists of nodes (circles) and arcs (arrows) that depict the relationships between activities. Two network planning methods were developed in the 1950s. The **program evaluation and review technique (PERT)** was created for the U.S. Navy's Polaris missile project, which involved 3,000 separate contractors and suppliers. The **critical path method (CPM)** was developed as a means of scheduling maintenance shutdowns at chemical-processing plants. Although early versions of PERT and CPM differed in their treatment of activity time estimates, today the differences are minor. For purposes of our discussion, we refer to them collectively as PERT/CPM. These methods offer several benefits to project managers, including the following:

1. Considering projects as networks forces project teams to identify and organize the data required and to identify the interrelationships between activities. This process also provides a forum for managers of different functional areas to discuss the nature of the various activities and their resource requirements.
2. Networks enable project managers to estimate the completion time of projects, an advantage that can be useful in planning other events and in conducting contractual negotiations with customers and suppliers.
3. Reports based on project networks highlight the activities that are crucial to completing projects on schedule. They also highlight the activities that may be delayed without affecting completion dates, thereby freeing up resources for other, more critical activities.
4. Network methods enable project managers to analyze the time and cost implications of resource trade-offs.

Diagramming the project network involves establishing precedence relationships and estimating activity times.

precedence relationship
A relationship that determines a sequence for undertaking activities; it specifies that one activity cannot start until a preceding activity has been completed.

Establishing Precedence Relationships A **precedence relationship** determines a sequence for undertaking activities; it specifies that one activity cannot start until a preceding activity has been completed. For example, brochures announcing a conference for executives must first be designed by the program committee (activity A) before they can be printed (activity B). In other words, activity A must *precede* activity B. For large projects, establishing precedence relationships is essential because incorrect or omitted precedence relationships will result in costly delays. The precedence relationships are represented by a network diagram, similar to what we used for analyzing line balancing problems (see Chapter 5, "Constraint Management").

Estimating Activity Times When the same type of activity has been done many times before, time estimates will have a relatively high degree of certainty. Several methods can be used to get time estimates in such an environment. First, statistical methods can be used if the project team has access to data on actual activity times experienced in the past. Second, if activity times improve with the number of replications, the times can be estimated using learning curve models. Finally, the times for first-time activities are often estimated using managerial opinions based on similar prior experiences (see Chapter 8, "Forecasting"). If the estimates involve a high degree of uncertainty, probability distributions for activity times can be used. We discuss how to incorporate uncertainty in project networks when we address risk assessment later in this chapter. For now, we assume that the activity times are known with certainty.

EXAMPLE 7.1 Diagramming the St. John's Hospital Project

Judy Kramer, the project manager for the St. John's Hospital project, divided the project into two major modules. She assigned John Stewart the overall responsibility for the Organizing and Site Preparation module and Sarah Walker the responsibility for the Physical Facilities and Infrastructure module. Using the WBS shown in Figure 7.1, the project team developed the precedence relationships, activity time estimates, and activity responsibilities shown in the following table.

Activity	Immediate Predecessors	Activity Times (weeks)	Responsibility
ST. JOHN'S HOSPITAL PROJECT			Kramer
START		0	
ORGANIZING and SITE PREPARATION			Stewart
A. Select administrative staff	Start	12	Johnson
B. Select site and survey	Start	9	Taylor
C. Select medical equipment	A	10	Adams
D. Prepare final construction plans	B	10	Taylor
E. Bring utilities to site	B	24	Burton
F. Interview applicants for nursing and support staff	A	10	Johnson
PHYSICAL FACILITIES and INFRASTRUCTURE			Walker
G. Purchase and deliver equipment	C	35	Sampson
H. Construct hospital	D	40	Matta
I. Develop information system	A	15	Chang
J. Install medical equipment	E, G, H	4	Gonzalez
K. Train nurses and support staff	F, I, J	6	Ashton
FINISH	K	0	

For purposes of our example, we will assume a workweek consists of 5 workdays. Draw the network diagram for the hospital project.

SOLUTION

The network diagram, activities, and activity times for the hospital project are shown in Figure 7.2. The diagram depicts activities as circles, with arrows indicating the sequence in which they are to be performed. Activities A and B emanate from a *start* node because they have no immediate predecessors. The arrows connecting activity A to activities C, F, and I indicate that all three require completion of activity A before they can begin. Similarly, activity B must be completed before activities D and E can begin, and so on. Activity K connects to a *finish* node because no activities follow it. The start and finish nodes do not actually represent activities; they merely provide beginning and ending points for the network.

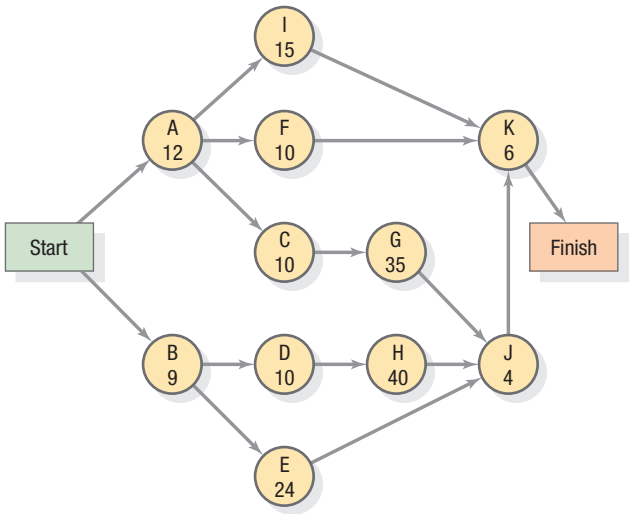


FIGURE 7.2
Network Showing Activity Times for the St. John's Hospital Project

Managerial Practice 7.1 shows how Cleveland Clinic used the principles of project management for the construction of a new hospital in London, United Kingdom, near Buckingham Palace.

MANAGERIAL PRACTICE 7.1 Cleveland Clinic

Cleveland Clinic is a leading global U.S.-based hospital group whose expertise is in specialized medical care. In addition to its 165-acre campus near downtown Cleveland, it has 11 regional hospitals throughout Northeast Ohio, 5 hospitals in Florida, facilities in Las Vegas, Nevada, and Toronto, Canada, and manages a hospital in Abu Dhabi, UAE. Although Cleveland Clinic had an international influence in Canada and the Middle East, it had no presence in Europe. After exploring various opportunities, 33 Grosvenor Place, London, United Kingdom, was chosen for the site of its first hospital in Europe. However, this site posed two complications for the project manager. First, 33 Grosvenor Place is directly across the street from Buckingham Palace and surrounded by prestigious offices and foreign embassies. Consequently, the *scope and objectives of the project* would have to reflect a thoughtful approach that respected the royal household and other buildings nearby, as well as the sensitive conservation areas surrounding the site. Second, there already was a large six-story office building on the site that had to experience major demolition to be transformed into a new ultramodern private hospital. That in itself would have not been much of a problem—just bring in the wrecking balls and knock it down. However, one of the project's specifications was that the entire façade of the existing building had to be preserved because it was a historic building. In other words, the entire demolition and reconstruction to the specifications of the new hospital had to be done within the confines of the existing structure. This specification alone added a great deal of complexity to the project.



Erith Contractors Ltd

To be responsive to environmental concerns regarding the construction of the new Cleveland Clinic, a full-building fabric enclosure, complete with images of the building and windows, was used to reduce the dust and unsightliness of the demolition behind it.

Originally built in the 1950s as the headquarters of an energy company and then converted into speculative office space in the 1990s, the major architectural challenge was to transform the existing building from an all-office building to a private medical hospital. The *project objective statement* can be summarized as follows: Convert an existing office building into a 330,000-square-foot, 200-bed, private healthcare hospital for outstanding inpatient care, with private bedroom and suite facilities, eight operating theater suites, and a diagnostic and imaging center, all with sensitivity to the surrounding environment, by early 2021.

Obviously, because of the magnitude of this project, the *project team* had to consist of a diverse set of companies with expertise in various facets of the health care industry, including human resources and staffing, technology and equipment, and construction, all of which had to come together for a successful project. PLP Architecture won the design competition, and Sir Robert McAlpine won the contract for principal contractor and became the equivalent of the *project manager*. Because the project team consisted of separate companies, the only logical choice for the organizational structure was *pure project*.

The *work breakdown structure* for this project was complex, as you can imagine. For example, the construction activities can be divided into two major categories: demolition and reconstruction. Demolition can be divided into soft strip and hard demolition. Soft-strip activities involve removing non-structural elements, fittings, internal (non-load-bearing) walls, and internal ceilings. Hard demolition involves the use of heavy equipment to break apart concrete and steel structures and remove the resulting material and debris. Reconstruction involved lowering the basement floor by 5 feet and fabricating new supports for the exterior façade, creating new rooms and hallways, installing new windows, and changing the entrances to accommodate a level entry and improve the pedestrian approach. All six floors had to be rebuilt and reimagined for patient care in the decades ahead.

Imagine the myriad activities and their precedence relationships that constituted the project *network diagram*. Sequencing the activities was critical to reducing the time of the project. For example, demolition work was phased so that work progressed from the southern end of the building northward. Reconstruction work could then commence at the southern end before demolition was completed at the northern end. Also, carrying on simultaneous operations such as performing hard demolition activities on the upper floors while lowering the basement floor, although making for a complicated and more hazardous site, was credited with reducing the project time by as much as a year. After 3 years, the construction phase of the project was completed on December 6, 2019, when the final external beam was put in place.

You might be wondering about the environmental concerns elicited in the project objectives, with all of the construction dust and unsightliness of a hollowed-out building. To soften the visual impact, to reduce the dust and noise emissions, and to shelter workers from the wind and rain, a full-building fabric enclosure was commissioned, complete with images of the building and windows behind it stenciled to its surface. At 39,000 square feet, it is believed to be the largest wrap erected in the United Kingdom. The royal family, and those working in offices near the site, could rest easy during the construction phase.[2]

[2] *Sources:* David Taylor, "Delicate Demolition," The Construction Index, https://theconstructionindex.co.uk/news/view/delicate-demolition (April 12, 2018); plparchitecture.com/33-grosvenor-place.html (accessed April 17, 2020); consultqd.clevelandclinic.org/final-beam-placed-for-cleveland-clinic-london (December 6, 2019); Lars G. Svensson, Brian Donley, and Tomosso Falcone, "Cleveland Clinic Comes to London," *Cardio Pulse* in *European Heart Journal*, Volume 39, Issue 34, 07 September 2018, 3161–3163 (accessed April 9, 2020); "Cleveland Clinic: A Transformation in Central London," https://www.hksinc.com/what-we-do/case-studies/cleveland-clinic/ (accessed April 17, 2020).

Developing the Project Schedule

A key advantage of network planning methods is the creation of a schedule of project activities that will help managers achieve the objectives of the project. Given a project network, managers can (1) estimate the completion time of a project by finding the critical path, (2) identify the start and finish times for each activity for a project schedule, and (3) calculate the amount of slack time for each activity.

Critical Path

A crucial aspect of project management is estimating the time of completion of a project. If each activity in relocating the hospital were done in sequence, with work proceeding on only one activity at a time, the time of completion would equal the sum of the times for all the activities, or 175 weeks. However, Figure 7.2 indicates that some activities can be carried on simultaneously, given adequate resources. We call each sequence of activities between the project's start and finish a **path**. The network describing the hospital relocation project has five paths: (1) A–I–K, (2) A–F–K, (3) A–C–G–J–K, (4) B–D–H–J–K, and (5) B–E–J–K. The **critical path** is the sequence of activities between a project's start and finish that takes the longest time to complete. Thus, the activities along the critical path determine the completion time of the project; that is, if one of the activities on the critical path is delayed, the entire project will be delayed. The estimated times for the paths in the hospital project network are as follows:

path
The sequence of activities between a project's start and finish.

critical path
The sequence of activities between a project's start and finish that takes the longest time to complete.

Path	Estimated Time (weeks)
A–I–K	33
A–F–K	28
A–C–G–J–K	67
B–D–H–J–K	69
B–E–J–K	43

The activity string B–D–H–J–K is estimated to take 69 weeks to complete. As the longest, it constitutes the critical path. Because the critical path defines the completion time of the project, Judy Kramer and the project team should focus on these activities and any other path that is close in length to the critical path.

Project Schedule

The typical objective is to finish the project as early as possible as determined by the critical path. The project schedule is specified by the start and finish times for each activity. For any activity, managers can use the earliest start and finish times, the latest start and finish times (and still finish the project on time), or times in between these extremes if the activity is not on the critical path.

- **Earliest Start and Earliest Finish Times** The earliest start and earliest finish times are obtained as follows:

  1. The **earliest finish time (EF)** of an activity equals its earliest start time plus its estimated duration, t, or $EF = ES + t$.
  2. The **earliest start time (ES)** for an activity is the earliest finish time of the immediately preceding activity. For activities with more than one preceding activity, ES is the latest of the earliest finish times of the preceding activities.

     To calculate the duration of the entire project, we determine the EF for the last activity on the critical path.

earliest finish time (EF)
An activity's earliest start time plus its estimated duration, t, or $EF = ES + t$.

earliest start time (ES)
The earliest finish time of the immediately preceding activity.

- **Latest Start and Latest Finish Times** To obtain the latest start and latest finish times, we must work backward from the finish node. We start by setting the latest finish time of the project equal to the earliest finish time of the last activity on the critical path.

  1. The **latest finish time (LF)** for an activity is the latest start time of the activity that immediately follows. For activities with more than one activity that immediately follow, LF is the earliest of the latest start times of those activities.
  2. The **latest start time (LS)** for an activity equals its latest finish time minus its estimated duration, t, or $LS = LF - t$.

latest finish time (LF)
The latest start time of the activity that immediately follows.

latest start time (LS)
The latest finish time minus its estimated duration t, or $LS = LF - t$.



Xinhua/Alamy Stock Photo

Large projects require close attention to schedules. Here, the construction project of the Chengdu Tianfu International Airport, in southwest China's Sichuan Province, includes three runways and a terminal which covers an area of 600,000 meters.

EXAMPLE 7.2 Calculating Start and Finish Times for the Activities

Calculate the ES, EF, LS, and LF times for each activity in the hospital project. Which activity should Kramer start immediately? Figure 7.2 contains the activity times.

SOLUTION

To compute the early start and early finish times, we begin at the start node at time 0. Because activities A and B have no predecessors, the earliest start times for these activities are also zero. The earliest finish times for these activities are

$$EF_A = 0 + 12 = 12 \text{ and } EF_B = 0 + 9 = 9$$

Because the earliest start time for activities I, F, and C is the earliest finish time of activity A,

$$ES_I = 12, ES_F = 12, \text{ and } ES_C = 12$$

Similarly,

$$ES_D = 9 \text{ and } ES_E = 9$$

After placing these ES values on the network diagram (Figure 7.3), we determine the EF times for activities I, F, C, D, and E:

$$EF_I = 12 + 15 = 27, EF_F = 12 + 10 = 22, EF_C = 12 + 10 = 22,$$
$$EF_D = 9 + 10 = 19, \text{ and } EF_E = 9 + 24 = 33$$

The earliest start time for activity G is the latest EF time of all immediately preceding activities. Thus,

$$ES_G = EF_C = 22, ES_H = EF_D = 19$$
$$EF_G = ES_G + t = 22 + 35 = 57, EF_H = ES_H + t = 19 + 40 = 59$$

The project team can now determine the earliest time any activity can be started. Because activity J has several predecessors, the earliest time that activity J can begin is the latest of the EF times of any of its preceding activities: EF_G, EF_H, or EF_E. Thus, $EF_J = 59 + 4 = 63$. Similarly, $ES_K = 63$ and $EF_K = 63 + 6 = 69$. Because activity K is the last activity on the critical path, the earliest the project can be completed is week 69. The earliest start and finish times for all activities are shown in Figure 7.3.

To compute the latest start and latest finish times, we begin by setting the latest finish activity time of activity K at week 69, which is its earliest finish time as determined in Figure 7.3. Thus, the latest start time for activity K is

$$LS_K = LF_K - t = 69 - 6 = 63$$

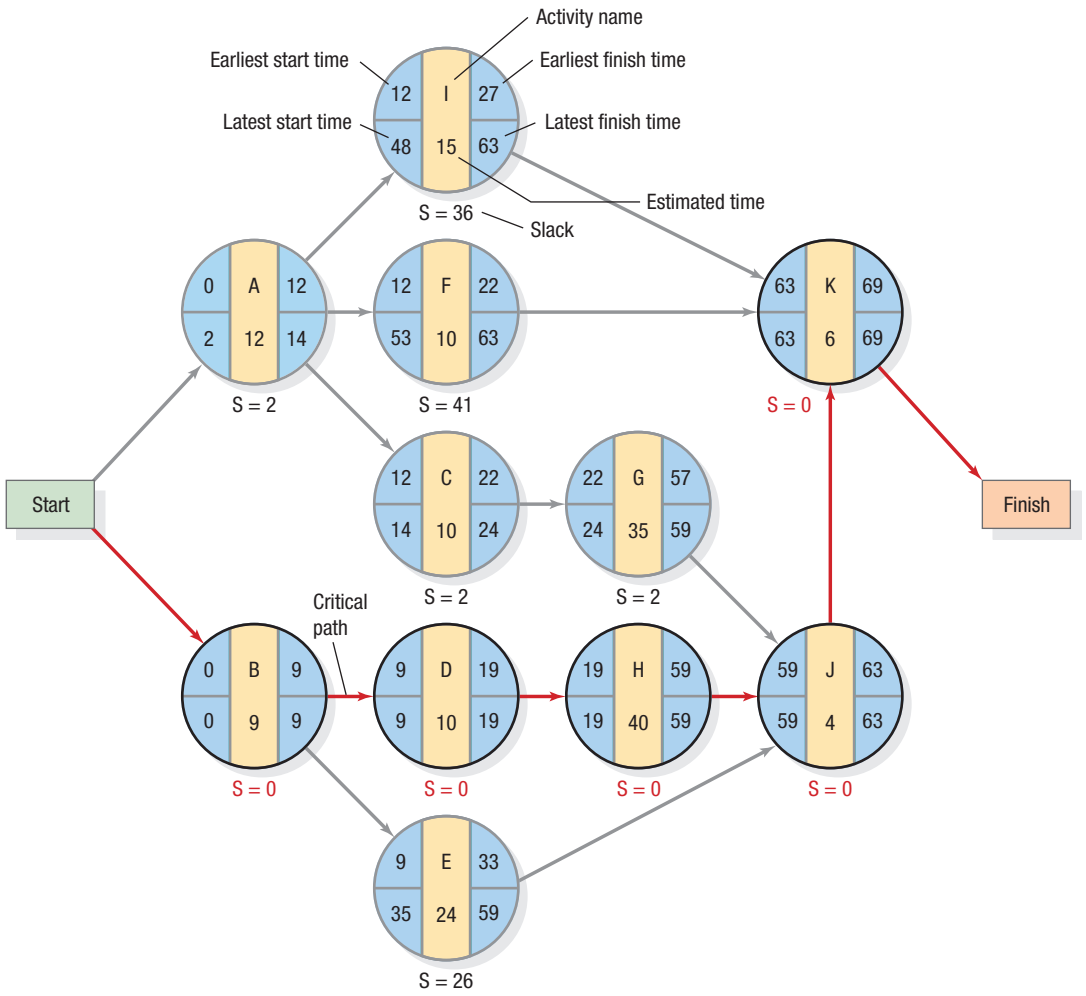


FIGURE 7.3
Network Diagram Showing Start and Finish Times and Activity Slack

If activity K is to start no later than week 63, all its predecessors must finish no later than that time. Consequently,

$$LF_I = 63,\ LF_F = 63,\ \text{and}\ LF_J = 63$$

The latest start times for these activities are shown in Figure 7.3 as

$$LS_I = 63 - 15 = 48,\ LS_F = 63 - 10 = 53,\ \text{and}\ LS_J = 63 - 4 = 59$$

After obtaining LS_J, we can calculate the latest start times for the immediate predecessors of activity J:

$$LS_G = 59 - 35 = 24,\ LS_H = 59 - 40 = 19,\ \text{and}\ LS_E = 59 - 24 = 35$$

Similarly, we can now calculate the latest start times for activities C and D:

$$LS_C = 24 - 10 = 14\ \text{and}\ LS_D = 19 - 10 = 9$$

Activity A has more than one immediately following activity: I, F, and C. The earliest of the latest start times is 14 for activity C. Thus,

$$LS_A = 14 - 12 = 2$$

Similarly, activity B has two immediate followers: D and E. Because the earliest of the latest start times of these activities is 9,

$$LS_B = 9 - 9 = 0$$

DECISION POINT

The earliest or latest start times can be used for developing a project schedule. For example, Kramer should start activity B immediately because the latest start time is zero; otherwise, the project will not be completed by week 69. When the LS is greater than the ES for an activity, that activity could be

scheduled for any date between ES and LS. Such is the case for activity E, which could be scheduled to start anytime between week 9 and week 35, depending on the availability of resources. The earliest start and earliest finish times and the latest start and latest finish times for all activities are shown in Figure 7.3.

Activity Slack

activity slack

The maximum length of time that an activity can be delayed without delaying the entire project, calculated as S = LS − ES or S = LF − EF.

The maximum length of time that an activity can be delayed without delaying the entire project is called **activity slack**. Consequently, *activities on the critical path have zero slack*. Information on slack can be useful because it highlights activities that need close attention. In this regard, activity slack is the amount of schedule slippage that can be tolerated for an activity before the entire project will be delayed. Slack at an activity is reduced when the estimated time duration of an activity is exceeded or when the scheduled start time for the activity must be delayed because of resource considerations. Activity slack can be calculated in one of two ways for any activity:

$$S = LS - ES \text{ or } S = LF - EF$$

Online Resource

Active Model 7.1 provides additional insight on Gantt charts and their uses for the St. John's Hospital project.

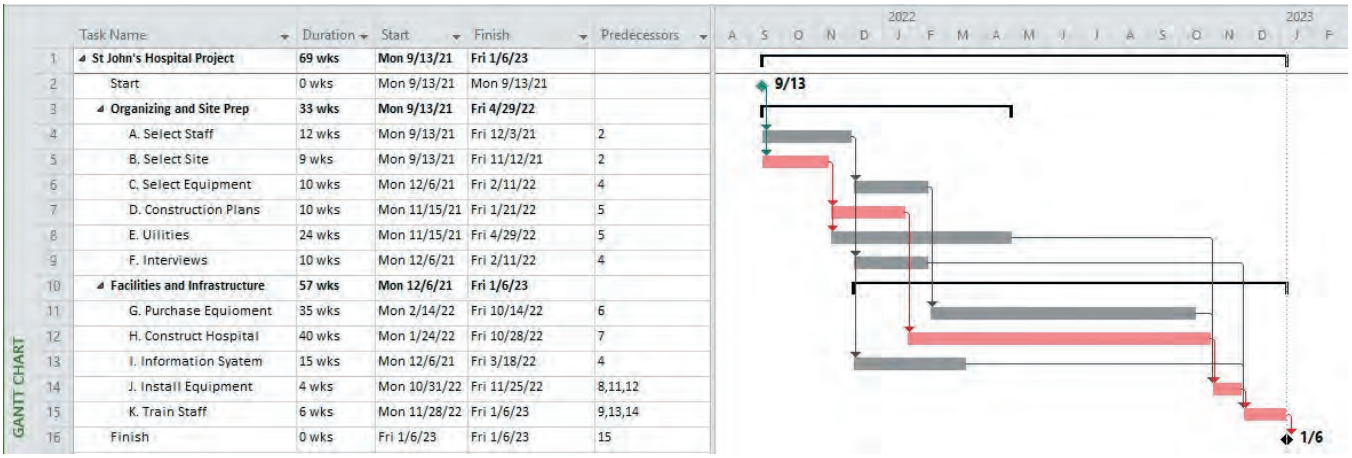
Computers calculate activity slack and prepare periodic reports for large projects, enabling managers to monitor progress. Using these reports, managers can sometimes manipulate slack to overcome scheduling problems. When resources can be used on several different activities in a project, they can be taken from activities with slack and given to activities that are behind schedule until the slack is used up. The slack for each activity in the hospital project is shown in Figure 7.3.

Gantt chart

A project schedule, usually created by the project manager using computer software, that superimposes project activities, with their precedence relationships and estimated duration times, on a time line.

Gantt Chart The project manager, often with the assistance of computer software, creates the project schedule by superimposing project activities, with their precedence relationships and estimated duration times, on a time line. The resulting diagram is called a **Gantt chart**. Figure 7.4 shows a Gantt chart for the hospital project created with Microsoft Project Professional, a popular software package for project management. The critical path is B-D-H-K, the longest path in the network (shown in red). The chart clearly shows which activities can be undertaken simultaneously and when they should be started. Figure 7.4 also shows the earliest start schedule for the project. Microsoft Project can also be used to show the latest start schedule or to change the definition of the work week to declare Saturday and Sunday as workdays, for example. Gantt charts are popular because they are intuitive and easy to construct.

▼ **FIGURE 7.4**
MS Project Gantt Chart for the St. John's Hospital Project Schedule



	Task Name	Duration	Start	Finish	Predecessors
1	St John's Hospital Project	69 wks	Mon 9/13/21	Fri 1/6/23	
2	Start	0 wks	Mon 9/13/21	Mon 9/13/21	
3	Organizing and Site Prep	33 wks	Mon 9/13/21	Fri 4/29/22	
4	A. Select Staff	12 wks	Mon 9/13/21	Fri 12/3/21	2
5	B. Select Site	9 wks	Mon 9/13/21	Fri 11/12/21	2
6	C. Select Equipment	10 wks	Mon 12/6/21	Fri 2/11/22	4
7	D. Construction Plans	10 wks	Mon 11/15/21	Fri 1/21/22	5
8	E. Utilities	24 wks	Mon 11/15/21	Fri 4/29/22	5
9	F. Interviews	10 wks	Mon 12/6/21	Fri 2/11/22	4
10	Facilities and Infrastructure	57 wks	Mon 12/6/21	Fri 1/6/23	
11	G. Purchase Equioment	35 wks	Mon 2/14/22	Fri 10/14/22	6
12	H. Construct Hospital	40 wks	Mon 1/24/22	Fri 10/28/22	7
13	I. Information Syatem	15 wks	Mon 12/6/21	Fri 3/18/22	4
14	J. Install Equipment	4 wks	Mon 10/31/22	Fri 11/25/22	8,11,12
15	K. Train Staff	6 wks	Mon 11/28/22	Fri 1/6/23	9,13,14
16	Finish	0 wks	Fri 1/6/23	Fri 1/6/23	15

Analyzing Cost–Time Trade-Offs

normal time (NT)

In the context of project management, the time necessary to complete an activity under normal conditions.

normal cost (NC)

The activity cost associated with the normal time.

Keeping costs at acceptable levels is almost always as important as meeting schedule dates. In this section, we discuss the use of PERT/CPM methods to obtain minimum-cost schedules.

The reality of project management is that there are always cost–time trade-offs. For example, a project can often be completed earlier than scheduled by hiring more workers or running extra shifts. Such actions could be advantageous if savings or additional revenues accrue from completing the project early. *Total project costs* are the sum of direct costs, indirect costs, and penalty costs. These costs are dependent either on activity times or on project completion time. *Direct costs* include labor, materials, and any other costs directly related to project activities. *Indirect costs* include administration, depreciation, financial, and other variable overhead costs that can

be avoided by reducing total project time: The shorter the duration of the project, the lower the indirect costs will be. Finally, a project may incur *penalty costs* if it extends beyond some specific date, whereas *an incentive* may be provided for early completion. Managers can shorten individual activity times by using additional direct resources, such as overtime, personnel, or equipment. Thus, a project manager may consider *crashing*, or expediting, some activities to reduce overall project completion time and total project costs.

Cost to Crash

To assess the benefit of crashing certain activities—from either a cost or a schedule perspective—the project manager needs to know the following times and costs:

1. The **normal time (NT)** is the time necessary to complete an activity under normal conditions.
2. The **normal cost (NC)** is the activity cost associated with the normal time.
3. The **crash time (CT)** is the shortest possible time to complete an activity.
4. The **crash cost (CC)** is the activity cost associated with the crash time.

Our cost analysis is based on the assumption that direct costs increase linearly as activity time is reduced from its normal time. This assumption implies that for every week the activity time is reduced, direct costs increase by a proportional amount. For example, suppose that the normal time for activity C in the hospital project is 10 weeks and is associated with a direct cost of $4,000. Also, suppose that we can crash its time to only 5 weeks at a total cost of $7,000; the net time reduction is 5 weeks at a net cost increase of $3,000. We assume that crashing activity C costs $3,000/5 = $600 per week—an assumption of linear marginal costs that is illustrated in Figure 7.5. Thus, if activity C were expedited by 2 weeks (i.e., its time reduced from 10 weeks to 8 weeks), the estimated direct costs would be $4,000 + 2($600) = $5,200. For any activity, the cost to crash an activity by 1 week is

$$\text{Cost to crash per period} = \frac{\text{CC} - \text{NC}}{\text{NT} - \text{CT}}$$

Table 7.1 contains direct cost and time data, as well as the costs of crashing per week for the activities in the hospital project.

Minimizing Costs

The objective of cost analysis is to determine the project schedule that minimizes total project costs. Suppose that project indirect costs are $8,000 per week. Suppose also that, after week 65, the Regional Hospital Board imposes on St. John's a penalty cost of $20,000 per week if the hospital is not fully operational. With a critical path completion time of 69 weeks, the hospital faces potentially large penalty costs unless the schedule is changed. For every week that the project is shortened—to week 65—the hospital saves 1 week of penalty *and* indirect costs, or $28,000. For reductions beyond week 65, the savings are only the weekly indirect costs of $8,000.

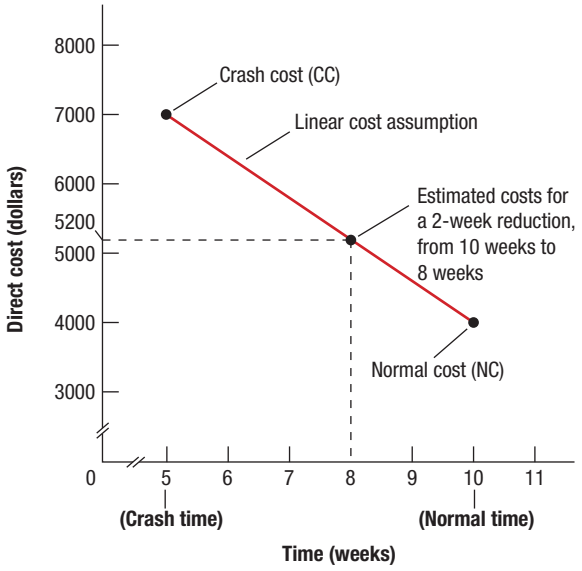
The minimum possible project duration can be found by using the crash times of each activity for scheduling purposes. However, the cost of that schedule could be prohibitive. Project managers are most interested in minimizing the costs of their projects so that budgets are not exceeded. In determining the **minimum-cost schedule**, we start with the normal time schedule and crash activities along the critical path, whose length equals the length of the project.



Xinhua / Alamy Stock Photo

People work at the construction site of the electric railway in Dire Dawa, Ethiopia. The first overseas electric railway built to Chinese standards started having its tracks laid in Dire Dawa, Ethiopia, on May 8, 2014. The railway, which will stretch 740 kilometers linking Ethiopian capital Addis Ababa with Djibouti's capital Djibouti, was inaugurated in October, 2016, with a total investment of 4 billion U.S. dollars.

▼ **FIGURE 7.5**
Cost–Time Relationships in Cost Analysis



crash time (CT)
The shortest possible time to complete an activity.

crash cost (CC)
The activity cost associated with the crash time.

minimum-cost schedule
A schedule determined by starting with the normal time schedule and crashing activities along the critical path, in such a way that the costs of crashing do not exceed the savings in indirect and penalty costs.

We want to determine how much we can add in crash costs without exceeding the savings in indirect and penalty costs. The procedure involves the following steps:

TABLE 7.1 | DIRECT COST AND TIME DATA FOR THE ST. JOHN'S HOSPITAL PROJECT

Activity	Normal Time (NT) (wks)	Normal Cost (NC) ($)	Crash Time (CT) (wks)	Crash Cost (CC) ($)	Maximum Time Reduction (wks)	Cost of Crashing per Week ($)
A	12	$12,000	11	13,000	1	1,000
B	9	50,000	7	64,000	2	7,000
C	10	4,000	5	7,000	5	600
D	10	16,000	8	20,000	2	2,000
E	24	120,000	14	200,000	10	8,000
F	10	10,000	6	16,000	4	1,500
G	35	500,000	25	530,000	10	3,000
H	40	1,200,000	35	1,260,000	5	12,000
I	15	40,000	10	52,500	5	2,500
J	4	10,000	1	13,000	3	1,000
K	6	30,000	5	34,000	1	4,000
	Totals	$1,992,000		$2,209,500		

Step 1. Determine the project's critical path(s).

Step 2. Find the activity or activities on the critical path(s) with the lowest cost of crashing per week.

Step 3. Reduce the time for this activity until (a) it cannot be further reduced, (b) another path becomes critical, or (c) the increase in direct costs exceeds the indirect and penalty cost savings that result from shortening the project. If more than one path is critical, the time for an activity on each path may have to be reduced simultaneously.

Step 4. Repeat this procedure until the increase in direct costs is larger than the savings generated by shortening the project.

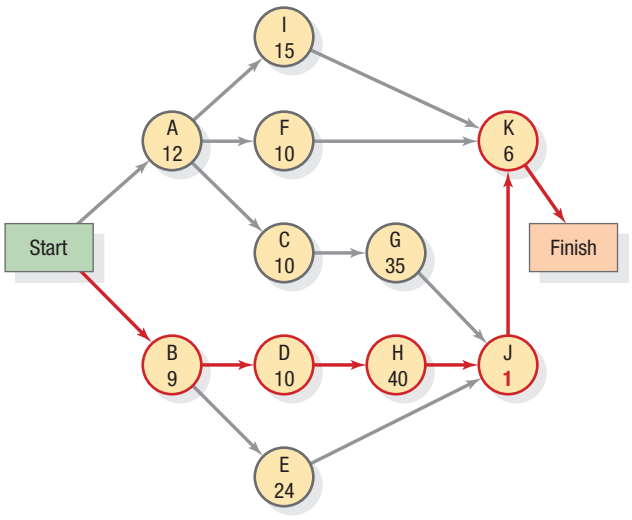
EXAMPLE 7.3 Find a Minimum-Cost Schedule

Online Resource
Active Model 7.2 provides additional insight on cost analysis for the St. John's Hospital project.

Determine the minimum-cost schedule for the St. John's Hospital project. Use the information provided in Table 7.1 and Figure 7.3.

SOLUTION

The projected completion time of the project is 69 weeks. The project costs for that schedule are $1,992,000 in direct costs, 69($8,000) = $552,000 in indirect costs, and (69 − 65)($20,000) = $80,000 in penalty costs, for total project costs of $2,624,000. The five paths in the network have the following normal times:



STAGE 1

A–I–K:	33 weeks
A–F–K:	28 weeks
A–C–G–J–K:	67 weeks
B–D–H–J–K:	69 weeks
B–E–J–K:	43 weeks

It will simplify our analysis if we can eliminate some paths from further consideration. If all activities on A–C–G–J–K were crashed, the path duration would be 47 weeks. Crashing all activities on B–D–H–J–K results in a project duration of 56 weeks. Because the *normal* times of A–I–K, A–F–K, and B–E–J–K are less than the minimum times of the other two paths, we can disregard those three paths; they will never become critical regardless of the crashing we may do.

STAGE 1

Step 1. The critical path is B–D–H–J–K.

Step 2. The cheapest activity to crash per week is J at $1,000, which is much less than the savings in indirect and penalty costs of $28,000 per week.

Step 3. Crash activity J by its limit of 3 weeks because the critical path remains unchanged. The new expected path times are

A–C–G–J–K: 64 weeks and B–D–H–J–K: 66 weeks

The net savings are 3($28,000) − 3($1,000) = $81,000. The total project costs are now $2,624,000 − $81,000 = $2,543,000.

STAGE 2

Step 1. The critical path is still B–D–H–J–K.

Step 2. The cheapest activity to crash per week is now D at $2,000.

Step 3. Crash D by 2 weeks. The first week of reduction in activity D saves $28,000 because it eliminates 1 week of penalty costs, as well as indirect costs. Crashing D by a second week saves only $8,000 in indirect costs because, after week 65, no more penalty costs are incurred. These savings still exceed the cost of crashing D for a second week. Updated path times are

A–C–G–J–K: 64 weeks and B–D–H–J–K: 64 weeks

The net savings are $28,000 + $8,000 − 2($2,000) = $32,000. Total project costs are now $2,543,000 − $32,000 = $2,511,000.

STAGE 3

Step 1. After crashing D, we now have two critical paths. *Both* critical paths must now be shortened to realize any savings in indirect project costs. If one is shortened and the other is not, the length of the project remains unchanged.

Step 2. Our alternatives are to crash one of the following combinations of activities—(A, B), (A, H), (C, B), (C, H), (G, B), (G, H)—or to crash activity K, which is on both critical paths (J has already been crashed). We consider only those alternatives for which the cost of crashing is less than the potential savings of $8,000 per week. The only viable alternatives are (C, B) at a cost of $7,600 per week and K at $4,000 per week. We choose activity K to crash.

Step 3. We crash activity K to the greatest extent possible—a reduction of 1 week—because it is on both critical paths. Updated path times are

A–C–G–J–K: 63 weeks and B–D–H–J–K: 63 weeks

The net savings are $8,000 − $4,000 = $4,000. Total project costs are $2,511,000 − $4,000 = $2,507,000.

STAGE 4

Step 1. The critical paths are B–D–H–J–K and A–C–G–J–K.

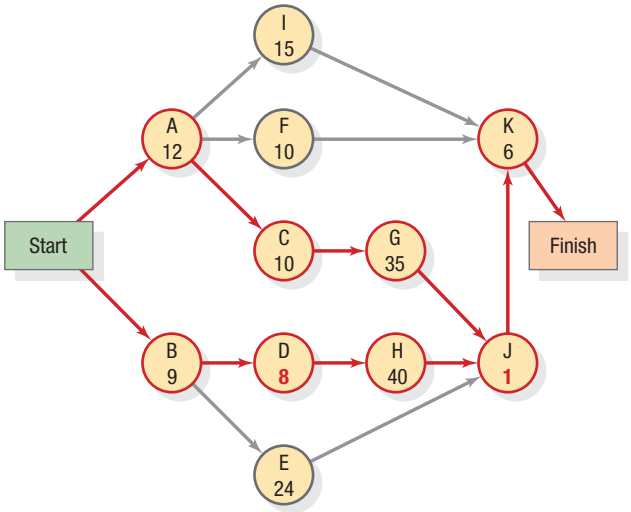
Step 2. The only viable alternative at this stage is to crash activities B and C simultaneously at a cost of $7,600 per week. This amount is still less than the savings of $8,000 per week.

Step 3. Crash activities B and C by 2 weeks, the limit for activity B. Updated path times are

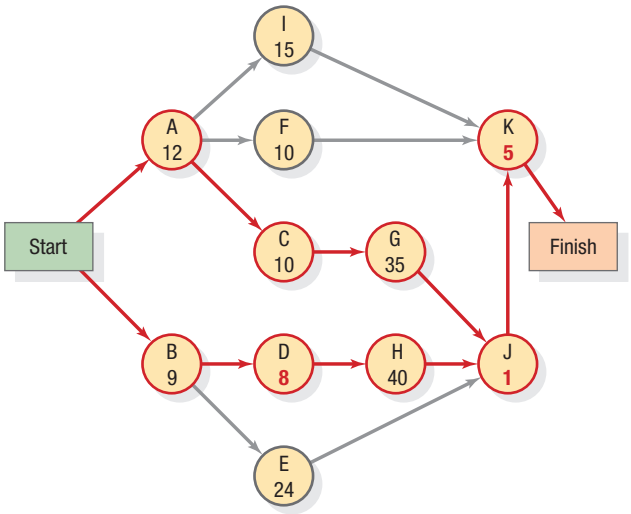
A–C–G–J–K: 61 weeks and B–D–H–J–K: 61 weeks

Net savings are 2($8,000) − 2($7,600) = $800. Total project costs are $2,507,000 − $800 = $2,506,200.

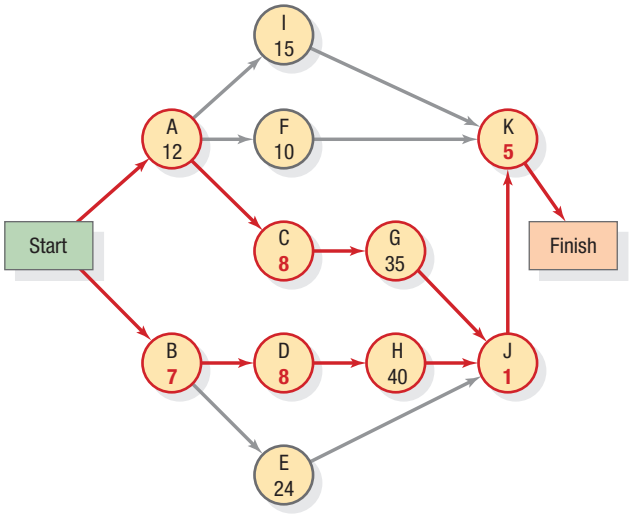
The following table summarizes the analysis.



STAGE 2



STAGE 3



STAGE 4

Stage	Crash Activity	Time Reduction (wks)	Resulting Critical Path(s)	Project Duration (wks)	Project Direct Costs, Last Trial ($000)	Crash Cost Added ($000)	Total Indirect Costs ($000)	Total Penalty Costs ($000)	Total Project Costs ($000)
0	—	—	B–D–H–J–K	69	1,992.0	—	552.0	80.0	2,624.0
1	J	3	B–D–H–J–K	66	1,992.0	3.0	528.0	20.0	2,543.0
2	D	2	B–D–H–J–K	64	1,995.0	4.0	512.0	0.0	2,511.0
			A–C–G–J–K						
3	K	1	B–D–H–J–K	63	1,999.0	4.0	504.0	0.0	2,507.0
			A–C–G–J–K						
4	B, C	2	B–D–H–J–K	61	2,003.0	15.2	488.0	0.0	2,506.2
			A–C–G–J–K						

DECISION POINT

Because the crash costs exceed weekly indirect costs, any other combination of activities will result in a net increase in total project costs. The minimum-cost schedule is 61 weeks, with a total cost of $2,506,200. To obtain this schedule, the project team must crash activities B, D, J, and K to their limits and activity C to 8 weeks. The other activities remain at their normal times. This schedule costs $117,800 less than the normal-time schedule.

Assessing and Analyzing Risks

Risk is a measure of the probability and consequence of not reaching a defined project goal. Risk involves the notion of uncertainty as it relates to project timing and costs. Often, project teams must deal with uncertainty caused by labor shortages, weather, supply delays, or the outcomes of critical tests. In this section, we discuss risk-management plans and the tools managers can use to analyze the risks, such as simulation and statistical analysis, which enable managers to estimate the probability of completing a project on time and the potential for near-critical paths to affect the project completion time.

Risk-Management Plans

risk-management plan

A plan that identifies the key risks to a project's success and prescribes ways to circumvent them.

A major responsibility of the project manager at the start of a project is to develop a **risk-management plan**, which identifies the key risks to a project's success and prescribes ways to circumvent them. A good risk-management plan will quantify the risks, predict their impact on the project, and provide contingency plans. Project risk can be assessed by examining four categories:

- **Strategic Fit** The project may not be a good strategic fit in that it may not be clearly linked to the strategic goals of the firm.
- **Service/Product Attributes** If the project involves the development of a new service or product, market, technological, or legal risks may arise. There is a chance that competitors may offer a superior product, or a technological discovery may render the service or product obsolete before it even hits the market. There may also be a legal risk of potential lawsuits or liability that could force a design change after product development has begun.
- **Project Team Capability** The project team may not have the capability to complete the project successfully because of the size and complexity of the project or the technology involved.
- **Operations** An operations risk may occur because of poor information accuracy, lack of communication, missing precedence relationships, or bad estimates for activity times.

These risks should be identified, and the significant ones should have contingency plans in case something goes wrong. The riskier a project is, the more likely the project will experience difficulties.

Simulation PERT/CPM networks can be used to quantify risks associated with project timing. Often, the uncertainty associated with an activity can be reflected in the activity's time duration. For example, an activity in a new product development project might be developing the enabling technology to manufacture it, an activity that may take from 8 months to 1 year. To incorporate uncertainty into the network model, probability distributions of activity times can be calculated using two approaches: (1) computer simulation and (2) statistical analysis. With simulation, the time for each activity is randomly chosen from its probability distribution (see online Supplement E, "Simulation"). The critical path of the network is determined, and the completion date of the project computed. The procedure is repeated many times, which results in a probability

distribution for the completion date. We will have more to say about simulation when we discuss near-critical paths later in this chapter.

Statistical Analysis

The statistical analysis approach requires that activity times be stated in terms of three reasonable time estimates:

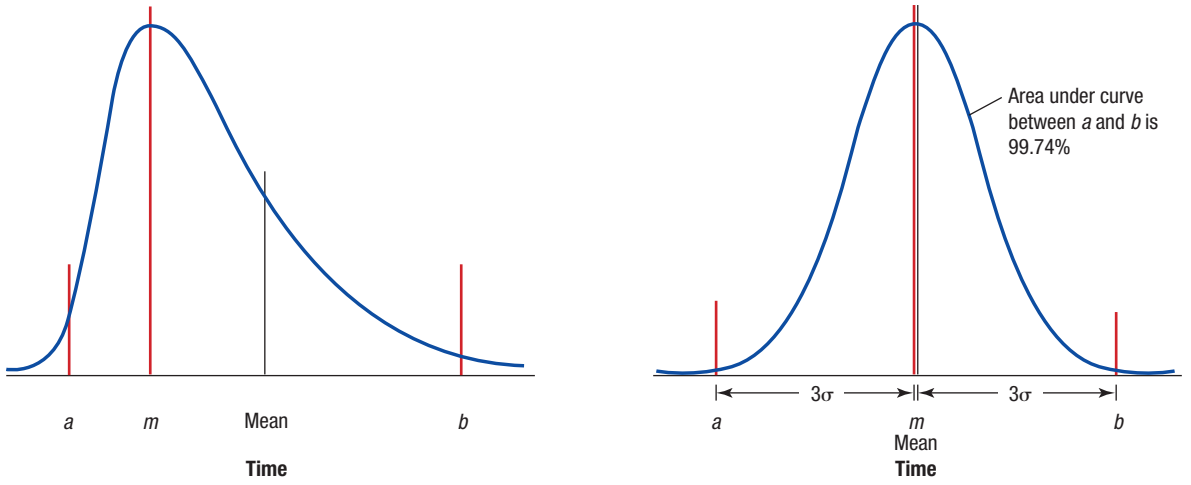
1. The **optimistic time (*a*)** is the shortest time in which an activity can be completed, if all goes exceptionally well.
2. The **most likely time (*m*)** is the probable time required to perform an activity.
3. The **pessimistic time (*b*)** is the longest estimated time required to perform an activity.

optimistic time (*a*)
The shortest time in which an activity can be completed, if all goes exceptionally well.

most likely time (*m*)
The probable time required to perform an activity.

pessimistic time (*b*)
The longest estimated time required to perform an activity.

With three time estimates—the optimistic, the most likely, and the pessimistic—the project manager has enough information to estimate the probability that an activity will be completed on schedule. To do so, the project manager must first calculate the mean and variance of a probability distribution for each activity. In PERT/CPM, each activity time is treated as though it were a random variable derived from a beta probability distribution. This distribution can have various shapes, allowing the most likely time estimate (m) to fall anywhere between the pessimistic (b) and optimistic (a) time estimates. The most likely time estimate is the *mode* of the beta distribution, or the time with the highest probability of occurrence. This condition is not possible with the normal distribution: Being symmetrical, the mode must be equidistant from the end points of the distribution. Figure 7.6 shows the difference between the two distributions.



(a) **Beta distribution:** The most likely time (m) has the highest probability and can be placed anywhere between the optimistic (a) and pessimistic (b) times.

(b) **Normal distribution:** The mean and most likely times must be the same. If a and b are chosen to be 6σ apart, there is a 99.74% chance that the actual activity time will fall between them.

▲ **FIGURE 7.6**
Differences Between Beta and Normal Distributions for Project Risk Analysis

Two key assumptions are required. First, we assume that a, m, and b can be estimated accurately. The estimates might best be considered values that define a reasonable time range for the activity duration negotiated between the project manager and the team members responsible for the activities. Second, we assume that the standard deviation, σ, of the activity time is one-sixth the range $b - a$. Thus, the chance that actual activity times will fall between a and b is high. Why does this assumption make sense? If the activity time followed the normal distribution, six standard deviations would span approximately 99.74 percent of the distribution.

Even with these assumptions, derivation of the mean and variance of each activity's probability distribution is complex. These derivations show that the mean of the beta distribution can be estimated by using the following weighted average of the three time estimates:

$$t_e = \frac{a + 4m + b}{6}$$

Note that the most likely time has four times the weight of the pessimistic and optimistic estimates.

The variance of the beta distribution for each activity is

$$\sigma^2 = \left(\frac{b - a}{6}\right)^2$$

The variance, which is the standard deviation squared, increases as the difference between b and a increases. This result implies that the less certain a person is in estimating the actual time for an activity, the greater will be the variance.

EXAMPLE 7.4 **Calculating Means and Variances**

Suppose that the project team has arrived at the following time estimates for activity B (Select Site and Survey) of the St. John's Hospital project:

$$a = 7 \text{ weeks}, m = 8 \text{ weeks}, \text{ and } b = 15 \text{ weeks}$$

a. Calculate the expected time and variance for activity B.

b. Calculate the expected time and variance for the other activities in the project.

SOLUTION

a. The expected time for activity B is

$$t_e = \frac{7 + 4(8) + 15}{6} = \frac{54}{6} = 9 \text{ weeks}$$

Note that the expected time (9 weeks) does not equal the most likely time (8 weeks) for this activity. These times will be the same only when the most likely time is equidistant from the optimistic and pessimistic times. We calculate the variance for activity B as

$$\sigma^2 = \left(\frac{15 - 7}{6}\right)^2 = \left(\frac{8}{6}\right)^2 = 1.78$$

b. The following table shows expected activity times and variances for the activities listed in the project description.

	TIME ESTIMATES (WKS)			ACTIVITY STATISTICS	
Activity	Optimistic (a)	Most Likely (m)	Pessimistic (b)	Expected Time (t_e)	Variance (σ^2)
A	11	12	13	12	0.11
B	7	8	15	9	1.78
C	5	10	15	10	2.78
D	8	9	16	10	1.78
E	14	25	30	24	7.11
F	6	9	18	10	4.00
G	25	36	41	35	7.11
H	35	40	45	40	2.78
I	10	13	28	15	9.00
J	1	2	15	4	5.44
K	5	6	7	6	0.11

DECISION POINT

The project team should notice that the greatest uncertainty lies in the time estimate for activity I, followed by the estimates for activities E and G. These activities should be analyzed for the source of the uncertainties, and actions should be taken to reduce the variance in the time estimates.

Analyzing Probabilities

Because time estimates for activities involve uncertainty, project managers are interested in determining the probability of meeting project completion deadlines. To develop the probability distribution for project completion time, we assume that the duration time of one activity does not depend on that of any other activity. This assumption enables us to estimate the mean and variance of the probability distribution of the time duration of the entire project by summing the duration times and variances of the activities along the critical path. However, if one work crew is assigned two activities that can be done at the same time, the activity times will be interdependent and the assumption is not valid. In addition, if other paths in the network have small amounts of slack, one of them might become the critical path before the project is completed; we should calculate a probability distribution for those paths as well.

Because of the assumption that the activity duration times are independent random variables, we can make use of the central limit theorem, which states that the sum of a group of independent, identically distributed random variables approaches a normal distribution as the number of random variables increases. The mean of the normal distribution is the sum of the expected activity times on the path. In the case of the critical path, it is the earliest expected finish time for the project:

$$T_E = \sum(\text{Expected activity times on the critical path}) = \text{Mean of normal distribution}$$

Similarly, because of the assumption of activity time independence, we use the sum of the variances of the activities along the path as the variance of the time distribution for that path. That is, for the critical path,

$$\sigma_P^2 = \sum(\text{Variances of activities on the critical path})$$

To analyze probabilities of completing a project by a certain date using the normal distribution, we focus on the *critical path* and use the *z*-transformation formula:

$$z = \frac{T - T_E}{\sigma_P}$$

where

$$T = \text{due date for the project}$$

Given the value of z, we use the Normal Distribution appendix to find the probability that the project will be completed by time T, or sooner. An implicit assumption in this approach is that no other path will become critical during the time span of the project. Example 7.5, part (a), demonstrates this calculation for the St. John's Hospital project.

The procedure for assessing the probability of completing any activity in a project by a specific date is similar to the one just discussed. However, instead of the critical path, we would use the longest time path of activities from the start node to the activity node in question.

Near-Critical Paths

A project's duration is a function of its critical path. However, paths that are close to the same duration as the critical path may ultimately become the critical path over the life of the project. In practice, at the start of the project, managers typically do not know the activity times with certainty and may never know which path was the critical path until the actual activity times are known at the end of the project. Nonetheless, this uncertainty does not reduce the usefulness of identifying the probability of one path or another causing a project to exceed its target completion time; it helps to identify the activities that need close management attention. To assess the chances of near-critical paths delaying the project completion, we can focus on the longest paths in the project network, keeping in mind that both duration and variance along the path must be considered. Shorter paths with high variances could have just as much a chance to delay the project as longer paths with smaller variances. We can then estimate the probability that a given path will exceed the project target completion time. We demonstrate that approach using statistical analysis in Example 7.5, part (b).

Alternatively, simulation can be used to estimate the probabilities. The advantage of simulation is that you are not restricted to the use of the beta distribution for activity times. Also, activity or path dependencies, such as decision points that could involve different groups of activities to be undertaken, can be incorporated in a simulation model much more easily than with the statistical analysis approach. Fortunately, regardless of the approach used, it is rarely necessary to evaluate every path in the network. In large networks, many paths will have both short durations and low variances, making them unlikely to affect the project duration.

EXAMPLE 7.5 Calculating the Probability of Completing a Project by a Given Date

Calculate the probability that St. John's Hospital will become operational in 72 weeks, using (a) the critical path and (b) near-critical path A–C–G–J–K.

Online Resource

Active Model 7.3 provides additional insight on probability analysis for the St. John's Hospital project.

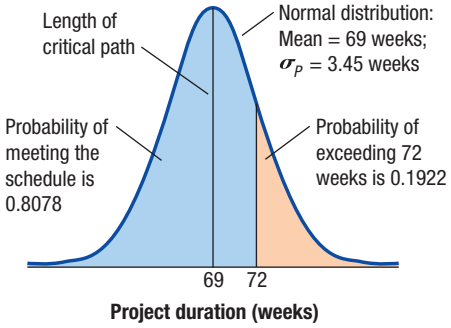
SOLUTION

a. The critical path B–D–H–J–K has a length of 69 weeks. From the table in Example 7.4, we obtain the variance of path B–D–H–J–K: $\sigma_P^2 = 1.78 + 1.78 + 2.78 + 5.44 + 0.11 = 11.89$. Next, we calculate the *z*-value:

$$z = \frac{72 - 69}{\sqrt{11.89}} = \frac{3}{3.45} = 0.87$$

Using the Normal Distribution appendix, we go down the left-hand column until we arrive at the value 0.8 and then across until we arrive at the 0.07 column, which shows a tabular value of 0.8078. Consequently, we find that the probability is about 0.81 that the length of path B–D–H–J–K will be no greater than 72 weeks. Because this path is the critical path, there is a 19 percent probability that the project will take longer than 72 weeks. This probability is shown graphically in Figure 7.7.

▼ FIGURE 7.7
Probability of Completing the St. John's Hospital Project on Schedule



b. From the table in Example 7.4, we determine that the sum of the expected activity times on path A–C–G–J–K is 67 weeks and that $\sigma_P^2 = 0.11 + 2.78 + 7.11 + 5.44 + 0.11 = 15.55$. The z-value is

$$z = \frac{72 - 67}{\sqrt{15.55}} = \frac{5}{3.94} = 1.27$$

The probability is about 0.90 that the length of path A–C–G–J–K will be no greater than 72 weeks.

DECISION POINT

The project team should be aware of the 10 percent chance that path A–C–G–J–K will exceed the target completion date of week 72. Although the probability is not high for that path, activities A, C, and G bear watching during the first 57 weeks of the project to make sure no more than 2 weeks of slippage occurs in their schedules. This attention is especially important for activity G, which has a high time variance.

Risk Caused by Changing Requirements: Scrum

Scrum
An agile project management framework that focuses on allowing teams to respond rapidly, efficiently, and effectively to change.

Uncertainty in activity times or costs can certainly create angst on the part of project managers, however uncertainty in the project *requirements* is at another level. Such uncertainty arises in product development projects, such as software products, which have a number of functionalities that must be created. The project team must be agile in order to deal with unexpected changes in their assigned activities. **Scrum** is an agile project management framework that focuses on allowing teams to respond rapidly, efficiently, and effectively to change. Traditional project management methods, which we have presented in this chapter, fix project requirements (scope) in an effort to manage time and cost. The Cleveland Clinic project in Managerial Practice 7.1 is an example of a project suitable for the traditional approach. It is large and complex, involves many work teams, has requirements that are clearly defined at the start, emphasizes the sequentiality of phases, and has a project manager who has overall responsibility. Scrum, however, fixes time and cost in an effort to manage requirements, which are the product's features. The development of a software package is an example of a project well-suited for Scrum. It is small or medium scale, involves a small team with multiple skills such as developer, designer, and database administrator, has a set of functional product requirements that are subject to change throughout the project, has steps known in advance that do not have to be done in a sequential manner, and allows the team to make decisions as to how to build the product.

There are three roles in Scrum known as the Scrum Team: The ScrumMaster, who facilitates team communication, removes obstacles to progress, and negotiates with those external to the team; the Product Owner, who has authority to make decisions about the product and prioritize its features; and the Development Team, which consists of a small multifunctional group of people who are responsible for the delivery of the product. The Development Team estimates the time to accomplish the tasks, assigns ownership of tasks, and has daily meetings called the Daily Scrum, which takes its name from rugby where teams form a circle and try to get the ball back into play. The Development Team is self-organizing and chooses how it will build the features of the product.

The project begins by formalizing a set of product features or product changes and putting them in a Product Backlog in order of importance. The Development Team, in conjunction with the Product Owner and ScrumMaster, selects a time box, called a *sprint*, usually one to four weeks, and then selects product features from the Product Backlog it thinks it can complete within the sprint. Daily scrums iron out problems and convey project status. At the end of the sprint the Team demos the work it has completed to the Product Owner, selects new features from the product Backlog along with those left unfinished from the last sprint, and begins the next sprint. Over the life of the project, features can be added or removed from the Product Backlog, which emphasizes the need to have an agile approach to project management.

Choosing the best approach for a project must be done with care because each approach comes with its shortcomings. With the traditional approach, it is hard to adapt quickly to shifting environments and requirements because problems at the operating level must be sent up stream to managers for resolution, making it difficult to overcome budgetary and timeline issues before they cause real harm. Client involvement is restricted to the early stages and any changes later on causes backtracking and waste. A sudden change to requirements can bring the whole project to a halt. Scrum, on the other hand, also has its drawbacks. The organization must be committed to an agile management style, which may strip authority from some people.

Due to its incremental and quick-change nature, it can make coordinating large projects more complex. Finally, scrum loses it effectiveness when the customer is not actively engaged. Changes to requirements, problems in development, and progress must be consistently conveyed between all parties. In summary, when choosing between the traditional approach and Scrum, be sure to consider project complexity, organizational infrastructure, corporate culture, and leadership style.[3]

Monitoring and Controlling Projects

Once project planning is over, the challenge becomes keeping the project on schedule within the budget of allocated resources. In this section, we discuss how to monitor project status and resource usage. In addition, we identify the features of project management software useful for monitoring and controlling projects.

Monitoring Project Status

A good tracking system will help the project team accomplish its project goals. Effective tracking systems collect information on three topics: (1) open issues, (2) risks, and (3) schedule status.

Open Issues and Risks One of the duties of the project manager is to make sure that issues raised during the project, referred to as open issues, actually get resolved in a timely fashion. The tracking system should remind the project manager of due dates for open issues and who was responsible for seeing that they are resolved. Likewise, it should provide the status of each risk to project delays specified in the risk-management plan so that the team can review them at each meeting. To be effective, the tracking system requires team members to update information periodically regarding their respective responsibilities.

Schedule Status Even the best laid project plans can go awry. A tracking system that provides periodic monitoring of slack time in the project schedule can help the project manager control activities along the critical path. Periodic updating of the status of ongoing activities in the project allows the tracking system to recalculate activity slacks and indicate those activities that are behind schedule or are in danger of using up all of their slack. Managers can then focus on those activities and reallocate resources as needed.



Boeing via NASA

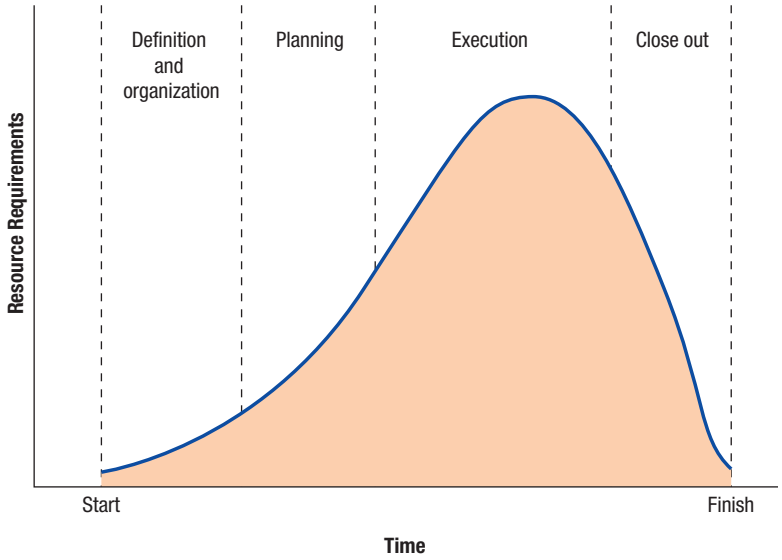
An engineer guides the upper dome of a Boeing CST-100 Starliner as it is connected to the lower dome to complete the first hull of the Starliner's Structural Test Article (STA), a prototype spacecraft that is identical to the operational versions but not meant to fly in space. The work was performed inside the Commercial Crew and Cargo Processing Facility at NASA's Kennedy Space Center in Florida. The STA is built to endure harsh tests mimicking conditions of spaceflight to prove the design and its manufacturing techniques will work for space-bound Starliners. Monitoring and controlling complex projects is critical to keeping them on schedule.

Monitoring Project Resources

Experience has shown that the resources allocated to a project are consumed at an uneven rate that is a function of the timing of the schedules for the project's activities. Projects have a *life cycle* that consists of four major phases: (1) definition and organization, (2) planning, (3) execution, and (4) closeout. Figure 7.8 shows that each of the four phases requires different resource commitments.

We have already discussed the activities associated with the project definition and organization and project planning phases. The phase that takes the most resources is the *execution phase*, during which managers focus on activities pertaining to deliverables. The project schedule becomes very important because it shows when each resource devoted to a given activity will be required. Monitoring the progress of activities throughout the project is important to avoid potential overloading of resources. Problems arise when a specific resource, such as a construction crew or staff specialist, is required on several activities with overlapping schedules.

[3]Additional information on Scrum can be found at the following sources: Sliger, M. "Agile Project Management with Scrum," Paper presented at PMI Global Congress 2011 – North America, Dallas, TX. Newton Square, PA: Project Management Institute (October 22, 2011). Schwaber, Ken. "Agile Project Management with Scrum," *Microsoft Press* (2004); "Agile project Management vs. Traditional Project Management," https://www.vivifyscrum.com/insights/agile-project=management-vs-traditional-project-management, (April 17, 2019).



▲ **FIGURE 7.8**
Project Life Cycle

Project managers have several options to alleviate resource problems, including the following:

- *Resource Leveling.* The attempt to reduce the peaks and valleys in resource needs by shifting the schedules of conflicting activities within their earliest and latest start dates. Software packages such as MS Project Professional have algorithms that move activities to avoid violating resource constraints.
- *Resource Allocation.* The assignment of resources to the most important activities. Most popular project management software packages have a few priority rules that can be used to decide which activity a critical resource should be scheduled to perform when conflicts arise. For example, for all the activities requiring a given resource, assign the resource to the one with the earliest start time. An activity slack report identifies potential candidates for resource shifting—shift resources from high slack activities to those behind schedule.
- *Resource Acquisition.* The addition of more of an overloaded resource to maintain the schedule of an activity. Obviously, this tactic is constrained by the project budget.

Controlling Projects

Project managers have the responsibilities of accounting for the effective use of the firm's resources as well as managing the activities to achieve the time and quality goals of the project. The firm's assets include the physical assets, human resources, and financial resources. Physical assets are controlled by the timely maintenance of machines and equipment so that their failure does not delay the project. Inventories must be received, stored for future use, and replenished. Project managers are also responsible for human resource development. Projects provide a rich environment to develop future leaders; project managers can take advantage of the situation by assigning team members important activities to aid in their managerial development. Last, but not least, project managers must control the expenditures of the firm's financial resources. Most project management software packages contain accounting reports, budget reports, capital investment controls, and cash flow reports. Deviations from the project plan, often referred to as variances, must be periodically reported and analyzed for their causes.

closeout
An activity that includes writing final reports, completing remaining deliverables, and compiling the team's recommendations for improving the project process.

Monitoring and controlling projects are ongoing activities throughout the execution phase of the project life cycle. The project **closeout**, however, is an activity that many project managers forget to include in their consideration of resource usage. The purpose of this final phase in the project life cycle is to write final reports and complete remaining deliverables. A key ingredient of the report should be a thorough analysis of the achievement of the iron triangle goals: on time, within budget, and meet the specifications of the project to the satisfaction of the customer. An important aspect of this phase, however, is compiling the team's recommendations for improving the project process of which they were a part. Many team members will be assigned to other projects in which they can apply what they learned.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
7.1 Explain the major activities associated with defining and organizing a project.	Read the opener to the chapter, which shows the four major phases of the project to build the Burj Khalifa tower, the introduction to the chapter, and the section "Defining and Organizing Projects."	
7.2 Describe the procedure for constructing a project network.	Focus on the section "Constructing Project Networks," paying close attention to Example 7.1.	**SmartDraw**—Free trial
7.3 Develop the schedule of a project.	Review the section "Developing the Project Schedule." The schedule is determined when activity slacks and the critical path are computed. Focus on Example 7.2 and Figure 7.3.	**Active Model Exercise:** 7.1: Gantt Chart **OME Solver:** Single Time Estimates **POM for Windows:** Single Time Estimates **Supplement H:** Measuring Output Rates **Supplement I:** Learning Curve Analysis

Learning Objective	Guidelines for Review	Online Resources
7.4 Analyze cost–time trade-offs in a project network.	The section "Analyzing Cost–Time Trade-offs" and Example 7.3 demonstrate how the relevant costs must be considered to minimize costs. Figure 7.5 explains a key assumption in the analysis. Solved Problem 1 contains a detailed solution.	**Active Model Exercise:** 7.2: Cost Analysis **POM for Windows:** Crashing
7.5 Assess the risk of missing a project deadline.	See the section "Assessing and Analyzing Risks," which explains the risks faced by project managers and how to compute the probabilities. Be sure to understand Examples 7.4 and 7.5 and Solved Problem 2.	**Active Model Exercise:** 7.3: Probability Analysis **OME Solver:** Three Time Estimates **POM for Windows:** Triple Time Estimates; Mean/Standard Deviation Given **Simquick Simulation Exercise:** Software Development Company **Supplement E:** Simulation
7.6 Identify the options available to monitor and control projects.	See the section "Monitoring and Controlling Projects."	**OME Solver:** Project Budgeting **POM for Windows:** Cost Budgeting

Key Equations

Developing the Project Schedule

1. Start and finish times:

t = estimated time duration of the activity

ES = latest of the EF times of all activities immediately preceding activity

EF = ES + t

LF = earliest of the LS times of all activities immediately following activity

LS = LF − t

2. Activity slack:

$$\text{S} = \text{LS} - \text{ES} \quad \text{or} \quad \text{S} = \text{LF} - \text{EF}$$

Analyzing Cost–Time Trade-offs

3. Project costs:

$$\text{Crash cost per period} = \frac{\text{Crash cost} - \text{Normal cost}}{\text{Normal time} - \text{Crash time}}$$

$$= \frac{\text{CC} - \text{NC}}{\text{NT} - \text{CT}}$$

Assessing and Analyzing Risks

4. Activity time statistics:

t_e = mean of an activity's beta distribution

$$t_e = \frac{a + 4m + b}{6}$$

σ^2 = variance of the activity time

$$\sigma^2 = \left(\frac{b - a}{6}\right)^2$$

5. z-transformation formula:

$$z = \frac{T - T_E}{\sigma_P}$$

where

T = due date for the project

T_E = $\sum$(expected activity times on the critical path)

= mean of normal distribution of critical path time

σ_P = standard deviation of critical path time distribution

Key Terms

activity 278
activity slack 286
closeout 296
crash cost (CC) 287
crash time (CT) 287
critical path 283
critical path method (CPM) 280
earliest finish time (EF) 283
earliest start time (ES) 283
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precedence relationship 280
program 276
program evaluation and review technique (PERT) 280
project 276
project management 276
risk-management plan 290
Scrum 294
work breakdown structure (WBS) 278

Solved Problem 1

Your company has just received an order from a good customer for a specially designed electric motor. The contract states that, starting on the 13th day from now, your firm will experience a penalty of $100 per day until the job is completed. Indirect project costs amount to $200 per day. The data on direct costs and activity precedence relationships are given in Table 7.2.

TABLE 7.2 | ELECTRIC MOTOR PROJECT DATA

Activity	Normal Time (days)	Normal Cost ($)	Crash Time (days)	Crash Cost ($)	Immediate Predecessor(s)
A	4	1,000	3	1,300	None
B	7	1,400	4	2,000	None
C	5	2,000	4	2,700	None
D	6	1,200	5	1,400	A
E	3	900	2	1,100	B
F	11	2,500	6	3,750	C
G	4	800	3	1,450	D, E
H	3	300	1	500	F, G

a. Draw the project network diagram.
b. What completion date would you recommend?

SOLUTION

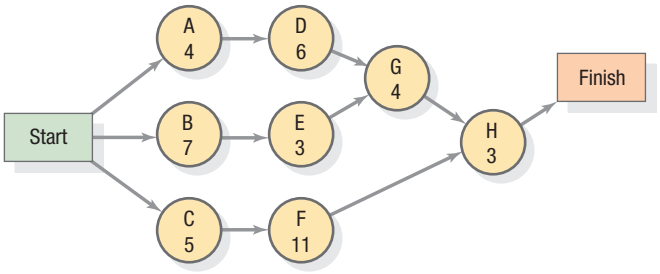
a. The network diagram, including normal activity times, for this procedure is shown in Figure 7.9. Keep the following points in mind while constructing a network diagram.

1. Always have start and finish nodes.
2. Try to avoid crossing paths to keep the diagram simple.
3. Use only one arrow to directly connect any two nodes.
4. Put the activities with no predecessors at the left and point the arrows from left to right.
5. Be prepared to revise the diagram several times before you come up with a correct and uncluttered diagram.

b. With these activity durations, the project will be completed in 19 days and incur a $700 penalty. Determining a good completion date requires the use of the minimum-cost schedule procedure. Using the data provided in Table 7.2, you can determine the maximum crash-time reduction and crash cost per day for each activity. For example, for activity A:

$$\begin{aligned}\text{Maximum crash time} &= \text{Normal time} - \text{Crash time}\\ &= 4 \text{ days} - 3 \text{ days} = 1 \text{ day}\end{aligned}$$

$$\text{Crash cost per day} = \frac{\text{Crash cost} - \text{Normal cost}}{\text{Normal time} - \text{Crash time}}$$
$$= \frac{\text{CC} - \text{NC}}{\text{NT} - \text{CT}}$$
$$= \frac{\$1{,}300 - \$1{,}000}{4 \text{ days} - 3 \text{ days}} = \$300$$



◀ **FIGURE 7.9**
Network Diagram for the Electric Motor Project

Activity	Crash Cost per Day ($)	Maximum Time Reduction (days)
A	300	1
B	200	3
C	700	1
D	200	1
E	200	1
F	250	5
G	650	1
H	100	2

Table 7.3 summarizes the analysis and the resultant project duration and total cost. The critical path is C–F–H at 19 days, which is the longest path in the network. The cheapest of these activities to crash is H, which costs only an extra $100 per day to crash. Doing so saves $200 + $100 = $300 per day in indirect and penalty costs. If you crash this activity for 2 days (the maximum), the lengths of the paths are now

A−D−G−H: 15 days, B−E−G−H: 15 days, and C−F−H: 17 days

The critical path is still C–F–H. The next cheapest critical activity to crash is F at $250 per day. You can crash F only 2 days because at that point you will have three critical paths. Further reductions in project duration will require simultaneous crashing of more than one activity (D, E, and F). The cost to do so, $650, exceeds the savings, $300. Consequently, you should stop. Note that every activity is critical. The project costs are minimized when the completion date is day 15. However, some goodwill costs may be associated with disappointing a customer who wants delivery in 12 days.

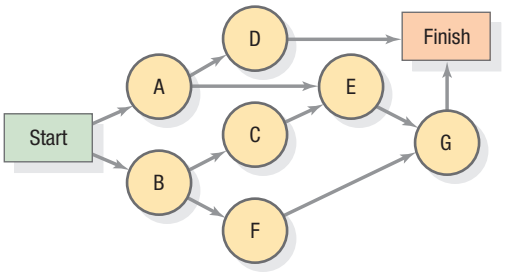
TABLE 7.3 | PROJECT COST ANALYSIS

Stage	Crash Activity	Time Reduction (days)	Resulting Critical Path(s)	Project Duration (days)	Project Direct Costs, Last Trial ($)	Crash Cost Added ($)	Total Indirect Costs ($)	Total Penalty Costs ($)	Total Project Costs ($)
0	—	—	C–F–H	19	10,100	—	3,800	700	14,600
1	H	2	C–F–H	17	10,100	200	3,400	500	14,200
2	F	2	A–D–G–H	15	10,300	500	3,000	300	14,100
			B–E–G–H						
			C–F–H						

Solved Problem 2

An advertising project manager developed the network diagram shown in Figure 7.10 for a new advertising campaign. In addition, the manager gathered the time information for each activity, as shown in the accompanying table.

	TIME ESTIMATES (WKS)			
Activity	**Optimistic**	**Most Likely**	**Pessimistic**	**Immediate Predecessor(s)**
A	1	4	7	—
B	2	6	7	—
C	3	3	6	B
D	6	13	14	A
E	3	6	12	A, C
F	6	8	16	B
G	1	5	6	E, F



▲ **FIGURE 7.10**
Network Diagram for the Advertising Project

a. Calculate the expected time and variance for each activity.
b. Calculate the activity slacks and determine the critical path, using the expected activity times.
c. What is the probability of completing the project within 23 weeks?

SOLUTION

a. The expected time and variance for each activity are calculated as follows:

$$t_e = \frac{a + 4m + b}{6}$$

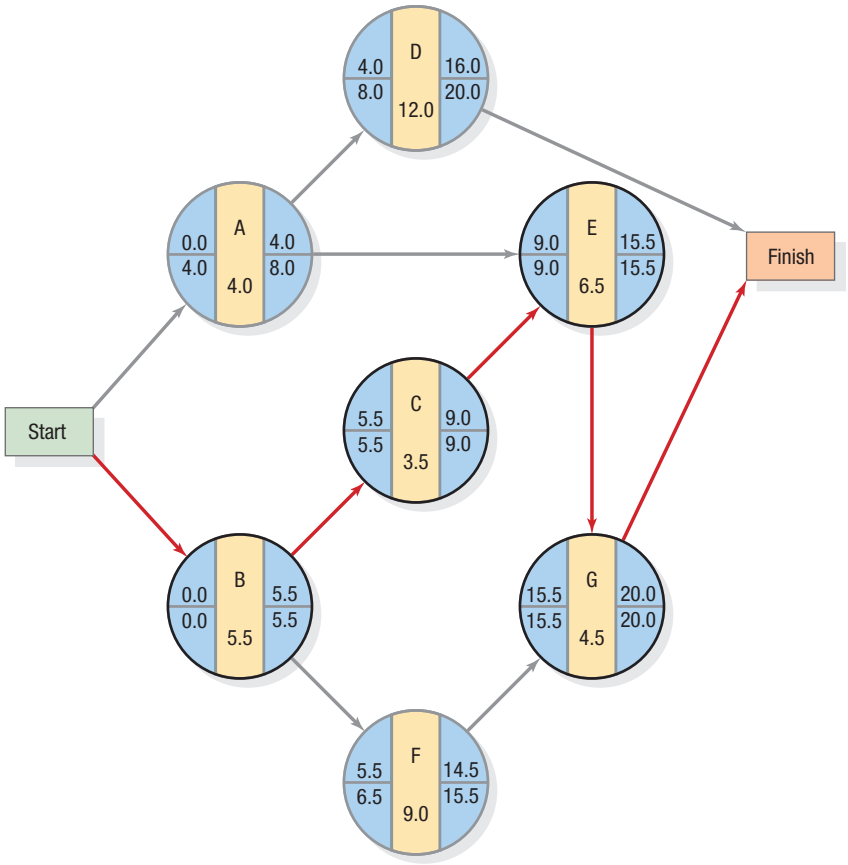
Activity	**Expected Time (wks)**	**Variance (σ^2)**
A	4.0	1.00
B	5.5	0.69
C	3.5	0.25
D	12.0	1.78
E	6.5	2.25
F	9.0	2.78
G	4.5	0.69

b. We need to calculate the earliest start, latest start, earliest finish, and latest finish times for each activity. Starting with activities A and B, we proceed from the beginning of the network and move to the end, calculating the earliest start and finish times:

Activity	**Earliest Start (wks)**	**Earliest Finish (wks)**
A	0	0 + 4.0 = 4.0
B	0	0 + 5.5 = 5.5
C	5.5	5.5 + 3.5 = 9.0
D	4.0	4.0 + 12.0 = 16.0
E	9.0	9.0 + 6.5 = 15.5
F	5.5	5.5 + 9.0 = 14.5
G	15.5	15.5 + 4.5 = 20.0

Based on expected times, the earliest finish for the project is week 20, when activity G has been completed. Using that as a target date, we can work backward through the network, calculating the latest start and finish times (shown graphically in Figure 7.11):

Activity	Latest Start (wks)	Latest Finish (wks)
G	15.5	20.0
F	6.5	15.5
E	9.0	15.5
D	8.0	20.0
C	5.5	9.0
B	0.0	5.5
A	4.0	8.0



◀ **FIGURE 7.11**
Network Diagram with All Time Estimates Needed to Compute Slack

We now calculate the activity slacks and determine which activities are on the critical path:

	START (WKS)		FINISH (WKS)			
Activity	Earliest	Latest	Earliest	Latest	Slack	Critical Activity
A	0.0	4.0	4.0	8.0	4.0	No
B	0.0	0.0	5.5	5.5	0.0	Yes
C	5.5	5.5	9.0	9.0	0.0	Yes
D	4.0	8.0	16.0	20.0	4.0	No
E	9.0	9.0	15.5	15.5	0.0	Yes
F	5.5	6.5	14.5	15.5	1.0	No
G	15.5	15.5	20.0	20.0	0.0	Yes

The paths, and their total expected times and variances, are

Path	Total Expected Time (wks)	Total Variance (σ_P^2)
A–D	4 + 12 = 16	1.00 + 1.78 = 2.78
A–E–G	4 + 6.5 + 4.5 = 15	1.00 + 2.25 + 0.69 = 3.94
B–C–E–G	5.5 + 3.5 + 6.5 + 4.5 = 20	0.69 + 0.25 + 2.25 + 0.69 = 3.88
B–F–G	5.5 + 9 + 4.5 = 19	0.69 + 2.78 + 0.69 = 4.16

The critical path is B–C–E–G, with a total expected time of 20 weeks. However, path B–F–G is 19 weeks and has a large variance.

c. We first calculate the z-value:

$$z = \frac{T - T_E}{\sigma_P} = \frac{23 - 20}{\sqrt{3.88}} = 1.52$$

Using the Normal Distribution appendix, we find that the probability of completing the project in 23 weeks or fewer is 0.9357. Because the length of path B–F–G is close to that of the critical path and has a large variance, it might well become the critical path during the project.

Discussion Questions

1. One of your colleagues comments that software is the ultimate key to project management success. How would you respond?
2. Explain how to determine the slack for each activity in a project. Why is it important for managers to know where the slack is in their projects?
3. Risk is a measure of the probability and consequence of not reaching a defined project goal. Assume you are the project manager for a construction project. Identify the major risks to the project's success and prescribe ways to circumvent them.

Problems

The OM Explorer and POM for Windows software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations.

Developing the Project Schedule

1. Consider the following data for a project to install a new server at the Northland Pines High School.

Activity	Activity Time (days)	Immediate Predecessor(s)
A	2	—
B	4	A
C	5	A
D	2	B
E	1	B
F	8	B, C
G	3	D, E
H	5	F
I	4	F
J	7	G, H, I

   a. Draw the network diagram.

   b. Calculate the critical path for this project.

   c. How much slack is in each of the activities G, H, and I?

2. The following information is known about a project to upgrade a point-of-sale system at Kids and Tots Apparel.

Activity	Activity Time (days)	Immediate Predecessor(s)
A	7	—
B	2	A
C	4	A
D	4	B, C
E	4	D
F	3	E
G	5	E

a. Draw the network diagram for this project.

b. Determine the critical path and project duration.

c. Calculate the slack for each activity.

3. A project for improving a billing process has the following precedence relationships and activity times.

Activity	Activity Time (wks)	Immediate Predecessor(s)
A	3	—
B	11	—
C	7	A
D	13	B, C
E	10	B
F	6	D
G	5	E
H	8	F, G

a. Draw the network diagram.

b. Calculate the slack for each activity. Which activities are on the critical path?

4. The following information is available about a project to organize an event to honor the mayor of West Allis at the Nathan Hale High School.

Activity	Activity Time (days)	Immediate Predecessor(s)
A	3	—
B	4	—
C	5	—
D	4	—
E	7	A
F	2	B, C, D
G	4	E, F
H	6	F
I	4	G
J	3	G
K	3	H

a. Draw the network diagram.

b. Find the critical path.

5. The following information has been gathered for a project to install a new machine lathe at Diamond Manufacturing, Inc.

Activity	Activity Time (wks)	Immediate Predecessor(s)
A	4	—
B	7	A
C	9	B
D	3	B
E	14	D
F	10	C, D
G	11	F, E

a. Draw the network diagram.

b. Calculate the slack for each activity and determine the critical path. How long will the project take?

6. Consider the following information for a project to add a drive-through window at Crestview Bank.

Activity	Activity Time (wks)	Immediate Predecessor(s)
A	5	—
B	2	—
C	6	—
D	2	A, B
E	7	B
F	3	D, C
G	9	E, C
H	11	F, G

a. Draw the network diagram for this project.

b. Specify the critical path.

c. Calculate the slack for activities A and D.

7. Consider the following data for a project to reorganize the office space at Platinum Financial Advisors.

Activity	Expected Time t_e (wks)	Immediate Predecessor(s)
A	5	—
B	3	—
C	2	A
D	5	B
E	4	C, D
F	7	D

a. Draw the network diagram for this project.

b. Identify the critical path and estimate the project's duration.

c. Calculate the slack for each activity.

8. Good Souls, a charitable organization, is embarking on a new project aimed at rehabilitating prisoners by providing them with education, occupational skills, and financial support. The following data are available for the project.

Activity	Activity Time (months)	Predecessor(s)
A	5	—
B	6	—
C	3	A
D	4	B
E	5	C, D

a. Draw the network diagram for the project.

b. Determine the project's critical path and duration.

c. What is the slack for each activity?

9. Reliable Garage is completing production of the J2000 kit car. The following data are available for the project.

Activity	Activity Time (days)	Immediate Predecessor(s)
A	2	—
B	6	A
C	4	B
D	5	C
E	7	C
F	5	C
G	5	F
H	3	D, E, G

a. Draw the network diagram for the project.

b. Determine the project's critical path and duration.

c. What is the slack for each activity?

10. The following information concerns a project to raise money for the Kids Against Crime Foundation.

Activity	Activity Time (days)	Immediate Predecessor(s)
A	10	—
B	11	—
C	9	A, B
D	5	A, B
E	8	A, B
F	13	C, E
G	5	C, D
H	10	G
I	6	F, G
J	9	E, H
K	11	I, J

a. Draw the network diagram for this project.

b. Determine the critical path and project completion time.

11. **[D]** Table 7.4 provides information about a refurbishment project of a residential property.

a. How many weeks will it take to complete this project and what is the total slack?

b. As the project manager, you are interested in completing your project as soon as possible by allocating additional resources. The only option is to redeploy manpower from one task to another. However, other tasks will suffer a corresponding delay due to redeployment. Given this situation, will it be possible to reduce overall project duration?

TABLE 7.4 | PROJECT DATA FOR REFURBISHMENT PROJECT

Activity	Activity Time (weeks)	Predecessor(s)
START	0	—
A	3	START
B	5	START
C	6	A
D	8	C
E	5	D
F	3	D, E
G	2	B, F
FINISH	0	F, G

Analyzing Cost–Time Trade-offs

12. Computer Systems Limited is currently deploying a nationwide CRM software system across all its retail outlets. Upon examination, the company realized it can reduce project duration by deploying additional resources. However, this involves additional costs. Table 7.5 contains information about cost and schedule.

TABLE 7.5 | CRM SOFTWARE PROJECT DATA

Activity	Predecessor (s)	Normal Time (months)	Crash Time (months)	Cos to Crash (£/month)
A	None	5	4	300
B	None	10	8	350
C	A	5	3	300
D	A	4	—	
E	B	1	—	
F	C, D	1	—	
G	D, E	2	1	500
H	F	2	1	500
I	G	1	—	

What would be the impact of crashing the project schedule in terms of duration and costs?

13. The Advanced Tech Company has a project to design an integrated information database for a major bank. Data for the project are given in Table 7.6. Indirect project costs amount to $300 per day. The company will incur a $150 per day penalty for each day the project lasts beyond day 14.

a. What is the project's duration if only normal times are used?

b. What is the minimum-cost schedule?

c. What is the critical path for the minimum-cost schedule?

TABLE 7.6 | DATABASE DESIGN PROJECT DATA

Activity	Normal Time (days)	Normal Cost ($)	Crash Time (days)	Crash Costs ($)	Immediate Predecessor(s)
A	6	1,000	5	1,200	—
B	4	800	2	2,000	—
C	3	600	2	900	A, B
D	2	1,500	1	2,000	B
E	6	900	4	1,200	C, D
F	2	1,300	1	1,400	E
G	4	900	4	900	E
H	4	500	2	900	G

14. You are the manager of a project to improve a billing process at your firm. Table 7.7 contains the data you will need to conduct a cost analysis of the project. Indirect costs are $1,600 per week, and penalty costs are $1,200 per week after week 12.

a. What is the minimum-cost schedule for this project?

b. What is the difference in total project costs between the earliest completion time of the project using "normal" times and the minimum-cost schedule you derived in part (a)?

TABLE 7.7 | DATA FOR THE BILLING PROCESS PROJECT

Activity	Immediate Predecessor(s)	Normal Time (wks)	Crash Time (wks)	Normal Cost ($)	Crash Cost ($)
A	—	4	1	5,000	8,000
B	—	5	3	8,000	10,000
C	A	1	1	4,000	4,000
D	B	6	3	6,000	12,000
E	B, C	7	6	4,000	7,000
F	D	7	6	4,000	7,000

15. Table 7.8 contains data for the installation of imported generators from Germany in your office premises in Nigeria. The indirect costs are €200 per week, and a penalty cost of €900 per week will be incurred by your company for every week the project is delayed beyond week 50 days.

a. What is the shortest time duration for this project regardless of cost?

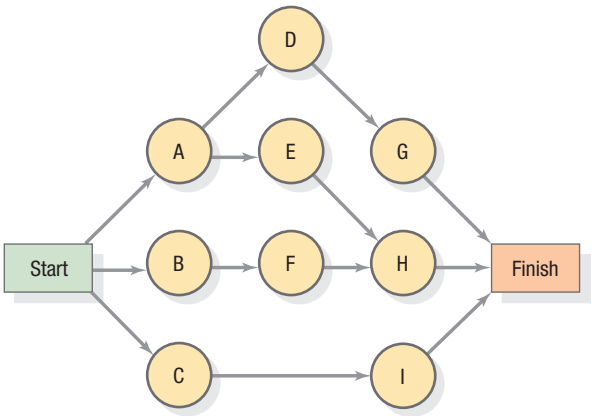
b. What is the total cost associated with completing the project using "normal" times?

c. What is the total time of the minimum-cost schedule?

TABLE 7.8 | DATA FOR INSTALLING GENERATORS

Activity	Immediate Predecessor(s)	Normal Time (days)	Crash Time (days)	Normal Cost (€)	Crash Cost (€)
A	—	10	5	700	1,000
B	—	10	10	300	300
C	A	17	6	1,200	4,000
D	B	17	12	1,200	2,800
E	C	7	7	800	800
F	D, E	30	20	500	1,500
G	E	17	12	900	1,800

16. The diagram in Figure 7.12 was developed for the project launch of Kitty Condo, a new product in the luxury cat cage market. Suppose that you, as project manager, are interested in finding ways to speed up the project at minimal additional cost. Determine the schedule for completing the project in 25 days at minimum cost. Penalty and project-overhead costs are negligible. Time and cost data for each activity are shown in Table 7.9.



▲ **FIGURE 7.12**
Network Diagram for Kitty Condo

TABLE 7.9 | PROJECT ACTIVITY AND COST DATA

	NORMAL		CRASH	
Activity	Time (days)	Cost ($)	Time (days)	Cost ($)
A	12	1,300	11	1,900
B	13	1,050	9	1,500
C	18	3,000	16	4,500
D	9	2,000	5	3,000
E	12	650	10	1,100
F	8	700	7	1,050
G	8	1,550	6	1,950
H	2	600	1	800
I	4	2,200	2	4,000

17. **[D]** You are in charge of a project at the local community center. The center needs to remodel one of the rooms in time for the start of a new program. Delays in the project mean that the center must rent other space at a nearby church at additional cost. Time and cost data for your project are contained in Table 7.10. Your interest is in minimizing the cost of the project to the community center.

a. Using the *normal times* for each activity, what is the earliest date you can complete the project?

b. Suppose the variable overhead costs are $50 per day for your project. Also, suppose that the center must pay $40 per day for a temporary room on day 15 or beyond. Find the minimum-cost project schedule.

TABLE 7.10 | DATA FOR THE COMMUNITY CENTER PROJECT

Activity	Normal Time (days)	Normal Cost ($)	Crash Time (days)	Crash Cost ($)	Immediate Predecessor(s)
START	0	0	0	0	—
A	10	50	8	150	START
B	4	40	2	200	START
C	7	70	6	160	B
D	2	20	1	50	A, C
E	3	30	3	30	A, C
F	8	80	5	290	B
G	5	50	4	180	D
H	6	60	3	180	E, F
FINISH	0	0	0	0	G, H

18. **[D]** The information in Table 7.11 is available for a large fundraising project.

a. Determine the critical path and the expected completion time of the project.

b. Plot the total project cost, starting from day 1 to the expected completion date of the project, assuming the earliest start times for each activity. Compare that result to a similar plot for the latest start times. What implication does the time differential have for cash flows and project scheduling?

TABLE 7.11 | FUNDRAISING PROJECT DATA

Activity	Activity Time (days)	Activity Cost ($)	Immediate Predecessor(s)
A	3	100	—
B	4	150	—
C	2	125	A
D	5	175	B
E	3	150	B
F	4	200	C, D
G	6	75	C
H	2	50	C, D, E
I	1	100	E
J	4	75	D, E
K	3	150	F, G
L	3	150	G, H, I
M	2	100	I, J
N	4	175	K, M
O	1	200	H, M
P	5	150	N, L, O

19. **[D]** You are the project manager of the software installation project in Table 7.12. You would like to find the minimum-cost schedule for your project. There is a $1,000-per-week penalty for each week the project is delayed beyond week 25. In addition, your project team determined that indirect project costs are $2,500 per week.

a. What would be your target completion week?

b. How much would you save in total project costs with your schedule?

TABLE 7.12 | DATA FOR SOFTWARE INSTALLATION PROJECT

Activity	Immediate Predecessors	Normal Time (wks)	Normal Cost ($)	Crash Time (wks)	Crash Cost ($)
A	—	5	2,000	3	4,000
B	—	8	5,000	7	8,000
C	A	10	10,000	8	12,000
D	A, B	4	3,000	3	7,000
E	B	3	4,000	2	5,000
F	D	9	8,000	6	14,000
G	E, F	2	2,000	2	2,000
H	G	8	6,000	5	9,000
I	C, F	9	7,000	7	15,000

Assessing and Analyzing Risks

20. Jordanne King, the project manager for Webjets International, Inc., compiled the table below showing time estimates for each of the activities of a project to upgrade the company's Web page, including optimistic, most likely, and pessimistic.

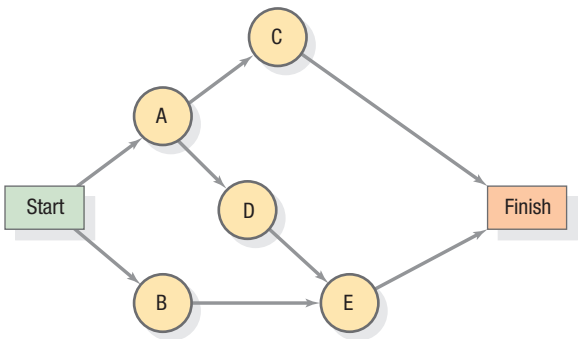
a. Calculate the expected time, t_e, for each activity.

b. Calculate the variance, σ^2, for each activity.

Activity	Optimistic (days)	Most Likely (days)	Pessimistic (days)
A	3	8	19
B	12	15	18
C	2	6	16
D	4	9	20
E	1	4	7

21. Recently, you were assigned to manage a project to remodel the seminar room for your company. You have constructed a network diagram depicting the various activities in the project (Figure 7.13). In addition, you have asked your team to estimate the amount of time that they would expect each of the activities to take. Their responses are shown in the following table.

	TIME ESTIMATES (DAYS)		
Activity	Optimistic	Most Likely	Pessimistic
A	5	8	11
B	4	8	11
C	5	6	7
D	2	4	6
E	4	7	10



▲ **FIGURE 7.13**
Network Diagram for Problem 21

a. What is the expected completion time of the project?

b. What is the probability of completing the project in 21 days or less?

c. What is the probability of completing the project in 17 days or less?

22. In Solved Problem 2, estimate the probability that the noncritical path B–F–G will take more than 20 weeks. *Hint:* Subtract from 1.0 the probability that B–F–G will take 20 weeks or less.

23. The director of continuing education at Bluebird University just approved the planning for a sales training seminar. Her administrative assistant identified the various activities that must be done and their relationships to each other, as shown in Table 7.13.

TABLE 7.13 | ACTIVITIES FOR THE SALES TRAINING SEMINAR

Activity	Description	Immediate Predecessor(s)
A	Design brochure and course announcement	—
B	Identify prospective teachers	—
C	Prepare detailed outline of course	—
D	Send brochure and student applications	A
E	Send teacher applications	B
F	Select teacher for course	C, E
G	Accept students	D
H	Select text for course	F
I	Order and receive texts	G, H
J	Prepare room for class	G

Because of the uncertainty in planning the new course, the assistant also has supplied the following time estimates for each activity.

	TIME ESTIMATES (DAYS)		
Activity	Optimistic	Most Likely	Pessimistic
A	5	7	8
B	6	8	12
C	3	4	5
D	11	17	25
E	8	10	12
F	3	4	5
G	4	8	9
H	5	7	9
I	8	11	17
J	4	4	4

The director wants to conduct the seminar 47 working days from now. What is the probability that everything will be ready in time?

24. Gabrielle Foley owner of Pet Paradise, is opening a new store in Columbus, Ohio. Her major concern is the hiring of a manager and several associates who are animal lovers. She also has to coordinate the renovation of a building that was previously owned by a chic clothing store. Foley has gathered the data shown in Table 7.14.

a. How long is the project expected to take?

b. Suppose that Foley has a personal goal of completing the project in 14 weeks. What is the probability that it will happen this quickly?

TABLE 7.14 | DATA FOR THE PET PARADISE PROJECT

			TIME (WKS)		
Activity	Description	Immediate Predecessor(s)	*a*	*m*	*b*
A	Interview for new manager	—	1	3	6
B	Renovate building	—	6	9	12
C	Place ad for associates and interview applicants	—	6	8	16
D	Have new manager prospects visit	A	2	3	4
E	Purchase equipment for new store and install	B	1	3	11
F	Check employee applicant references and make final selection	C	5	5	5
G	Check references for new manager and make final selection	D	1	1	1
H	Hold orientation meetings and do payroll paperwork	E, F, G	3	3	3

25. **[D]** The project manager of Good Public Relations gathered the data shown in Table 7.15 for a new advertising campaign.

a. How long is the project likely to take?

b. What is the probability that the project will take more than 38 weeks?

c. Consider the path A–E–G–H–J. What is the probability that this path will exceed 38 weeks?

TABLE 7.15 | ACTIVITY DATA FOR ADVERTISING PROJECT

	TIME ESTIMATES (WKS)			
Activity	**Optimistic**	**Most Likely**	**Pessimistic**	**Immediate Predecessor(s)**
A	8	10	12	START
B	5	8	17	START
C	7	8	9	START
D	1	2	3	B
E	8	10	12	A, C
F	5	6	7	D, E
G	1	3	5	D, E
H	2	5	8	F, G
I	2	4	6	G
J	4	5	8	H
K	2	2	2	H

26. **[D]** Consider the office renovation project data in Table 7.16. A "zero" time estimate means that the activity could take a very small amount of time and should be treated as a numeric zero in the analysis.

a. Based on the critical path, find the probability of completing the office renovation project by 39 days.

b. Find the date by which you would be 90 percent sure of completing the project.

TABLE 7.16 | DATA FOR THE OFFICE RENOVATION PROJECT

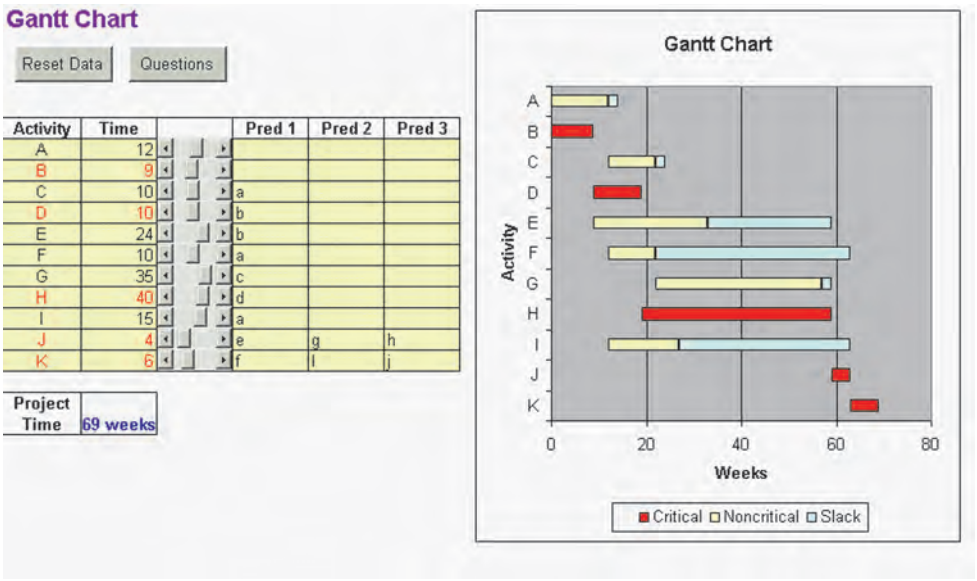
	TIME ESTIMATES (DAYS)			
Activity	**Optimistic**	**Most Likely**	**Pessimistic**	**Immediate Predecessor(s)**
START	0	0	0	—
A	6	10	14	START
B	0	1	2	A
C	16	20	30	A
D	3	5	7	B
E	2	3	4	D
F	7	10	13	C
G	1	2	3	D
H	0	2	4	G
I	2	2	2	C, G
J	2	3	4	I
K	0	1	2	H
L	1	2	3	J, K
FINISH	0	0	0	E, F, L

Active Model Exercise

Active Model 7.1, Gantt Chart, is available online. It allows you to evaluate the sensitivity of the project time to changes in activity times and activity predecessors. In this exercise we use the data from Example 7.2 to develop a Gantt chart.

QUESTIONS

1. Activity B and activity K are critical activities. Describe the difference that occurs on the graph when you increase activity B versus when you increase activity K.
2. Activity F is not critical. Use the scroll bar to determine how many weeks you can increase activity F until it becomes critical.
3. Activity A is not critical. How many weeks can you increase activity A until it becomes critical? What happens when activity A becomes critical?
4. What happens when you increase activity A by 1 week after it becomes critical?
5. Suppose that building codes may change and, as a result, activity C would have to be completed before activity D could be started. How would this affect the project?



CASE The Pert Mustang

Roberts Auto Sales and Service (RASAS) consists of three car dealerships that sell and service several makes of American and Japanese cars, two auto parts stores, a large body shop and car painting business, and an auto salvage yard. Vicky Roberts, owner of RASAS, went into the car business when she inherited a Ford dealership from her father. She was able to capitalize on her knowledge and experience to build her business into the diversified and successful mini-empire it is today. Her motto, "Sell 'em today, repair 'em tomorrow!" reflects a strategy that she refers to in private as "Get 'em coming and going."

Roberts has always retained a soft spot in her heart for high-performance Mustangs and just acquired a 1965 Shelby Mustang GT 350 that needs a lot of restoration. She also notes the public's growing interest in the restoration of vintage automobiles. Roberts is thinking of expanding into the vintage car restoration business and needs help in assessing the feasibility of such a move. She wants to restore her 1965 Shelby Mustang to mint condition, or as close to mint condition as possible. If she decides to go into the car restoring business, she can use the Mustang as an exhibit in sales and advertising and take it to auto shows to attract business for the new shop.

Roberts believes that many people want the thrill of restoring an old car themselves, but they do not have the time to run down all the old parts. Still, others just want to own a vintage auto because it is different and many of them have plenty of money to pay someone to restore an auto for them.

Roberts wants the new business to appeal to both types of people. For the first group, she envisions serving as a parts broker for NOS ("new old stock"), new parts that were manufactured many years ago and are still packaged in their original cartons. It can be a time-consuming process to find the right part. RASAS could also machine new parts to replicate those that are hard to find or that no longer exist.

In addition, RASAS could assemble a library of parts and body manuals for old cars to serve as an information resource for do-it-yourself restorers. The do-it-yourselfers could come to RASAS for help in compiling parts lists, and RASAS could acquire the parts for them. For others, RASAS would take charge of the entire restoration.

Roberts asked the director of service operations to take a good look at her Mustang and determine what needs to be done to restore it to the

condition it was in when it came from the factory more than 50 years ago. She wants to restore this car in time to exhibit it at the Detroit Auto Show. If the car gets a lot of press, it will be a real public relations coup for RASAS—especially if Roberts decides to enter this new venture. Even if she does not, the car will be a showpiece for the rest of the business.

Roberts asked the director of service operations to prepare a report about what is involved in restoring the car and whether it can be done in time for the Detroit show in 45 working days using PERT/CPM. The parts manager, the body shop manager, and the chief mechanic have provided the following estimates of times and activities that need to be done, as well as cost estimates.

a. Order all needed material and parts (upholstery, windshield, carburetor, and oil pump). Time: 2 days. Cost (telephone calls and labor): $100.

b. Receive upholstery material for seat covers. Cannot be done until order is placed. Time: 30 days. Cost: $2,100.

c. Receive windshield. Cannot be done until order is placed. Time: 10 days. Cost: $800.

d. Receive carburetor and oil pump. Cannot be done until order is placed. Time: 7 days. Cost: $1,750.

e. Remove chrome from body. Can be done immediately. Time: 1 day. Cost: $200.

f. Remove body (doors, hood, trunk, and fenders) from frame. Cannot be done until chrome is removed. Time: 1 day. Cost: $300.

g. Have fenders repaired by body shop. Cannot be done until body is removed from frame. Time: 4 days. Cost: $1,000.

h. Repair doors, trunk, and hood. Cannot be done until body is removed from frame. Time: 6 days. Cost: $1,500.

i. Pull engine from chassis. Do after body is removed from frame. Time: 1 day. Cost: $200.

j. Remove rust from frame. Do after the engine has been pulled from the chassis. Time: 3 days. Cost $900.

k. Regrind engine valves. Do after the engine has been pulled from the chassis. Time: 5 days. Cost: $1,000.

l. Replace carburetor and oil pump. Do after engine has been pulled from chassis and after carburetor and oil pump have been received. Time: 1 day. Cost: $200.

m. Rechrome the chrome parts. Chrome must have been removed from the body first. Time: 3 days. Cost: $210.

n. Reinstall engine. Do after valves are reground and carburetor and oil pump have been installed. Time: 1 day. Cost: $200.

o. Put doors, hood, and trunk back on frame. The doors, hood, and trunk must have been repaired first. The frame must have had its rust removed first. Time: 1 day. Cost: $240.

p. Rebuild transmission and replace brakes. Do so after the engine has been reinstalled and the doors, hood, and trunk are back on the frame. Time: 4 days. Cost: $2,000.

q. Replace windshield. Windshield must have been received. Time: 1 day. Cost: $100.

r. Put fenders back on. The fenders must have been repaired first, the transmission rebuilt, and the brakes replaced. Time: 1 day. Cost: $100.

s. Paint car. Cannot be done until the fenders are back on and windshield replaced. Time: 4 days. Cost: $1,700.

t. Reupholster interior of car. Must have received upholstery material first. Car must have been painted first. Time: 7 days. Cost: $2,400.

u. Put chrome parts back on. Car must have been painted and chrome parts rechromed first. Time: 1 day. Cost: $100.

v. Pull car to the Detroit Auto Show. Must have completed reupholstery of interior and have put the chrome parts back on. Time: 2 days. Cost: $1,000.

Roberts wants to limit expenditures on this project to what could be recovered by selling the restored car. She has already spent $50,000 to acquire the car. In addition, she wants a brief report on some of the aspects of the proposed business, such as how it fits in with RASAS's other businesses and what RASAS's operations task should be with regard to cost, quality, customer service, and flexibility.

In the restoration business there are various categories of restoration. A basic restoration gets the car looking great and running, but a mint-condition restoration puts the car back in original condition—as it was "when it rolled off the line." When restored cars are resold, a car in mint condition commands a much higher price than one that is just a basic restoration. As cars are restored, they can also be customized. That is, something is put on the car that could not have been on the original. Roberts wants a mint-condition restoration for her Mustang without customization. (The proposed new business would accept any kind of restoration a customer wanted.)

The total budget cannot exceed $70,000 including the $50,000 Roberts has already spent. In addition, Roberts cannot spend more than $3,600 in any week given her present financial position. Even though much of the work will be done by Roberts's own employees, labor and materials costs must be considered. All relevant costs have been included in the cost estimates.[4]

QUESTIONS

1. Using the information provided, prepare the report that Vicky Roberts requested, assuming that the project will begin immediately. Assume 45 working days are available to complete the project, including transporting the car to Detroit before the auto show begins. Your report should briefly discuss the aspects of the proposed new business, such as the competitive priorities that Roberts asked about.
2. Construct a table containing the project activities using the letter assigned to each activity, the time estimates, and the precedence relationships from which you will assemble the network diagram.
3. Draw a network diagram of the project similar to Figure 7.3. Determine the activities on the critical path and the estimated slack for each activity.
4. Prepare a project budget showing the cost of each activity and the total for the project. Can the project be completed within the budget? Will the project require more than $3,600 in any week? To answer this question, assume that activities B, C, and D must be paid for when the item is received (the earliest finish time for the activity). Assume that the costs of all other activities that span more than 1 week can be prorated. Each week contains 5 workdays. If problems exist, how might Roberts overcome them?

[4] *Source:* This case was prepared by and is used by permission of Dr. Sue P. Siferd, Professor Emerita, Arizona State University (Updated September, 2007).

VIDEO CASE Project Management at Choice Hotels International

Choice Hotels International is the company behind well-known hotel brands that range from budget-friendly EconoLodge and Rodeway Inns to Quality, Comfort Inns and its luxury brands, Ascend and Cambria. Over 6,400 properties are part of the franchisor's offerings both domestically and abroad. This translates to over 500,000 rooms around the globe.

To help hotel guests find and book those rooms, Choice Hotels maintains a robust central reservation system, or CRS, that must connect travel agents, online reservation websites such as Trivago and Kayak, and mobile app users to the company's daily available inventory. On the back end, the system also must connect to each property's front check-in desk system and the organization's revenue management systems. For Choice, the CRS is the heart of hotel operations and the company could not operate without it.

The company first developed its CRS back in the 1980s using the latest project management techniques and information technology (IT) available. But the company's growth, coupled with dramatic changes in information technology and the cost of maintaining inflexible systems built for last century business that couldn't scale with growth, compelled the organization in 2014 to embark on a multimillion dollar, multiyear project, called choiceEDGE, to replace this mission-critical system by 2017. To replace such a vital system, Todd Davis, Choice's chief information officer (CIO), knew the company couldn't just remove the old software and hardware systems and then plug in brand-new ones. The risk was too high. Nor could Choice Hotels rely on a linear systems development approach that would require the company to deliver a finished solution that would be outdated at the end of several years of work. The world of business and technology were changing too rapidly to wait. The company has seen hospitality industry competitors spend hundreds of millions doing just that, with failed outcomes.

Instead, senior management at Choice Hotels committed to a new IT project management approach, called "Agile," that allowed development to occur iteratively around "projects within projects" so as each requirement outlined in its work breakdown structure (WBS) was completed, it could be deployed without disruption to the entire enterprise. This approach both minimized the risk of business disruption and allowed new features to be seamlessly rolled out without the need for major workforce training initiatives. It also allowed franchisees to start seeing the benefit of the new "heart" just months after helping to define the desired business outcomes, instead of waiting years.

To get started, Choice defined its project scope and objectives with input from its various stakeholders: thousands of franchisees, dozens of external business partners, millions of customers, and thousands of employees. Brian Kirkland, vice president of engineering, was chosen to head up the project team of nearly 120 systems architects, "scrum masters" (daily project managers), software developers, and quality assurance professionals at Choice's Scottsdale, Arizona, location. From the start, Kirkland wanted the team to use all the tools available to manage the project. For example, early on in the project, Denise Tower, director of IT project management and delivery, used WBS and Gantt charts to identify the critical path. Kirkland and his team quickly realized that the system's underlying distribution engine (the platform upon which all the functionality rested) was in the critical path. Any problems or delays would cause downstream delays and cost the company software programmer idle time. So resources were shifted to getting this core system functionality in place and off the critical path. Resources were then redirected back toward completion of the business outcomes that relied on the distribution engine, which were delivered weekly throughout the project's entire development process. Daily monitoring meetings, called "daily stand-ups," were held each morning to keep the focus on the work at hand, and ensured that issues got priority attention for resolution to avoid those parts of the project ending up in the critical path and causing downstream delays.



Choice Hotels International, Inc.

Cambria Hotels and Suites, such as this one on Times Square in New York, is a luxury product of Choice Hotels. With over 6,400 properties across all of its brands, and more than 500,000 rooms to fill, Choice must have a flexible and reliable reservation system to remain competitive.

Today, choiceEDGE is capable of quickly scaling to meet the business demands it faces in the competitive hospitality industry. The system processes over 250 million transactions a day that include simple shopping queries for room rates and availability, pricing and inventory updates, or actual room bookings. Amazon Web Services is used for cloud storage. And as the demand for mobile access to its systems continues to grow, the company's IT department is equipped to rapidly respond.

QUESTIONS

1. Assess the four categories of a risk-management plan for the choiceEDGE project. Given the information in the case, how risky is this project for Choice Hotels?
2. Go online to research "Agile" information systems development and the role of "scrum masters" in helping organizations manage successful IT projects. Why are leading organizations now turning to this approach for developing their systems projects?
3. Assume you are Denise Tower and have responsibility for the overall management of the choiceEDGE IT project. Describe what you might need to do to monitor and control the project to ensure scope, budget, and schedule are managed.

8

FORECASTING

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

8.1 Explain how managers can manage demand patterns.

8.2 Describe the two key decisions on making forecasts.

8.3 Calculate the five basic measures of forecast errors.

8.4 Compare and contrast the four approaches to judgmental forecasting.

8.5 Use regression to make forecasts with one or more independent variables.

8.6 Make forecasts using the five most common statistical approaches for time-series analysis.

8.7 Describe the big-data approach and the six steps in a typical forecasting process.

Starbucks



Sorbis/Shutterstock

Starbucks strives for quick, friendly service at every one of its locations worldwide. Here a barista in Saint Petersburg, Russia, prepares a special order for a customer.

It's a beautiful fall day and you begin your daily trek to the local Starbucks store during your lunch break. Your first decision is what to eat. Perhaps today it is the Ham and Swiss Panini or the Chipotle Chicken Wrap Protein Box. As for the drink decision, today it is custom—either a Holly Jolly Latte or a Raspberry Caramel Macchiato. Having made your decisions, you take out your smartphone, access the Starbucks app, tap in your choices, and pay for the order. By the time you get to the store, your order is ready and you find a nearby park bench on which to eat lunch and enjoy the scenery.

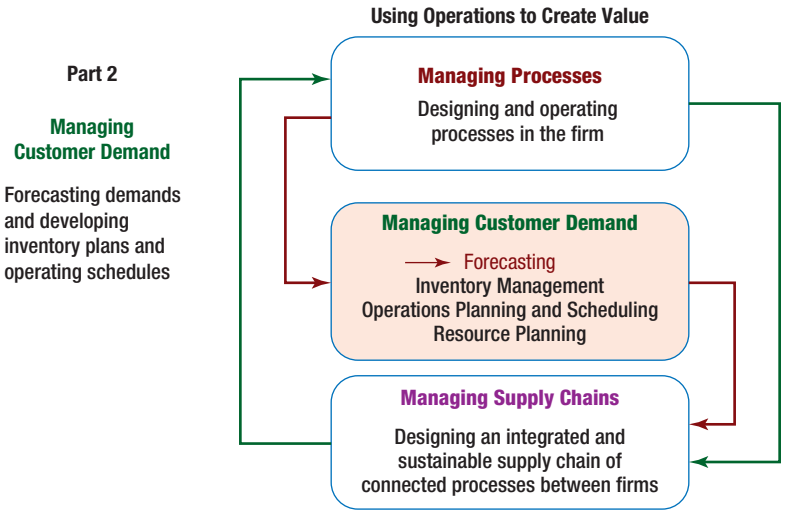
Stop and think for a minute of what must have taken place behind the scenes at Starbucks. All the ingredients of your order were available, a commendable feat given that there are 87,000 drink combinations alone! Further, the company conducts over 90 million transactions a week at more than 25,000 stores worldwide—a daunting task for the Starbucks supply chain. A key to success is a good forecast of demand for the various offerings at each store. How does Starbucks arrive at that forecast? The answer is twofold: data, lots of it, generated from each transaction, and using that data to develop forecasts of future demands while managing demand patterns in the short term. From the aggregate data generated from the 90 million weekly transactions, Starbucks knows a lot about what people are buying, where they are buying, and how they are buying, which proves useful for identifying future demand patterns. In addition, 17 million customers are using the Starbucks app, including 13 million enrolled in the Starbucks Reward Program, who have given Starbucks authorization to gather a lot of information about their coffee-buying habits. The company uses predictive analytics to combine the aggregate information with personal information and other data, like local weather, promotions, inventory, location, and insights into local events, to provide a more personalized experience. The company knows how much an app user spends on average and even knows that, for example, on Mondays the user is typically not alone and spends more on beverages or certain desserts. Consequently, the user may be targeted for specials or new desserts on other days. This capability allows Starbucks to manage its demand patterns to better match supply with demand in the short term. This sort of service generates loyalty and makes the job of forecasting easier. While the members of Starbucks Rewards program, dependable customers to be sure, constitute only about 18 percent of Starbucks 75 million customers, they account for 36 percent of total sales, and Starbucks knows a lot about their spending patterns.[1]

Part 2 of this text is about forecasting demands for products and services and developing the plans for satisfying these demands. In keeping with our building-block philosophy, the following chapters examine how inventories are planned to meet projected demands, reveal methods for producing sales and operations plans for products and services to meet forecasts at the aggregate level, show how to schedule processes and employees to meet those plans, and demonstrate how to schedule the timing of the resources needed down to the smallest component, all within the firm. Given that no firm can make everything it needs to produce a product or service, in Part 3 we connect processes within separate firms to form supply chains that aim to satisfy the demands for products and services at the top of the chain with efficient levels of inventory.

forecast
A prediction of future events used for planning purposes.

Balancing supply and demand begins with making accurate forecasts. A **forecast** is a prediction of future events used for planning purposes. Planning, in contrast, is the process of making management decisions on how to deploy resources to best respond to the demand forecasts. Forecasting methods may be based on mathematical models that use available historical data,

[1] *Sources*: Eric Wilson, "How Starbucks Uses Predictive Analytics and Your Loyalty Card Data," Institute of Business Forecasting & Planning, May 29, 2018, https://demand-planning.com/2018/29/05/how-starbucks-uses-predictive-analytics-and-your-loyalty-card-data; Soumik Roy, "How Starbucks Uses Data and Insights to Win Big," TechHQ, September 4, 2018, https://techhq.com/2018/09/how-starbucks-uses-data-and-insights-to-win-big/; Bernard Marr, "Starbucks: Using Big Data, Analytics and Artificial Intelligence to Boost Performance," Forbes, May 28, 2018, https://www.forbes.com/sites/bernardmarr/2018/05/28/starbucks-using-big-data-analytics-and-artificial-intelligence-to-boost-performance/2886ebef65cd.



or on qualitative methods that draw on managerial experience and judgments, or on a combination of both.

In this chapter our focus is on demand forecasts. We begin with different types of demand patterns. We examine forecasting methods in three basic categories: (1) judgment, (2) causal, and (3) time-series methods. Forecast errors are defined, providing important clues for making better forecasts. We next consider the forecasting techniques themselves, and then how they can be combined to bring together insights from several sources. We conclude with a discussion of new advanced forecasting methods that make use of the vast amounts of data available from cellular devices and the Internet, along with an overall process for making forecasts and designing the forecasting system.

Forecasts are useful for both managing processes and managing supply chains. At the supply chain level, a firm needs forecasts to coordinate with its customers and suppliers. At the process level, output forecasts are needed to design the various processes throughout the organization, including identifying and dealing with in-house bottlenecks.

As you might imagine, the organization-wide forecasting process cuts across functional areas. Forecasting overall demand typically originates with marketing, but internal customers throughout the organization depend on forecasts to formulate and execute their plans as well. Forecasts are critical inputs to business plans, annual plans, and budgets. Finance needs forecasts to project cash flows and capital requirements. Human resources will use forecasts to anticipate hiring and training needs. Marketing is an important source for sales forecast information because it is closest to external customers. Operations and supply chain managers need forecasts to plan output levels, purchases of services and materials, workforce and output schedules, inventories, and long-term capacities. Managers at all levels need estimates of future demands, so that they can plan activities consistent with the firm's competitive priorities.

Managing Demand

Before we get into the tools and techniques for forecasting demands, it is important to understand that the timing and sizing of customer demand can often be manipulated. Accurately forecasting customer demand is a difficult task because the demand for services and goods can vary greatly. For example, demand for lawn fertilizer predictably increases in the spring and summer months; however, the particular weekends when demand is heaviest may depend on uncontrollable factors such as the weather. These demand swings are costly to satisfy for any process, even if they are predictable. However, managers can often do two things to alleviate the pains of demand swings: first, understand the demand pattern they are facing; and second, use one or more options to alleviate any avoidable swings.

Demand Patterns

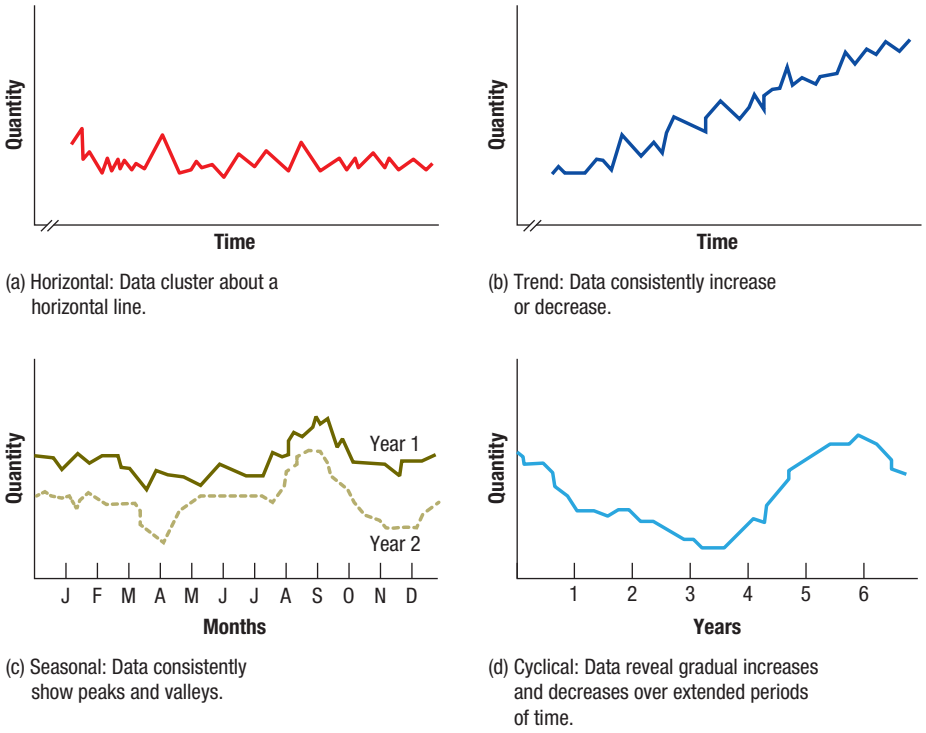
Forecasting demand requires uncovering the underlying patterns from available information. The repeated observations of demand for a service or product in their order of occurrence form a pattern known as a **time series**. There are five basic patterns of most demand time series:

time series
The repeated observations of demand for a service or product in their order of occurrence.

1. *Horizontal.* The fluctuation of data around a constant mean.
2. *Trend.* The systematic increase or decrease in the mean of the series over time.
3. *Seasonal.* A repeatable pattern of increases or decreases in demand, depending on the time of day, week, month, or season.
4. *Cyclical.* The less predictable gradual increases or decreases in demand over longer periods of time (years or decades).
5. *Random.* The unforecastable variation in demand.

Cyclical patterns arise from two influences. The first is the business cycle, which includes factors that cause the economy to go from recession to expansion over a number of years. The other influence is the service or product life cycle, which reflects the stages of demand from development through decline. Business cycle demand is difficult to predict because it is affected by national or international events.

FIGURE 8.1 ▶
Patterns of Demand



(a) Horizontal: Data cluster about a horizontal line.

(b) Trend: Data consistently increase or decrease.

(c) Seasonal: Data consistently show peaks and valleys.

(d) Cyclical: Data reveal gradual increases and decreases over extended periods of time.

The four patterns of demand—horizontal, trend, seasonal, and cyclical—combine in varying degrees to define the underlying time pattern of demand for a service or product. The fifth pattern, random variation, results from chance causes and thus cannot be predicted. Random variation is an aspect of demand that makes every forecast ultimately inaccurate. Figure 8.1 shows the first four patterns of a demand time series, all of which contain random variations.

Demand Management Options

Matching supply with demand becomes a challenge when forecasts call for uneven demand patterns—and uneven demand is more the rule than the exception. Demand swings can be from one month to the next, one week to the next, or even one hour to the next. Peaks and valleys in demand are costly or can cause poor customer service. Air New Zealand can lose sales because capacity is exceeded for one of its flights, while another of its flights to the same destination at about the same time has many empty seats. If nothing is done to even out demand, sales are lost or greater capacity cushions might be needed. All come at an extra cost. Here we deal with **demand management**, the process of changing demand patterns using one or more demand options.

demand management
The process of changing demand patterns using one or more demand options.

Various options are available in managing demand, including complementary products, promotional pricing, prescheduled appointments, reservations, revenue management, backlogs, backorders, and stockouts. In the chapter opening vignette, we saw that Starbucks has the capability of guiding Reward members to various complementary products with promotional pricing to manage demands at various store locations. In general, a manager may select one or more of the following options.

Complementary Products One demand option for a company to even out the load on resources is to produce **complementary products** (or services) that have similar resource requirements but different demand cycles. For example, manufacturers of matzoh balls for the Jewish Passover holiday are in a seasonal business. Almost half of annual sales can come in during the 8-day Passover holiday alone. A possible solution is to expand toward markets with year-round appeal, such as low-carb, low-fat foods, including canned soups and crackers, borscht, cake mixes, dressing and spreads, juices, and condiments.

complementary products
Services or products that have similar resource requirements but different demand cycles.

For service providers, a city parks and recreation department can counterbalance seasonal staffing requirements for summer activities by offering ice skating, tobogganing, or indoor activities during the winter months. The key is to find services and products that can be produced with the existing resources and can level off the need for resources over the year.

Promotional Pricing Promotional campaigns are designed to increase sales with creative pricing. Examples include automobile rebate programs, price reductions for winter clothing in the late summer months, reduced prices for hotel rooms during off-peak periods, and "two-for-the-price-of-one" automobile tire sales. Lower prices can increase demand for the product or service from new and existing customers during traditional slack periods or encourage customers to move up future buying.



Anil Kumar/Alamy Stock Photo

Online retailers such as Amazon can manage demand for certain products with promotional pricing through the use of apps.

Prescheduled Appointments Service providers often can schedule customers for definite periods of order fulfillment. With this approach, demand is leveled to not exceed supply capacity. An appointment system assigns specific times for service to customers. The advantages of this method are timely customer service and the high utilization of service personnel.

Doctors, dentists, lawyers, and automobile repair shops are examples of service providers that use appointment systems. Doctors can use the system to schedule parts of their day to visit hospital patients, and lawyers can set aside time to prepare cases. Care must be taken to tailor the length of appointments to individual customer needs rather than merely scheduling customers at equal time intervals.

Reservations Reservation systems, although quite similar to appointment systems, are used when the customer actually occupies or uses facilities associated with the service. For example, customers reserve hotel rooms, automobiles, airline seats, and concert seats. The major advantage of reservation systems is the lead time they give service managers and the ability to level demand. Managers can deal with no-shows with a blend of overbooking, deposits, and cancellation penalties. Sometimes overbooking means that a customer with reservations cannot be served as promised. In such cases, bonuses can be offered for compensation. For example, an airline passenger might not only get on the next available flight but also may be given a free ticket for a second flight sometime in the future.

Revenue Management A specialized combination of the pricing and reservation options for service providers is revenue management. **Revenue management** (sometimes called *yield management*) is the process of varying price at the right time for different customer segments to maximize revenues generated from existing supply capacity. It works best if customers can be segmented, prices can be varied by segment, fixed costs are high, variable costs are low, service duration is predictable, and capacity is lost if not used (sometimes called *perishable capacity*). Airlines, hotels, cruise lines, restaurants (early-bird specials), and rental cars are good examples. Computerized reservation systems can make hour-by-hour updates, using decision rules for opening or closing price classes depending on the difference between supply and continually updated demand forecasts. In the airlines industry, prices are lowered if a particular airline flight is not selling as fast as expected, until more seats are booked. Alternatively, if larger than expected demand is developing, prices for the remaining seats may be increased. Last-minute business travelers pay the higher prices, whereas leisure travelers making reservations well in advance and staying over the weekend get the bargain prices. Southwest Airlines now segments its customers by creating a "Business Select" ticket class that rewards more perks to frequent fliers willing to pay higher prices.

revenue management
Varying price at the right time for different customer segments to maximize revenues yielded by existing supply capacity.

Backlogs Much like the appointments or reservations of service providers, a **backlog** is an accumulation of customer orders that a manufacturer has promised for delivery at some future date. Manufacturers in the supply chain that maintain a backlog of orders as a normal business practice can allow the backlog to grow during periods of high demand and then reduce it during periods of low demand. Airplane manufacturers do not promise instantaneous delivery, as do wholesalers or retailers further forward in the supply chain. Instead, they impose a lead time between when the order is placed and when it is delivered. For example, an automotive parts manufacturer may agree to deliver to the repair department of a car dealership a batch of 100 door latches for a particular car model next Tuesday. The parts manufacturer uses that due date to plan its production of door latches within its capacity limits. Firms that are most likely to use backlogs—and increase the size of them during periods of heavy demand—make customized products and tend to have a make-to-order strategy. Backlogs reduce the uncertainty of future production requirements and also can be used to level demand. However, they become a competitive disadvantage if they get too big.

backlog
An accumulation of customer orders that a manufacturer has promised for delivery at some future date.

backorder
A customer order that cannot be filled when promised or demanded but is filled later.

stockout
An order that cannot be satisfied, resulting in a loss of the sale.

Backorders and Stockouts A last resort in demand management is to set lower standards for customer service, in the form of either backorders or stockouts. Not to be confused with a backlog, a **backorder** is a customer order that cannot be filled when promised or demanded but is filled later. Demand may be too unpredictable or the item may be too costly to hold it in inventory. Although the customer is not pleased with the delay, the customer order is not lost and it is filled at a later date. In contrast, a **stockout** is an order that cannot be satisfied, resulting in a loss of the sale. A backorder adds to the next period's demand requirement, whereas a stockout does not. Backorders and stockouts can lead dissatisfied customers to do their future business with another firm. Generally, backorders and stockouts are to be avoided.

Combinations of demand options can also be used. For example, a manufacturer of lighting equipment had several products characterized as "slow movers with spikes," where only two or three units were sold for several weeks, and then suddenly there was a huge order for 10,000 units the next week. The reason is that their product was purchased by commercial property managers who might be upgrading the lighting in a large office building. The result was a forecasting nightmare and having to resort to high-cost supply options to meet the demand spikes. The breakthrough in solving this problem was to combine the pricing and backlog options. Contractors are now offered a 3 percent discount (the pricing option) on any order in excess of 10,000 units that are placed 5+ weeks before they are needed (the backlog option). The advanced warning allows the manufacturer to smooth out its production processes, saving millions of dollars annually.

Key Decisions on Making Forecasts

Before using forecasting techniques, a manager must make two decisions: (1) what to forecast and (2) what type of forecasting technique to select for different items.

Deciding What to Forecast

Although some sort of demand estimate is needed for the individual services or goods produced by a company, forecasting total demand for groups or clusters and then deriving individual service or product forecasts may be easiest. Also, selecting the correct unit of measurement (e.g., units, customers, or machine-hours) for forecasting may be as important as choosing the best method.

aggregation
The act of clustering several similar services or products so that forecasts and plans can be made for whole families.

judgment methods
A forecasting method that translates the opinions of managers, expert opinions, consumer surveys, and salesforce estimates into quantitative estimates.

causal methods
A quantitative forecasting method that uses historical data on independent variables, such as promotional campaigns, economic conditions, and competitors' actions, to predict demand.

time-series analysis
A statistical approach that relies heavily on historical demand data to project the future size of demand and recognizes trends and seasonal patterns.

trend projection with regression
A forecasting model that is a hybrid between a time-series technique and the causal method.

Level of Aggregation Few companies err by more than 5 percent when forecasting the annual total demand for all their services or products. However, errors in forecasts for individual items and shorter time periods may be much higher. Recognizing this reality, many companies use a two-tier forecasting system. They first cluster (or "roll up") several similar services or products in a process called **aggregation**, making forecasts for families of services or goods that have similar demand requirements and common processing, labor, and materials requirements. Next, they derive forecasts for individual items, which are sometimes called stock-keeping units. A *stock-keeping unit (SKU)* is an individual item or product that has an identifying code and is held in inventory somewhere along the supply chain, such as in a distribution center.

Units of Measurement Rather than using dollars as the initial unit of measurement, forecasts often begin with service or product units, such as individual products, express packages to deliver, or customers needing maintenance service or repairs for their cars. Forecasted units can then be translated to dollars by multiplying them by the unit price. If accurately forecasting demand for a service or product is not possible in terms of number of units, forecast the standard labor or machine-hours required of each of the critical resources.

Choosing the Type of Forecasting Technique

Forecasting systems offer a variety of techniques, and no one of them is best for all items and situations. The forecaster's objective is to develop a useful forecast from the information at hand with the technique that is appropriate for the different patterns of demand. Two general types of forecasting techniques are used: judgment methods and quantitative methods. **Judgment methods** translate the opinions of managers, expert opinions, consumer surveys, and salesforce estimates into quantitative estimates. Quantitative methods include causal methods, time-series analysis, and trend projection with regression. **Causal methods** use historical data on independent variables, such as promotional campaigns, economic conditions, and competitors' actions, to predict demand. **Time-series analysis** is a statistical approach that relies heavily on historical demand data to project the future size of demand and recognizes trends and seasonal patterns. **Trend projection with regression** is a hybrid between a time-series technique and the causal method. Choosing the best approach is often done with the help of specialists in the field of information technology, as the following Managerial Challenge demonstrates.

MANAGERIAL CHALLENGE Information Technology

The Kramer Health Clinic (KHC) is a system of hospitals serving a metro population of one million. KHC provides services ranging from those offered by the emergency room to cardiovascular surgeries and long-term care for serious respiratory ailments. Staffing the clinic is a challenging task, given the uncertainty of the demands. Sylvia Chang, human resources director for KHC, uses forecasts of the various services to schedule the employees under contract with KHC, such as registered nurses, nurse's assistants, food services and housekeeping, operating room technicians, and medical technicians. Recently, the staffing levels have not met the demands in some areas. The software she has been using for the forecasts was developed years ago, and she decided that it needed a thorough review. Recently, at her direction, KHC hired Ken Whitcomb, a recent graduate in information technology. His first assignment is to review the forecasting system and make recommendations.

Ken immediately realized that each of the services performed by KHC had its own pattern of demand and probably its own forecasting approach in the current software package. What are the forecast errors for each? Are the correct units of measurement being used? What technique is used for each forecast (judgment, causal, time-series, or trend projection), and is it the best one for the particular demand pattern? He will have to recommend a forecasting technique for each service; what criteria should he use to select each one? Should he recommend a totally new approach for some of the forecasts, such as a big-data approach incorporating the expected population in the coming years, the market share of KHC, or the out-of-area draw? Finally, what is the forecasting process used by Sylvia and KHC? That is, what steps are taken to finally agree on a forecast, especially those that are long term? The remainder of this chapter should help Ken with his assignment.

Forecast Error

For any forecasting technique, it is important to measure the accuracy of its forecasts. Forecasts almost always contain errors. Random error results from unpredictable factors that cause the forecast to deviate from the actual demand. Forecasting analysts try to minimize forecast errors by selecting appropriate forecasting models, but eliminating all forms of errors is impossible.

Forecast error for a given period t is simply the difference found by subtracting the forecast from actual demand, or

forecast error
The difference found by subtracting the forecast from actual demand for a given period.

$$E_t = D_t - F_t$$

where

$$E_t = \text{forecast error for period } t$$
$$D_t = \text{actual demand for period } t$$
$$F_t = \text{forecast for period } t$$

This equation (notice the alphabetical order with D_t coming before F_t) is the starting point for creating several measures of forecast error that cover longer periods of time.

There are five basic measures of forecast error: CFE, MSE, (σ), MAD, and MAPE. Figure 8.2 shows the output from the *Error Analysis* routine in Forecasting's dropdown menu of POM for Windows. Part (a) gives a big-picture view of how well the forecast has been tracking the actual demand; Part (b) shows the detailed calculations needed to obtain the summary error terms; and Part (c) gives the summary error measures summarized across all 10 time periods, as derived from Part (b).

Cumulative Sum of Forecast Errors

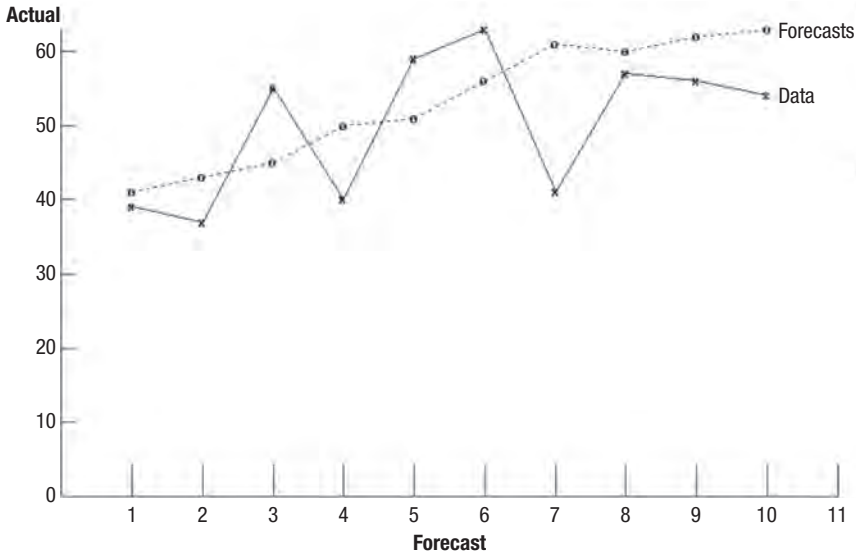
The **cumulative sum of forecast errors (CFE)** measures the total forecast error:

cumulative sum of forecast errors (CFE)
A measurement of the total forecast error that assesses the bias in a forecast.

$$\text{CFE} = \Sigma E_t$$

CFE is a cumulative sum. Figure 8.2(b) shows that it is the sum of the errors for all 10 periods. For any given period, it would be the sum of errors up through that period. For example, it would be -8 (or $-2-6$) for period 2. CFE is also called the *bias error* and results from consistent mistakes—the forecast is always too high or too low. This type of error typically causes the greatest disruption to planning efforts. For example, if a forecast is consistently lower than actual demand, then the value of CFE will gradually get larger and larger. This increasingly large error indicates

FIGURE 8.2(A) ▶
Graph of Actual and Forecast Demand Using *Error Analysis* of Forecasting in POM for Windows



some systematic deficiency in the forecasting approach. Over n periods, the average forecast error, sometimes called the *mean bias*, is simply

$$\bar{E} = \frac{\text{CFE}}{n}$$

Dispersion of Forecast Errors

mean squared error (MSE)
A measurement of the dispersion of forecast errors.

standard deviation of the errors (σ)
A measurement of the dispersion of forecast errors.

mean absolute deviation (MAD)
A measurement of the dispersion of forecast errors.

The **mean squared error (MSE)**, **standard deviation of the errors (σ)**, and **mean absolute deviation (MAD)** measure the dispersion of forecast errors attributed to trend, seasonal, cyclical, or random effects:

$$\text{MSE} = \frac{\Sigma E_t^2}{n}$$

$$\sigma = \frac{\Sigma (E_t - \bar{E})^2}{n - 1}$$

$$\text{MAD} = \frac{\Sigma |E_t|}{n}$$

Figure 8.2(b) shows the squared error in period 1 is 4, and MSE is 87.9 for the whole sample. The standard deviation of the errors, shown as 9.883 in Figure 8.2(b), is calculated using a separate

FIGURE 8.2(B) ▶
Detailed Calculations of Forecast Errors

	Actual	Forecast	Error	|Error|	Error^2	|Pct Error|
Past period 1	39	41	-2	2	4	5.128%
Past period 2	37	43	-6	6	36	16.216%
Past period 3	55	45	10	10	100	18.182%
Past period 4	40	50	-10	10	100	25%
Past period 5	59	51	8	8	64	13.559%
Past period 6	63	56	7	7	49	11.111%
Past period 7	41	61	-20	20	400	48.78%
Past period 8	57	60	-3	3	9	5.263%
Past period 9	56	62	-6	6	36	10.714%
Past period 10	54	63	-9	9	81	16.667%
TOTALS	501		-31	81	879	170.621%
AVERAGE	50.1		-3.1	8.1	87.9	17.062%
Next period forecast		0	(Bias)	(MAD)	(MSE)	(MAPE)
				Std err	9.883	

function available in Excel. The absolute value of the error in period 2 is 6, and MAD is 8.1 across the whole sample.

The mathematical symbol | | is used to indicate the absolute value—that is, it tells you to disregard positive or negative signs. If MSE, σ, or MAD is small, then the forecast is typically close to actual demand; by contrast, a large value indicates the possibility of large forecast errors. The measures do differ in the way they emphasize errors. Large errors get far more weight in MSE and σ because the errors are squared. MAD is a widely used measure of forecast error and is easily understood; it is merely the mean of the absolute forecast errors over a series of time periods, without regard to whether the error was an overestimate or an underestimate.

Mean Absolute Percent Error

The **mean absolute percent error (MAPE)** relates the forecast error to the level of demand and is useful for putting forecast performance in the proper perspective:

$$\text{MAPE} = \frac{(\Sigma |E_t| / D_t)(100)}{n} \text{ (expressed as a percentage)}$$

mean absolute percent error (MAPE)
A measurement that relates the forecast error to the level of demand and is useful for putting forecast performance in the proper perspective.

For example, an absolute forecast error of 100 results in a larger percentage error when the demand is 200 units than when the demand is 10,000 units. MAPE is the best error measure to use when making comparisons between time series for different SKUs. Looking again at Figure 8.2(b), the percent error in period 2 is 16.22 percent, and MAPE, the average over all 10 periods, is 17.062 percent.

Finally, Figure 8.2(c) summarizes the key error terms across all 10 time periods. They are actually found in selected portions of Figure 8.2(b). For example, CFE is −31, which is in the error column of Figure 8.2(b) in the TOTALS row. MAD is 8.1, found in the |Error| column and AVERAGE row. Finally, MAPE is 17.062 percent, which is in the |Pct Error| column and AVERAGE row.

Measure	Value
Error Measures	
CFE (Cumulative Forecast Error)	-31
MAD (Mean Absolute Deviation)	8.1
MSE (Mean Squared Error)	87.9
Standard Deviation of Errors	9.883
MAPE (Mean Absolute Percent Error)	17.062%

◀ **FIGURE 8.2(C)**
Error Measures
Source: Howard J. Weiss, POM for Windows, Pearson Prentice Hall.

EXAMPLE 8.1 **Calculating Forecast Error Measures**

The following table shows the actual sales of upholstered chairs for a furniture manufacturer and the forecasts made for each of the past 8 months. Calculate CFE, MSE, σ, MAD, and MAPE for this product.

Month, t	Demand, D_t	Forecast, F_t	Error, E_t	Error, Squared, E_t^2	Absolute Error, $\lvert E_t \rvert$	Absolute Percent Error, $(\lvert E_t \rvert / D_t)(100)$
1	200	225	−25	625	25	12.5%
2	240	220	20	400	20	8.3
3	300	285	15	225	15	5.0
4	270	290	−20	400	20	7.4
5	230	250	−20	400	20	8.7
6	260	240	20	400	20	7.7
7	210	250	−40	1,600	40	19.0
8	275	240	35	1,225	35	12.7
		Total	−15	5,275	195	81.3%

SOLUTION

Using the formulas for the measures, we get

Cumulative forecast error (bias):

CFE = −15 (the bias, or the sum of the errors for all time periods in the time series)

Average forecast error (mean bias):

$$\bar{E} = \frac{\text{CFE}}{n} = \frac{-15}{8} = -1.875$$

Mean squared error:

$$\text{MSE} = \frac{\Sigma E_t^2}{n} = \frac{5{,}275}{8} = 659.4$$

Standard deviation of the errors:

$$\sigma = \sqrt{\frac{\Sigma[E_t - (-1.875)]^2}{7}} = 27.4$$

Mean absolute deviation:

$$\text{MAD} = \frac{\Sigma|E_t|}{n} = \frac{195}{8} = 24.4$$

Mean absolute percent error:

$$\text{MAPE} = \frac{[\Sigma|E_t|/D_t|100}{n} = \frac{81.3\%}{8} = 10.2\%$$

A CFE of −15 indicates that the forecast has a slight bias to overestimate demand. The MSE, σ, and MAD statistics provide measures of forecast error variability. A MAD of 24.4 means that the average forecast error was 24.4 units in absolute value. The value of σ, 27.4, indicates that the sample distribution of forecast errors has a standard deviation of 27.4 units. A MAPE of 10.2 percent implies that, on average, the forecast error was within about 10 percent of actual demand. These measures become more reliable as the number of periods of data increases.

DECISION POINT

Although reasonably satisfied with these forecast performance results, the analyst decided to test out a few more forecasting methods before reaching a final forecasting method to use for the future.

Computer Support

Computer support, such as from OM Explorer or POM for Windows, makes error calculations easy when evaluating how well forecasting models fit with past data. Errors are measured across past data, often called the *history file* in practice. They show the various error measures across the entire history file for each forecasting method evaluated. They also make forecasts into the future, based on the method selected.

Judgment Methods

Forecasts from quantitative methods are possible only when historical data (i.e., the *history file*) are adequate. However, the history file may be nonexistent when a new product is introduced or when technology is expected to change. The history file might exist but be less useful when certain events (such as rollouts or special packages) are reflected in the past data, or when certain events are expected to occur in the future. In some cases, judgment methods are the only practical way to make a forecast. In other cases, judgment methods can also be used to modify forecasts that are generated by quantitative methods. They may recognize that one or two quantitative models have been performing particularly well in recent periods. Adjustments certainly would be called for if the forecaster has important contextual knowledge. *Contextual knowledge* is knowledge that practitioners gain through experience, such as cause-and-effect relationships, environmental cues, and organizational information that may have an effect on the variable being forecast. Adjustments also could account for unusual circumstances, such as a new sales promotion or unexpected international events. They could also have been used to remove the effect of special one-time events in the history file before quantitative methods are applied. Four of the more successful judgment methods are (1) salesforce estimates, (2) executive opinion, (3) market research, and (4) the Delphi method.

Salesforce estimates are forecasts compiled from estimates made periodically by members of a company's salesforce. The salesforce is the group most likely to know which services or products customers will be buying in the near future and in what quantities. Forecasts of individual salesforce members can be combined easily to get regional or national sales estimates. However, individual biases of the salespeople may taint the forecast. For example, some people are naturally optimistic, whereas others are more cautious. Adjustments in forecasts may need to be made to account for these individual biases.

Executive opinion is a forecasting method in which the opinions, experience, and technical knowledge of one or more managers or customers are summarized to arrive at a single forecast. All of the factors going into judgmental forecasts would fall into the category of executive opinion. Executive opinion can also be used for **technological forecasting**. The quick pace of technological change makes keeping abreast of the latest advances difficult.

Market research is a systematic approach to determine external consumer interest in a service or product by creating and testing hypotheses through data-gathering surveys. Conducting a market research study includes designing a questionnaire, deciding how to administer it, selecting a representative sample, and analyzing the information using judgment and statistical tools to interpret the responses. Although market research yields important information, it typically includes numerous qualifications and hedges in the findings.

The **Delphi method** is a process of gaining consensus from a group of experts while maintaining their anonymity. This form of forecasting is useful when no historical data are available from which to develop statistical models and when managers inside the firm have no experience on which to base informed projections. A coordinator sends questions to each member of the group of outside experts, who may not even know who else is participating. The coordinator prepares a statistical summary of the responses along with a summary of arguments for particular responses. The report is sent to the same group for another round, and the participants may choose to modify their previous responses. These rounds continue until consensus is obtained.

In the remainder of this chapter, we turn to the commonly used quantitative forecasting approaches.

salesforce estimates
The forecasts that are compiled from estimates of future demands made periodically by members of a company's salesforce.

executive opinion
A forecasting method in which the opinions, experience, and technical knowledge of one or more managers are summarized to arrive at a single forecast.

technological forecasting
An application of executive opinion to keep abreast of the latest advances in technology.

market research
A systematic approach to determine external consumer interest in a service or product by creating and testing hypotheses through data-gathering surveys.

Delphi method
A process of gaining consensus from a group of experts while maintaining their anonymity.

Causal Methods: Linear Regression

Causal methods are used when historical data are available and the relationship between the factor to be forecasted and other external or internal factors (e.g., government actions or advertising promotions) can be identified. These relationships are expressed in mathematical terms and can be complex. Causal methods are good for predicting turning points in demand and for preparing long-range forecasts. We focus on linear regression, one of the best known and most commonly used causal method.

In **linear regression**, one variable, called a dependent variable, is related to one or more independent variables by a linear equation. The **dependent variable** (such as demand for door hinges) is the one the manager wants to forecast. The **independent variables** (such as advertising expenditures and new housing starts) are assumed to affect the dependent variable and thereby "cause" the results observed in the past. Figure 8.3 shows how a linear regression line relates to the data. In technical terms, the regression line minimizes the squared deviations from the actual data.

linear regression
A causal method in which one variable (the dependent variable) is related to one or more independent variables by a linear equation.

dependent variable
The variable that one wants to forecast.

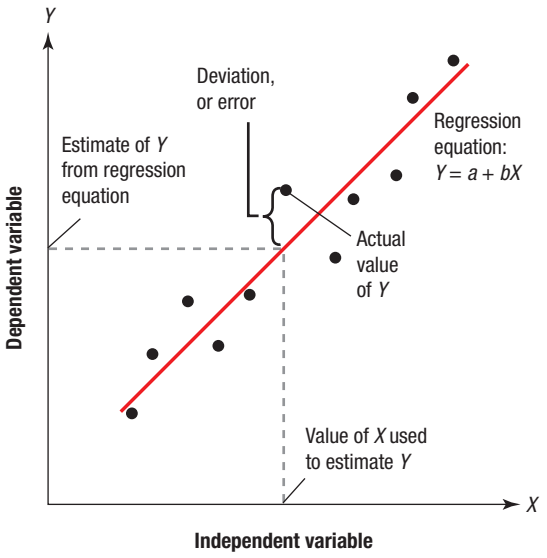
In the simplest linear regression models, the dependent variable is a function of only one independent variable and, therefore, the theoretical relationship is a straight line:

$$Y = a + bX$$

where

Y = dependent variable
X = independent variable
a = Y-intercept of the line
b = slope of the line

▼ **FIGURE 8.3**
Linear Regression Line Relative to Actual Demand



The objective of linear regression analysis is to find values of a and b that minimize the sum of the squared deviations of the actual data points from the graphed line. Computer programs are used for this purpose. For any set of matched observations for Y and X, the program computes the values of a and b and provides measures of forecast accuracy. Three measures commonly reported are (1) the sample correlation coefficient, (2) the sample coefficient of determination, and (3) the standard error of the estimate.

The *sample correlation coefficient*, r, measures the direction and strength of the relationship between the independent variable and the dependent variable. The value of r can range from -1.00 to $+1.00$. A correlation coefficient of $+1.00$ implies that period-by-period changes in

independent variables
Variables that are assumed to affect the dependent variable and thereby "cause" the results observed in the past.

direction (increases or decreases) of the independent variable are always accompanied by changes in the same direction by the dependent variable. An r of -1.00 means that decreases in the independent variable are always accompanied by increases in the dependent variable, and vice versa. A zero value of r means no linear relationship exists between the variables. The closer the value of r is to ± 1.00, the better the regression line fits the points.

The *sample coefficient of determination* measures the amount of variation in the dependent variable about its mean that is explained by the regression line. The coefficient of determination is the square of the correlation coefficient, or r^2. The value of r^2 ranges from 0.00 to 1.00. Regression equations with a value of r^2 close to 1.00 mean a close fit.

The *standard error of the estimate*, s_{xy}, measures how closely the data on the dependent variable cluster around the regression line. Although it is similar to the sample standard deviation, it measures the error from the dependent variable, Y, to the regression line, rather than to the mean. Thus, it is the standard deviation of the difference between the actual demand and the estimate provided by the regression equation.

EXAMPLE 8.2 Using Linear Regression to Forecast Product Demand

Online Resource
Active Model 8.1 provides insight on varying the intercept and slope of the model.

The supply chain manager seeks a better way to forecast the demand for door hinges and believes that the demand is related to advertising expenditures. The following are sales and advertising data for the past 5 months:

Month	Sales (in 1000s of units)	Advertising (in $1000s)
1	264	2.5
2	116	1.3
3	165	1.4
4	101	1.0
5	209	2.0

The company will spend $1,750 next month on advertising for the product. Use linear regression to develop an equation and a forecast for this product.

SOLUTION

We used POM for Windows to determine the best values of a, b, the correlation coefficient, the coefficient of determination, and the standard error of the estimate.

$$a = -8.135$$
$$b = 109.229$$
$$r = 0.980$$
$$r^2 = 0.960$$
$$s_{yx} = 15.603$$

The regression equation is

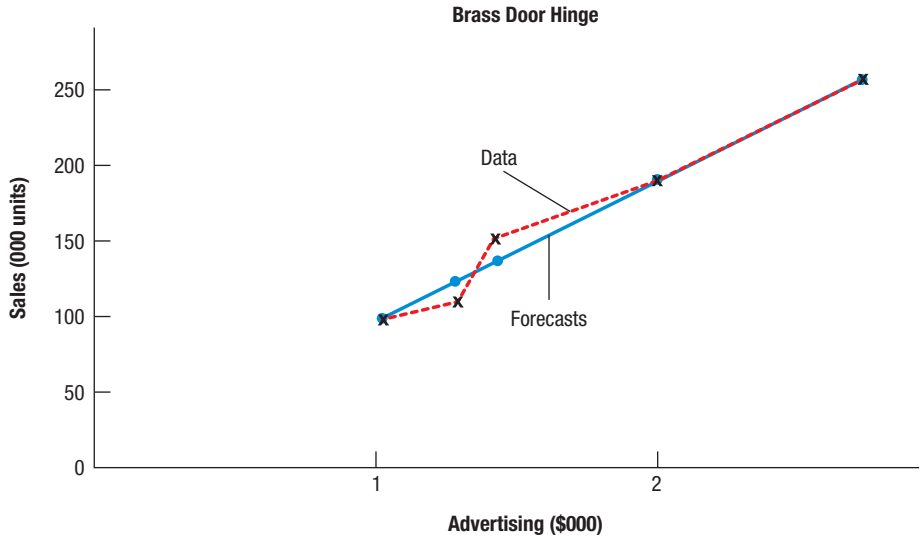
$$Y = -8.135 + 109.229X$$

and the regression line is shown in Figure 8.4. The sample correlation coefficient, r, is 0.98, which is unusually close to 1.00 and suggests an unusually strong positive relationship exists between sales and advertising expenditures. The sample coefficient of determination, r^2, implies that 96 percent of the variation in sales is explained by advertising expenditures.

DECISION POINT

The supply chain manager decided to use the regression model as input to planning production levels for month 6. As the advertising expenditure will be $1,750, the forecast for month 6 is $Y = -8.135 + 109.229\,(1.75) = 183.016$, or 183,016 units.

Often several independent variables may affect the dependent variable. For example, advertising expenditures, new corporation startups, and residential building contracts all may be important for estimating the demand for door hinges. In such cases, *multiple regression analysis* is helpful in determining a forecasting equation for the dependent variable as a function of several independent variables. Such models can be analyzed with POM for Windows or OM Explorer and can be quite useful for predicting turning points and solving many planning problems.



◀ **FIGURE 8.4**
Linear Regression Line for the Sales and Advertising Data Using POM for Windows

Time-Series Methods

Rather than using independent variables for the forecast as regression models do, time-series methods use historical information regarding only the dependent variable. These methods are based on the assumption that the dependent variable's past pattern will continue in the future. Time-series analysis identifies the underlying patterns of demand that combine to produce an observed historical pattern of the dependent variable and then develops a model to replicate it. In this section, we focus on five statistical time-series methods that address the horizontal, trend, and seasonal patterns of demand: simple moving averages, weighted moving averages, exponential smoothing, trend projection with regression, and multiplicative seasonal method. Before we discuss statistical methods, let us take a look at the simplest time-series method for addressing all patterns of demand—the naïve forecast.

Naïve Forecast

A method often used in practice is the **naïve forecast**, whereby the forecast for the next period (F_{t+1}) equals the demand for the current period (D_t). So if the actual demand for Wednesday is 35 customers, the forecasted demand for Thursday is 35 customers. Despite its name, the naïve forecast can perform well, depending on the underlying dynamics of the time series.

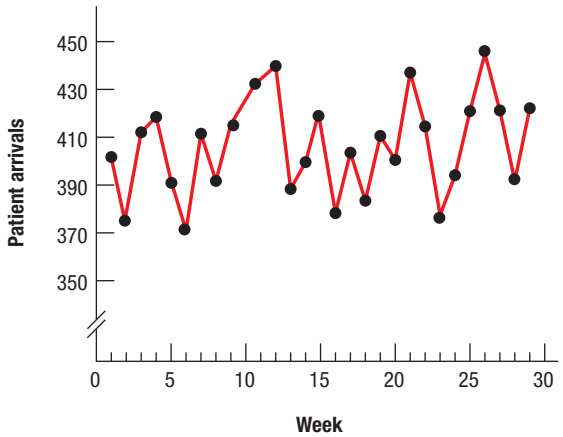
naïve forecast
A time-series method whereby the forecast for the next period equals the demand for the current period, or Forecast $= D_t$.

The naïve forecast method may be adapted to take into account a demand trend. The increase (or decrease) in demand observed between the last two periods is used to adjust the current demand to arrive at a forecast. Suppose that last week the demand was 120 units and the week before it was 108 units. Demand increased 12 units in 1 week, so the forecast for next week would be 120 + 12 = 132 units. The naïve forecast method also may be used to account for seasonal patterns. If the demand last July was 50,000 units, and assuming no underlying trend from one year to the next, the forecast for this July would be 50,000 units. The method works best when the horizontal, trend, or seasonal patterns are stable and random variation is small.

Horizontal Patterns: Estimating the Average

We begin our discussion of statistical methods of time-series forecasting with demand that has no apparent trend, seasonal, or cyclical patterns. The horizontal pattern in a time series is based on the mean of the demands, so we focus on forecasting methods that estimate the average of a time series of data. The forecast of demand for *any* period in the future is the average of the time series computed in the current period. For example, if the average of past demand calculated on Tuesday is 65 customers, the forecasts for Wednesday, Thursday, and Friday are 65 customers each day.

Consider Figure 8.5, which shows arrivals of patients at a medical clinic over the past 28 weeks. Assuming that the time series has only a horizontal and random pattern, one approach is simply to calculate the average of the data. However, this approach has no adaptive



▲ **FIGURE 8.5**
Weekly Patient Arrivals at a Medical Clinic

quality if a trend, seasonal, or cyclical pattern is present. The statistical techniques that do have an adaptive quality in estimating the average in a time series are (1) simple moving averages, (2) weighted moving averages, and (3) exponential smoothing.

simple moving average method

A time-series method used to estimate the average of a demand time series by averaging the demand for the n most recent time periods.

Simple Moving Averages The **simple moving average method** simply involves calculating the average demand for the n most recent time periods and using it as the forecast for future time periods. For the next period, after the demand is known, the oldest demand from the previous average is replaced with the most recent demand and the average is recalculated. In this way, the n most recent demands are used, and the average "moves" from period to period.

Specifically, the forecast for period $t + 1$ can be calculated at the end of period t (after the actual demand for period t is known) as

$$F_{t+1} = \frac{\text{Sum of last } n \text{ demands}}{n} = \frac{D_t + D_{t-1} + D_{t-2} + \cdots + D_{t-n+1}}{n}$$

where

D_t = actual demand in period t

n = total number of periods in the average

F_{t+1} = forecast for period $t + 1$

EXAMPLE 8.3 Using the Moving Average Method to Estimate Average Demand

Online Resources

Active Model 8.2 provides insight on the impact of varying n using the example in Figure 8.5.

Tutor 8.1 in OM Explorer provides another example to practice making forecasts with the moving average method.

a. Compute a *3-week* moving average forecast for the arrival of medical clinic patients in week 4. The numbers of arrivals for the past 3 weeks were as follows:

Week	Patient Arrivals
1	400
2	380
3	411

b. If the actual number of patient arrivals in week 4 is 415, what is the forecast error for week 4?

c. What is the forecast for week 5?

SOLUTION

a. The moving average forecast at the end of week 3 is

$$F_4 = \frac{411 + 380 + 400}{3} = 397.0$$

b. The forecast error for week 4 is

$$E_4 = D_4 - F_4 = 415 - 397 = 18$$

c. The forecast for week 5 requires the actual arrivals from weeks 2 through 4, the three most recent weeks of data.

$$F_5 = \frac{415 + 411 + 380}{3} = 402.0$$

DECISION POINT

Thus, the forecast at the end of week 3 would have been 397 patients for week 4, which fell short of actual demand by 18 patients. The forecast for week 5, made at the end of week 4, would be 402 patients. If a forecast is needed now for week 6 and beyond, it would also be for 402 patients.

The moving average method may involve the use of as many periods of past demand as desired. Large values of n should be used for demand series that are stable, and small values of n should be used for those that are susceptible to changes in the underlying average. If n is set to its lowest level (i.e., 1), it becomes the naïve method.

Weighted Moving Averages In the simple moving average method, each demand has the same weight in the average—namely, $1/n$. In the **weighted moving average method**, each historical demand in the average can have its own weight. The sum of the weights equals 1.0. For example, in a *three-period* weighted moving average model, the most recent period might be assigned a weight of 0.50, the second most recent might be weighted 0.30, and the third most recent might be weighted 0.20. The average is obtained by multiplying the weight of each period by the value for that period and adding the products together:

weighted moving average method
A time-series method in which each historical demand in the average can have its own weight; the sum of the weights equals 1.0.

$$F_{t+1} = 0.50D_t + 0.30D_{t-1} + 0.20D_{t-2}$$

For a numerical example of using the weighted moving average method to estimate average demand, see Solved Problem 2 and Tutor 8.2 of OM Explorer.

The advantage of a weighted moving average method is that it allows you to emphasize recent demand over earlier demand. (It can even handle seasonal effects by putting higher weights on prior years in the same season.) The forecast will be more responsive to changes in the underlying average of the demand series than the simple moving average forecast.

Exponential Smoothing The **exponential smoothing method** is a sophisticated weighted moving average method that calculates the average of a time series by implicitly giving recent demands more weight than earlier demands, all the way back to the first period in the history file. It is the most frequently used formal forecasting method because of its simplicity and the small amount of data needed to support it. Unlike the weighted moving average method, which requires n periods of past demand and n weights, exponential smoothing requires only three items of data: (1) the last period's forecast; (2) the actual demand for this period; and (3) a smoothing parameter, alpha (α), which has a value between 0 and 1.0. The equation for the exponentially smoothed forecast for period $t + 1$ is calculated

exponential smoothing method
A weighted moving average method that calculates the average of a time series by implicitly giving recent demands more weight than earlier demands.

$$F_{t+1} = \alpha D_t + (1 - \alpha)F_t$$

The emphasis given to the most recent demand levels can be adjusted by changing the smoothing parameter. Larger α values emphasize recent levels of demand and result in forecasts more responsive to changes in the underlying average. Smaller α values treat past demand more uniformly and result in more stable forecasts. Smaller α values are analogous to increasing the value of n in the moving average method and giving greater weight to past demand. In practice, various values of α are tried and the one producing the best forecasts is chosen.

Exponential smoothing requires an initial forecast to get started. There are several ways to get this initial forecast. OM Explorer and POM for Windows use the actual demand in the first period as a default setting, which becomes the forecast for the second period. Forecasts and forecast errors then are calculated beginning with period 2. If some historical data are available, the initial forecast can be found by calculating the average of several recent periods of demand. The effect of the initial estimate of the average on successive estimates of the average diminishes over time.

EXAMPLE 8.4 Using Exponential Smoothing to Estimate Average Demand

a. Reconsider the patient arrival data in Example 8.3. It is now the end of week 3, so the actual number of arrivals is known to be 411 patients. Using $\alpha = 0.10$, calculate the exponential smoothing forecast for week 4.

b. What was the forecast error for week 4 if the actual demand turned out to be 415?

c. What is the forecast for week 5?

Online Resources
Active Model 8.3 provides insight on the impact of varying α in Figure 8.5.

Tutor 8.3 in OM Explorer provides a new practice example of how to make forecasts with the exponential smoothing method.

SOLUTION

a. The exponential smoothing method requires an initial forecast. Suppose that we take the demand data for the first 2 weeks and average them, obtaining (400 + 380)/2 = 390 as an initial forecast. (POM for Windows and OM Explorer simply use the actual demand for the first week as a default setting for the initial forecast for period 1, and do not begin tracking forecast errors until the second period.) To obtain the forecast for week 4, using exponential smoothing with $D_3 = 411$, $\alpha = 0.10$, and $F_3 = 390$, we calculate the forecast for week 4 as

$$F_4 = 0.10(411) + 0.90(390) = 392.1$$

Thus, the forecast for week 4 would be 392 patients.

b. The forecast error for week 4 is

$$E_4 = 415 - 392 = 23$$

c. The new forecast for week 5 would be

$$F_5 = 0.10(415) + 0.90(392.1) = 394.4$$

or 394 patients. Note that we used F_4, not the integer-value forecast for week 4, in the computation for F_5. In general, we round off (when it is appropriate) only the final result to maintain as much accuracy as possible in the calculations.

DECISION POINT

Using this exponential smoothing model, the analyst's forecasts would have been 392 patients for week 4 and then 394 patients for week 5 and beyond. As soon as the actual demand for week 5 is known, then the forecast for week 6 will be updated.

Because exponential smoothing is simple and requires minimal data, it is inexpensive and attractive to firms that make thousands of forecasts for each time period. However, its simplicity also is a disadvantage when the underlying average is changing, as in the case of a demand series with a trend. Like any method geared solely to the assumption of a stable average, exponential smoothing results will lag behind changes in the underlying average of demand. Higher α values may help reduce forecast errors when a change occurs in the average; however, the lags will still occur if the average is changing systematically. Typically, if large α values (e.g., larger than 0.50) are required for an exponential smoothing application, chances are good that another model is needed because of a significant trend or seasonal influence in the demand series.

Trend Patterns: Using Regression

Let us now consider a demand time series that has a trend. A *trend* in a time series is a systematic increase or decrease in the average of the series over time. Where a significant trend is present, forecasts from naïve, moving average, and exponential smoothing approaches are adaptive, but still lag behind actual demand and tend to be below or above the actual demand.

Trend projection with regression is a forecasting model that accounts for the trend with simple regression analysis. To develop a regression model for forecasting the trend, let the dependent variable, Y, be a period's demand and the independent variable, t, be the time period. For the first period, let $t = 1$; for the second period, let $t = 2$; and so on. The regression equation is

$$F_t = a + bt$$

One advantage of the trend projection with regression model is that it can forecast demand well into the future. The previous models project demand just one period ahead, and assume that demand beyond that will remain at that same level. Of course, all of the models (including the trend projection with regression model) can be updated each period to stay current. One *apparent* disadvantage of the trend with regression model is that it is not adaptive. The solution to this problem comes when you answer the following question: If you had the past sales of Ford automobiles since 1920, would you include each year in your regression analysis, giving equal weight to each year's sales, or include just the sales for more recent years? You most likely would decide to include just the more recent years, making your regression model more adaptive. The trend projection with regression model can thus be made more or less adaptive by the selection of historical data periods to include in the same way as moving average (changing n) or exponential smoothing (changing α) models do.

The trend projection with regression model can be solved with either the *Trend Projection with Regression* Solver or the *Time Series Forecasting* Solver in OM Explorer. Both solvers provide the regression coefficients, coefficient of determination r^2, error measures, and forecasts into the future. POM for Windows has an alternative model (we do not cover that model in the textbook, although a description is provided in the software available online) that includes the trend, called the *Trend-Adjusted Smoothing* model.

The *Trend Projection with Regression* Solver focuses exclusively on trend analysis. Its graph gives a big-picture view of how well the model fits the actual demand. Its sliders allow you to control when the regression begins, how many periods are included in the regression analysis, and how many periods you want forecasted into the future. The *Time Series Forecasting* Solver, in contrast, covers all time-series models, including the trend projection with regression. It also computes a combination forecast, which we cover in a subsequent section on using multiple techniques.

EXAMPLE 8.5 Using Trend Projection with Regression to Forecast a Demand Series with a Trend

Medanalysis, Inc., provides medical laboratory services to patients of Health Providers, a group of 10 family-practice doctors associated with a new health maintenance program. Managers are interested in forecasting the number of blood analysis requests per week. Recent publicity about the damaging effects of cholesterol on the heart has caused a national increase in requests for standard blood tests. The arrivals over the past 16 weeks are given in Table 8.1. What is the forecasted demand for the next three periods?

TABLE 8.1 | ARRIVALS AT MEDANALYSIS FOR PAST 16 WEEKS

Week	Arrivals	Week	Arrivals
1	28	9	61
2	27	10	39
3	44	11	55
4	37	12	54
5	35	13	52
6	53	14	60
7	38	15	60
8	57	16	75

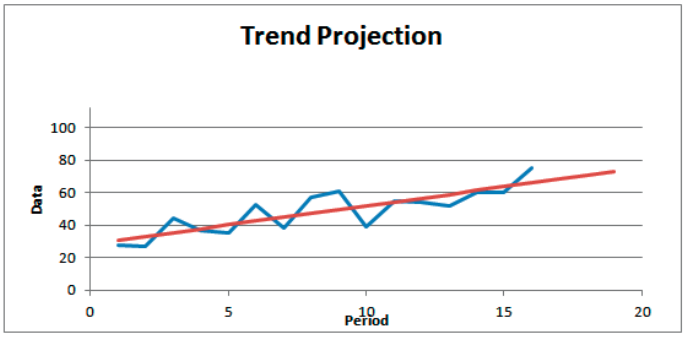
SOLUTION

Figure 8.6(a) shows the results using the *Trend Projection with Regression* Solver when all 16 weeks are included in the regression analysis, with Figure 8.6(b) showing the worksheet that goes with it.

Looking at the Results sheet of Figure 8.6(a), we see that the *Y*-intercept of the trend line (*a*) is 28.50 and the slope of the line (*b*) is 2.35. Thus, the trend equation is $F_t = a + bt$, where t is the time period for which you are forecasting. The forecast for period 19 is 28.5 + 2.35(19) = 73. The error terms are

Solver - Trend Projection with Regression

Regression begins in period	1
Error analysis begins in period	1
Number of future forecasts	3



a (Y intercept)	28.50
b (slope or trend)	2.35
r2	0.69
CFE	0.00
MAD	6.21
MSE	52.96
MAPE	13.53%
Forecast for period 17	68.375
Forecast for period 18	70.72059
Forecast for period 19	73.06618

◀ **FIGURE 8.6(A)** Trend Projection with Regression Results

CFE = 0 (which is to be expected when the regression begins at the same time that error analysis begins), MAD = 6.21, MSE = 52.96, and MAPE = 13.53 percent. The coefficient of determination r^2 is decent at 0.69. The trend line is rising gently and reaches 73 for period 19. Each period, the forecast predicts an increase of 2.35 arrivals per week.

FIGURE 8.6(B) ▶
Detailed Calculations of Forecast Errors

					Averages		
				CFE	MSE	MAD	MAPE
				0.000	52.958	6.210	13.53%
Period #	Actual Demand	Forecast	Error	Running CFE	Error Squared	Absolute Error	Abs % Error
1	28	31	-2.846	-2.846	8.097	2.846	10.16%
2	27	33	-6.191	-9.037	38.331	6.191	22.93%
3	44	36	8.463	-0.574	71.626	8.463	19.23%
4	37	38	-0.882	-1.456	0.779	0.882	2.38%
5	35	40	-5.228	-6.684	27.331	5.228	14.94%
6	53	43	10.426	3.743	108.711	10.426	19.67%
7	38	45	-6.919	-3.176	47.874	6.919	18.21%
8	57	47	9.735	6.559	94.776	9.735	17.08%
9	61	50	11.390	17.949	129.725	11.390	18.67%
10	39	52	-12.956	4.993	167.855	12.956	33.22%
11	55	54	0.699	5.691	0.488	0.699	1.27%
12	54	57	-2.647	3.044	7.007	2.647	4.90%
13	52	59	-6.993	-3.949	48.897	6.993	13.45%
14	60	61	-1.338	-5.287	1.791	1.338	2.23%
15	60	64	-3.684	-8.971	13.571	3.684	6.14%
16	75	66	8.971	0.000	80.471	8.971	11.96%

Seasonal Patterns: Using Seasonal Factors

Seasonal patterns are regularly repeating upward or downward movements in demand measured in periods of less than 1 year (hours, days, weeks, months, or quarters). In this context, the time periods are called *seasons*. For example, customer arrivals at a fast-food shop on any day may peak between 11 A.M. and 1 P.M. and again from 5 P.M. to 7 P.M.

An easy way to account for seasonal effects is to use one of the techniques already described, but to limit the data in the time series to those time periods in the same season. For example, for a day-of-the-week seasonal effect, one time series would be for Mondays, one for Tuesdays, and so on. Such an approach accounts for seasonal effects, but has the disadvantage of discarding considerable information on past demand.

multiplicative seasonal method
A method whereby seasonal factors are multiplied by an estimate of average demand to arrive at a seasonal forecast.

Other methods are available that analyze all past data, using one model to forecast demand for all the seasons. We describe only the **multiplicative seasonal method**, whereby an estimate of average demand is multiplied by seasonal factors to arrive at a seasonal forecast. The four-step procedure presented here involves the use of simple averages of past demand, although more sophisticated methods for calculating averages, such as a moving average or exponential smoothing approach, could be used. The following description is based on a seasonal pattern lasting 1 year and seasons of 1 month, although the procedure can be used for any seasonal pattern and season of any length.

1. For each year, calculate the average demand per season by dividing annual demand by the number of seasons per year.
2. For each year, divide the actual demand for a season by the average demand per season. The result is a *seasonal factor* for each season in the year, which indicates the level of demand relative to the average demand. For example, a seasonal factor of 1.14 calculated for April implies that April's demand is 14 percent greater than the average demand per month.
3. Calculate the average seasonal factor for each season, using the results from step 2. Add the seasonal factors for a season and divide by the number of years of data.
4. Calculate each season's forecast for next year. Begin by forecasting next year's annual demand using the naïve method, moving averages, exponential smoothing, or trend projection with regression. Then, divide annual demand by the number of seasons per year to get the average demand per season. Finally, make the seasonal forecast by multiplying the average demand per season by the appropriate seasonal factor found in step 3.

EXAMPLE 8.6 Using the Multiplicative Seasonal Method to Forecast the Number of Customers

The manager of the Stanley Steemer carpet cleaning company needs a quarterly forecast of the number of customers expected next year. The carpet cleaning business is seasonal, with a peak in the third quarter and a trough in the first quarter. The manager wants to forecast customer demand for each quarter of year 5, based on an estimate of total year 5 demand of 2,600 customers.

SOLUTION

The following table calculates the seasonal factor for each week.

It shows the quarterly demand data from the past 4 years, as well as the calculations performed to get the average seasonal factor for each quarter.

	YEAR 1		YEAR 2		YEAR 3		YEAR 4		
Quarter	Demand	Seasonal Factor (1)	Demand	Seasonal Factor (2)	Demand	Seasonal Factor (3)	Demand	Seasonal Factor (4)	Average Seasonal Factor [(1+2+3+4)/4]
1	45	45/250 = 0.18	70	70/300 = 0.23333	100	100/450 = 0.22222	100	100/550 = 0.18182	0.2043
2	335	335/250 = 1.34	370	370/300 = 1.23333	585	585/450 = 1.30	725	725/550 = 1.31818	1.2979
3	520	520/250 = 2.08	590	590/300 = 1.96667	830	830/450 = 1.84444	1,160	1,160/550 = 2.10909	2.0001
4	100	100/250 = 0.40	170	170/300 = 0.56667	285	285/450 = 0.63333	215	215/550 = 0.39091	0.4977
Total	1,000		1,200		1,800		2,200		
Average	1,000/4 = 250		1,200/4 = 300		1,800/4 = 450		2,200/4 = 550		

For example, the seasonal factor for quarter 1 in year 1 is calculated by dividing the actual demand (45) by the average demand for the whole year (1,000/4 = 250). When this is done for all 4 years, we then can average the seasonal factors for quarter 1 over all 4 years. The result is a seasonal factor of 0.2043 for quarter 1.

Once seasonal factors are calculated for all four seasons (see last column in the previous table), we then turn to making the forecasts for year 5. The manager suggests a forecast of 2,600 customers for the whole year, which seems reasonable given that the annual demand has been increasing by an average of 400 customers each year (from 1,000 in year 1 to 2,200 in year 4, or 1,200/3 = 400). The computed forecast demand is found by extending that trend, and projecting an annual demand in year 5 of 2,200 + 400 = 2,600 customers. (This same result is confirmed using the *Trend Projection with Regression* Solver of OM Explorer.) The quarterly forecasts are straightforward. First, find the average demand forecast for year 5, which is 2,600/4 = 650. Then multiply this average demand by the average seasonal index, giving us

Quarter	Forecast
1	650 × 0.2043 = 132.795
2	650 × 1.2979 = 843.635
3	650 × 2.0001 = 1,300.065
4	650 × 0.4977 = 323.505

Figure 8.7 shows the computer solution using the *Seasonal Forecasting* Solver in OM Explorer. Figure 8.7(b), the results, confirms all of the calculations we've made in this example. Notice in Figure 8.7(a), the inputs sheet, that a computer demand forecast is provided as a default for year 5. However, there is an option for user-supplied demand forecast that overrides the computer-supplied forecast if the manager wishes to make a judgmental forecast based on additional information.

DECISION POINT

Using this seasonal method, the analyst makes a demand forecast as low as 133 customers in the first quarter and as high as 1,300 customers in the third quarter. The season of the year clearly makes a difference.

FIGURE 8.7
Demand Forecasts Using the *Seasonal Forecasting* Solver of OM Explorer

Period: Quarters

Starting Year: 1 Years: 4

Computed Forecast Demand for Year 5: 2600

User-supplied Forecast Demand for Year 5: 2600

Quarter	Year 1	2	3	4
1	45	70	100	100
2	335	370	585	725
3	520	590	830	1160
4	100	170	285	215

(a) Inputs sheet

Quarter	Seasonal Index	Forecast
1	0.2043	132.795
2	1.2979	843.635
3	2.0001	1300.065
4	0.4977	323.505

(b) Results

additive seasonal method
A method in which seasonal forecasts are generated by adding a seasonal constant to, or by subtracting a seasonal constant from, the estimate of average demand per season.

An alternative to the multiplicative seasonal method is the **additive seasonal method**, whereby seasonal forecasts are generated by adding a seasonal constant (say, 50 units) to, or by subtracting a seasonal constant (say, 50 units) from, the estimate of average demand per season. This approach is based on the assumption that the seasonal pattern is constant, regardless of average demand. The amplitude of the seasonal adjustment remains the same regardless of the level of demand.

Criteria for Selecting Time-Series Methods

Of all the time-series forecasting methods available, which should be chosen? Forecast error measures provide important information for choosing the best forecasting method for a service or product. They also guide managers in selecting the best values for the parameters needed for the method: n for the moving average method, the weights for the weighted moving average method, α for the exponential smoothing method, and when regression data begin for the trend projection with regression method. The criteria to use in making forecast method and parameter choices include (1) minimizing bias (CFE); (2) minimizing MAPE, MAD, or MSE; (3) maximizing r^2 for trend projections using regression; (4) using a holdout sample analysis; (5) using a tracking signal; (6) meeting managerial expectations of changes in the components of demand; and (7) minimizing the forecast errors in recent periods. The first three criteria relate to statistical measures based on historical performance, the fourth is a test under realistic conditions, the fifth evaluates forecast performance and the potential need to change the method, the sixth reflects expectations of the future that may not be rooted in the past, and the seventh is a way to use whatever method seems to be working best at the time a forecast must be made.

Using Statistical Criteria Statistical performance measures can be used in the selection of which forecasting method to use. The following guidelines will help when searching for the best time-series models:

1. For projections of more stable demand patterns, use lower α values or larger n values to emphasize historical experience.
2. For projections of more dynamic demand patterns using the models covered in this chapter, try higher α values or smaller n values. When historical demand patterns are changing, recent history should be emphasized.

Using a Holdout Sample Often, the forecaster must make tradeoffs between bias (CFE) and the measures of forecast error dispersion (MAPE, MAD, and MSE). Managers also must recognize that

the best technique in explaining the past data is not necessarily the best technique to predict the future, and that "overfitting" past data can be deceptive. A forecasting method may have small errors relative to the history file but may generate high errors for future time periods. For this reason, some analysts prefer to use a **holdout sample** as a final test (see Experiential Learning Exercise 8.1 at the end of this chapter). To do so, they set aside some of the more recent periods from the time series and use only the earlier time periods to develop and test different models. Once the final models have been selected in the first phase, they are tested again with the holdout sample. Performance measures, such as MAD and CFE, would still be used but they would be applied to the holdout sample. Whether this idea is used or not, managers should monitor future forecast errors and modify their forecasting approaches as needed. Maintaining data on forecast performance is the ultimate test of forecasting power—rather than how well a model fits past data or holdout samples.

holdout sample

Actual demands from the more recent time periods in the time series that are set aside to test different models developed from the earlier time periods.

Using a Tracking Signal A **tracking signal** is a measure that indicates whether a method of forecasting is accurately predicting actual changes in demand. The tracking signal measures the number of MADs represented by the cumulative sum of forecast errors, the CFE. The CFE tends to be close to 0 when a correct forecasting system is being used. At any time, however, random errors can cause the CFE to be a nonzero number. The tracking signal formula is

tracking signal

A measure that indicates whether a method of forecasting is accurately predicting actual changes in demand.

$$\text{Tracking signal} = \frac{\text{CFE}}{\text{MAD}} \text{ or } \frac{\text{CFE}}{\text{MAD}_t}$$

Each period, the CFE and MAD are updated to reflect current error, and the tracking signal is compared to some predetermined limits. The MAD can be calculated in one of two ways: (1) as the simple average of all absolute errors (as demonstrated in Example 8.1) or (2) as a weighted average determined by the exponential smoothing method:

$$\text{MAD}_t = \alpha|E_t| + (1 - \alpha)\text{MAD}_{t-1}$$

If forecast errors are normally distributed with a mean of 0, the relationship between σ and MAD is simple:

$$\sigma = (\sqrt{\pi/2})(\text{MAD}) \cong 1.25(\text{MAD})$$

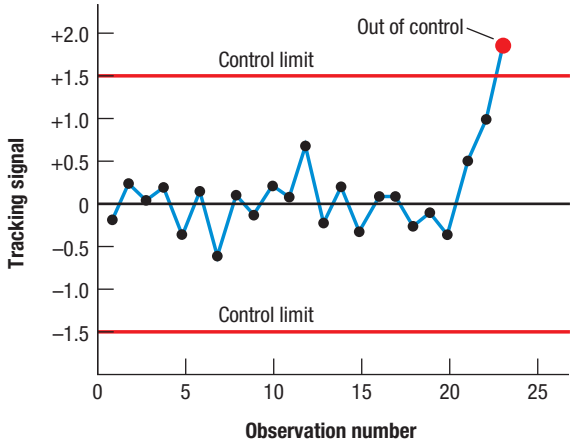
$$\text{MAD} = 0.7978\sigma \cong 0.8\sigma$$

where

$$\pi = 3.1416$$

This relationship allows use of the normal probability tables to specify limits for the tracking signal. If the tracking signal falls outside those limits, the forecasting model no longer is tracking demand adequately. A tracking system is useful when forecasting systems are computerized because it alerts analysts when forecasts are getting far from desirable limits. Figure 8.8 shows tracking signal results for 23 periods plotted on a *control chart*. The control chart is useful for determining whether any action needs to be taken to improve the forecasting model. In the example, the first 20 points cluster around 0, as we would expect if the forecasts are not biased. The CFE will tend toward 0. When the underlying characteristics of demand change but the forecasting model does not, the tracking signal eventually goes out of control. The steady increase after the 20th point in Figure 8.8 indicates that the process is going out of control. The 21st and 22nd points are acceptable, but the 23rd point is not.

▼ **FIGURE 8.8**
Tracking Signal



Big Data and the Forecasting Process

Often companies must prepare forecasts for hundreds or even thousands of services or products repeatedly. For example, a large network of health care facilities must calculate demand forecasts for each of its services for every department. This undertaking involves voluminous data that must be manipulated frequently. However, software can ease the burden of making these forecasts and coordinating the forecasts between customers and suppliers. Many forecasting software packages are available, including Manugistics, Forecast Pro, and SAS. The forecasting routines in OM Explorer and POM for Windows give some hint of their capabilities. In the hope of garnering improved insights into the demands for their products and services, a growing number of organizations are, however, going beyond these traditional forecasting capabilities and delving into the vast amounts of data that are being generated daily using advanced analytical methods. They realize that forecasting is not just a set of techniques, but instead a process that must be

designed and managed. While there is no one approach to effective demand forecasting that works for everyone, here we describe the challenges and benefits of harnessing vast amounts of relevant data for demand forecasting and a comprehensive forecasting process that can be quite effective in managing operations and the supply chain.

Big Data

Thus far we have discussed two general types of statistical forecasting models. First, causal models use data on a set of independent variables to predict a dependent variable, such as demand. The independent variables have been shown historically to have an influence on the dependent variable. The second type is time-series models, which use only data on past demands to predict the future. The assumption is that the demand pattern of the past will repeat itself in the future. Now, suppose that you have detailed data on every one of your organization's sales transactions on any given day, not only the type and quantity of the purchased product but also other products or services customers looked at, how long they looked, and how many products were temporarily placed in the shopping cart. Suppose you also have data on how much they were influenced by promotions and product recommendations, and how they navigated your website by looking at the sequence of mouse clicks. You can also accumulate data on what the weather was like, or even whether the Milwaukee Brewers had a home game that day. This could amount to a lot of data. For example, it is estimated that Walmart collects more than 2.5 petabytes of data every *hour* from its customer transactions. A petabyte is 1 quadrillion bytes, or the equivalent of about 20 million filing cabinets worth of text.[2] Walmart uses these data to estimate demand for its more than 16 million online products. Imagine the enormity of the data files for Amazon.com, which sells more than 405 million products online.

big data

Data sets that are so large or complex that traditional data processing applications are inadequate to deal with them.

To describe this phenomenon, information technologists have coined the term **big data**, which refers to data sets that are so large or complex that traditional data processing applications are inadequate to deal with them. Big data is a collection of data from traditional and digital sources that represent a source for discovery and analysis. In the opening vignette to this chapter, we saw how Starbucks used big data to forecast and manage its demand. Big data is characterized by three Vs: volume, variety, and velocity.

Volume More data cross the Internet every second than were stored in the entire Internet just 20 years ago. Where does the data come from? It comes from a myriad of sources, such as business sales records, smartphones, or real-time sensors used in the *Internet of Things (IoT)*. We have already noted how much data online retailers such as Walmart and Amazon collect. Fortunately, the cost of collecting and storing this amount of data has dramatically declined over time.

Variety Data useful for forecasting can come from a variety of sources. Mobile phones, online shopping, social networks, electronic communication, Global Positioning Systems (GPS), and instrumented machinery all produce data that can be used to predict future demands for products or services. For example, customer reviews of their experiences at a hotel on Travelocity can affect the demand for the services of that hotel. Data may exist in a wide variety of file types, including structured data (such as traditional database stores), unstructured data (such as Twitter communication), or streaming data (such as data from sensors in the Internet of Things).

Velocity Often it is the speed, or velocity, at which the data are created and analyzed that is critical. Every big-data analytics project will ingest, correlate, and analyze data sources in response to a particular query or need. Real-time or nearly real-time information makes it possible for a company to be more agile—an important competitive priority.

Big data seems to hold a lot of promise for predicting the demand for products and services. However, managers who want to tap its powers must take into account serious considerations. First, the computing power to quickly process high volumes and varieties of data can swamp a single server or cluster of servers. In some cases, it can take hundreds or thousands of servers to handle the load, which may only be used occasionally. Consequently, public cloud providers have emerged to host big-data projects. Companies are only charged for the storage and compute time actually used. An example is Amazon's Web Services (AWS), which is (as of 2019) a $35.03 billion business, and is one of the fastest growing cloud services. Well-known companies and organizations, such as NASA, Netflix, Facebook, ESPN, and the U.S. Navy, have moved their online customer service applications to the Amazon cloud service, where customer behavioral data are being accumulated and analyzed.[3]

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[2]For an overview of big data and its benefits, see Andrew McAfee and Erik Brynjolfsson, "Big Data: The Management Revolution," Harvard Business Review (October 2012), 60–68; Lisa Arthur, "What Is Big Data?" Forbes (August 15, 2013), http://onforb.es/127cyYm; Margaret Rouse, "Big Data," SearchCloudComputing.com (accessed January 13, 2017).

[3]See https://aws.amazon.com/solutions/case-studies/all/ for detailed cases of AWS clients (accessed January 20, 2017).

Second, many companies do not have the skills needed to execute a big-data project. Critical to success are data scientists and other professionals skilled at working with large quantities of information. Skills in cleaning and organizing large data sets that rarely come in structured formats are very important. Finally, management must develop a culture that allows for the acceptance of findings from a big-data project. Starting at the top, managers who have been making decisions based on their past experiences and intuition must be amenable to accepting results that counter that judgment. Further, managers, and not technicians, must be the ones to identify which problems to tackle using big-data methods, because they have the deepest knowledge of the problem domains. Cultural change in an organization is not an overnight process and takes total managerial commitment. Nonetheless, companies employing data-driven decisions tend to be more successful than others. Managerial Practice 8.1 shows how big-data approaches are being used in the health care industry.

MANAGERIAL PRACTICE 8.1 Big Data and Health Care Forecasting

Reliable health forecasts are important for a number of reasons. They can enhance efforts of preventive health care services, predict major life-threatening events, and estimate the demand for health care services. Big-data approaches are being used by health care facilities and researchers worldwide to improve the quality of life.

Preventive Health Care

The coronavirus pandemic required the development of big data sets of massive amounts of epidemiological and scientific data to enable health workers, scientists, epidemiologists, and policy makers to make more informed predictions and decisions. The near real-time COVID-19 trackers continuously pulled data from sources around the world and synthesized the incident data on a global basis. Beyond the novel viral infections, health care providers are being pressured by insurers and employers to find ways to prevent two other critical health conditions: diabetes and heart disease. If hospitals could forecast a patient's medical future, preemptive actions could reduce the chances of hospitalization and even premature death. Some hospitals are collecting new information from patients directly, while others have sought data from companies that sell consumer and financial information, or federal agencies that provide statistics on poverty, housing density, and unemployment under the assumption that how a person lives is important for predicting future medical intervention. For example, Fairview Health Services asks primary-care patients to complete a survey of their self-confidence to manage their illness. An analysis of responses over 1 year showed that patients without confidence to manage their diabetes were 56 percent more likely to be readmitted to the hospital than the most assured and knowledgeable patients. The analysis enables Fairview to identify the high-risk patients, set up a program to help them, and plan for the necessary resources.

Predicting Cardiac Arrests

Each year, approximately 209,000 patients suffer from an in-hospital cardiac arrest in the United States, with less than a quarter living long enough to be discharged. Big-data researchers are taking advantage of the vast availability of electronic medical records to develop prediction models that would pick out the high-risk patients so that medical personnel can treat them accordingly. To facilitate this effort, the Center for Research at the University of Chicago has created a massive data warehouse of 10 years of medical records. Researchers have created a model based on 60,000 records that produces a score for each patient, based on data such as the patient's medical record, respiratory rate, blood pressure, and recent lab results. The score is monitored in real time, and if it gets above a certain threshold, a response team is sent to intervene.



Derek Meijer/Alamy Stock Photo

Big data is useful for forecasting demands for healthcare services in all facets of hospital operations. Here doctors treat a patient in an intensive care unit.

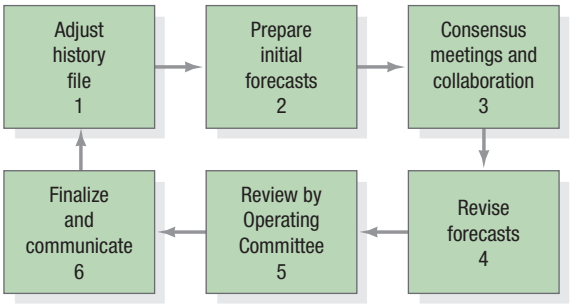
Demand Forecasting

Reliable demand forecasting is critical for determining staff sizes as well as capacity requirements. Such was the case when New York's Long Beach Medical Center was destroyed by Hurricane Sandy in 2012. Declaring bankruptcy after the disaster, it never reopened as a full-service hospital. The question arose as to whether another hospital should be built to replace it. Demand forecasts using data such as the size of the expected population in the coming years, the market share of the old hospital, out-of-area draw, the percentage of the population that would use the facility for inpatient care or surgery, and demographic information on the surrounding area were used to estimate the required number of physicians, assistants, rooms, and beds. The conclusion was to use freestanding emergency rooms with ambulatory care, a solution many hospitals favor over expanding of traditional hospital facilities.[4]

[4] *Sources:* Melanie Evans, "Doctors Dig for More Data About Patients," *Wall Street Journal* (September 25, 2016); Laura Landro, "Hospitals See Data-Crunching as a Key to a Better ICU," *Wall Street Journal* (June 29, 2015); Meeri Kim, "A Netflix-Like Predictive Model: Hospital Systems Could Pinpoint Which Patients Are Most Likely to Code on Their Watch," *Washington Post* (December 4, 2015); Tammy Worth, "Healthcare Providers Increase Reliance on Demand Forecasting," *Healthcare Finance* (December 4, 2014), 1–9; Randy Bean, "Big Data in the Time of Coronavirus (COVID-19)," *Forbes* (March 30, 2020), https://www.forbes.com; Jennifer Bresnick, "10 High-Value Use Cases for Predictive Analytics in Healthcare," *Health IT Analytics* (September 4, 2018).

A Typical Forecasting Process

There are many inputs to the forecasting process. A key input to the database is a history file on past demand, which is kept up to date with the actual demands as they occur. Clarifying notes and adjustments are made to the database to explain unusual demand behavior, such as the impact of special promotions and closeouts. Final forecasts just made at the end of the prior cycle are entered in the history file so as to track forecast errors. Other information sources in the database are from salesforce estimates, outstanding bids on new orders, booked orders, market research studies, competitor behavior, economic outlook, new product introductions, pricing, and promotions. If point-of-sale (POS) data are used, then considerable information sharing will take place with retail customers. For new products, a history database is constructed based on the firm's experience with prior products and the judgment of personnel.



Outputs of the process are forecasts for multiple time periods into the future. Typically, they are on a monthly basis and are projected out from 6 months to 2 years, or, as in the case of some big-data applications, the time horizon may be measured in hours. Most software packages have the ability to "roll up" or "aggregate" forecasts for individual stock-keeping units (SKUs) into forecasts for whole product families. Forecasts can also be "blown down" or "disaggregated" into smaller pieces. In a make-to-stock environment, forecasts tend to be more detailed and can get down to specific individual products. In a make-to-order environment, the forecasts tend to be for groups of products or services, or may actually be focused on the resources needed to produce them. Similarly, if the lead times to buy raw materials and manufacture a product or provide a service are long, the forecasts go further out into the future.

The typical forecast process, predicated on a monthly forecast cycle, consists of six structured steps, facilitated by a demand manager and assisted by forecast analysts as needed. Shorter cycles, and a different process, are needed when forecast horizons are less than a month, as in some of the health care examples in Managerial Practice 8.1.

Step 1. The cycle begins midmonth just after the forecasts have been finalized and communicated to the stakeholders. Now is the time to update the history file and review forecast accuracy. At the end of the month, enter actual demand and review forecast accuracy.



Paul Zimmerman/Stringer/Getty Images Entertainment/Getty Images

The demand forecasting process for the Moto Z Droid smartphone was considerably improved by closely collaborating with major retailers, obtaining point-of-sale data from them.

Step 2. Prepare initial forecasts using some forecasting software package and judgment. Adjust the parameters of the software to find models that fit the past demand well and yet reflect the demand manager's judgment on irregular events and information about future sales pulled from various sources and business units.

Step 3. Hold consensus meetings with the stakeholders, such as marketing, sales, supply chain planners, and finance. Make it easy for business unit and field sales personnel to make inputs. Use the Internet to get collaborative information from key customers and suppliers. The goal is to arrive at consensus forecasts from all important players.

Step 4. Revise the forecasts using judgment, considering the inputs from the consensus meetings and collaborative sources.

Step 5. Present the forecasts to the operating committee for review and to reach a final set of forecasts. It is important to have a set of forecasts that everybody agrees upon and will work to support.

Step 6. Finalize the forecasts based on the decisions of the operating committee and communicate them to the important stakeholders. Supply chain planners are usually the biggest users.

As with all work activity, forecasting is a process and should be continually reviewed for improvements. A better process will foster better relationships between departments such as marketing, sales, and operations. It will also produce better forecasts. While sophisticated forecasting models are helpful, communication and collaboration are key ingredients of successful forecasting processes.

Using Multiple Forecasting Methods Step 2 of the forecasting process relates to preparing an initial forecast. However, we need not rely on a single forecasting method. Several different forecasts can be used to arrive at a final forecast. Initial statistical forecasts using several time-series methods and regression are distributed to knowledgeable individuals, such as marketing directors and sales teams

(and sometimes even suppliers and customers) for their adjustments. They can account for current market and customer conditions that are not necessarily reflected in past data. Multiple forecasts may come from different sales teams, and some teams may have a better record on forecast errors than others.

Research during the past two decades suggests that combining forecasts from multiple sources often produces more accurate forecasts. **Combination forecasts** are produced by averaging independent forecasts based on different methods, different sources, or different data. It is intriguing that combination forecasts often perform better over time than even the *best* single forecasting procedure. For example, suppose that the forecast for the next period is 100 units from technique 1 and 120 units from technique 2. Technique 1, which uses different information than technique 2, has generally provided more accurate forecasts to date; however, technique 2 occasionally beats it. A combination forecast for next period, giving equal weight to each technique, is 110 units (or $0.5 \times 100 + 0.5 \times 120$). Other weighting schemes could be used, such as 60–40 in favor of technique 1. It is possible that an averaging technique used consistently into the future will be much more accurate than those of any single best forecasting technique (in this example, technique 1). Combining is most effective when the individual forecasts bring different kinds of information into the forecasting process. Forecasters have achieved excellent results by weighting such forecasts equally, and this is a good starting point. However, unequal weights may provide better results under some conditions. OM Explorer and POM for Windows allow you to evaluate several forecasting models and create combination forecasts from them. In fact, the *Time Series Forecasting* Solver of OM Explorer automatically computes a combination forecast as a weighted average, using the weights that you supply for the various models that it evaluates. The models include the naïve, moving average, exponential smoothing, and regression trend projector methods. Alternatively, you can create a simple Excel spreadsheet that combines forecasts generated by POM for Windows to create combination forecasts. The *Time Series Forecasting* Solver also allows you to evaluate your forecasting process with a holdout sample. The forecaster makes a forecast just one period ahead, and learns of given actual demand. Next the solver computes forecasts and forecast errors for the period. The process continues to the next period in the holdout sample, with the forecaster committing to a forecast for the next period. To be informed, the forecaster should also be aware of how well the other forecasting methods have been performing, particularly in the recent past.

combination forecasts

Forecasts that are produced by averaging independent forecasts based on different methods, different sources, or different data.

Another way to take advantage of multiple techniques is **focus forecasting**, which selects the best forecast (based on past error measures) from a group of forecasts generated by individual techniques. Every period, all techniques are used to make forecasts for each item. The forecasts are made with a computer because there can be 100,000 SKUs at a company, each needing to be forecast. Using the history file as the starting point for each method, the computer generates forecasts for the current period. The forecasts are compared to actual demand, and the method that produces the forecast with the least error is used to make the forecast for the next period. The method used for each item may change from period to period.

focus forecasting

A method of forecasting that selects the best forecast from a group of forecasts generated by individual techniques.

Adding Collaboration to the Process In step 3 of the forecasting process, we try to achieve consensus of the forecast. One way to achieve that consensus in a formal way is to employ **collaborative planning, forecasting, and replenishment (CPFR)**, a process for supply chain integration that allows a supplier and its customers to collaborate on making the forecast by using the Internet. Traditionally, suppliers and buyers in most supply chains prepare independent demand forecasts. With CPFR, firms initiate customer-focused operations teams that share with retailers their real-time data and plans, including forecasts, inventories, sales to retailers' shelves, promotions, product plans, and exceptions. CPFR involves four interactive activities:

collaborative planning, forecasting, and replenishment (CPFR)

A process for supply chain integration that allows a supplier and its customers to collaborate on making the forecast by using the Internet.

- **Strategy and Planning:** to establish the ground rules for the collaborative relationship, such as business goals, scope of collaboration, and assignment of roles and responsibilities.
- **Demand and Supply Management:** to develop sales forecasts, procedures for order planning, and inventory positions.
- **Execution:** to manage the generation of orders between supplier and customers and the production, shipment, and delivery of products for customer purchase.
- **Analysis:** to monitor the planning process and operations for out-of-bound conditions and to evaluate achievement of business goals.

Many firms have used CPFR to coordinate forecasts and plans up and down the supply chain. CPFR enables firms to collaborate with their retailers' distribution centers' customers and increase their ability to forecast effectively. The real key to a successful implementation of CPFR is the forging of a cultural alliance that involves peer-to-peer relations and cross-functional teams.

Forecasting is not a stand-alone activity, but part of a larger process that encompasses the remaining chapters. After all, demand is only half the equation—the other half is supply. Future plans must be developed to supply the resources needed to meet the forecasted demand. Resources include the workforce, materials, inventories, dollars, and equipment capacity. Making sure that demand and supply plans are in balance begins in the next chapter, Chapter 9, "Inventory Management," and continues with Chapter 10, "Operations Planning and Scheduling," and Chapter 11, "Resource Planning."



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Ever wonder how CPFR came into existence? Walmart has long been known for its careful analysis of cash register receipts and for working with suppliers to reduce inventories. To combat the ill effects of forecast errors on inventories, Benchmarking Partners, Inc. was funded in the mid-1990s by Walmart, IBM, SAP, and Manugistics to develop a software package. Walmart initiated the new system with Listerine, a primary product of Warner-Lambert (now produced by Johnson & Johnson). How did it work? Walmart and Warner-Lambert independently calculated the demand they expected for Listerine six months into the future, taking into consideration factors such as past sales trends and sales promotions. If the forecasts differed by more than a predetermined percentage, they exchanged written comments and supporting data. They went through as many cycles as needed to converge to an acceptable forecast. The program was successful; Walmart saw a reduction in stockouts from 15 percent to 2 percent, increased sales, and reduced inventory costs, while Warner-Lambert benefitted from a smoother production plan and lower average costs. The system was later generalized and called collaborative planning, forecasting, and replenishment, or CPFR.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
8.1 Explain how managers can manage demand patterns.	Review the section "Managing Demand." Focus on "Demand Management Options" and the eight ways managers can change demand patterns.	
8.2 Describe the two key decisions on making forecasts.	In the section "Key Decisions on Making Forecasts," focus on the considerations for deciding what to forecast and choosing the right forecasting technique.	
8.3 Calculate the five basic measures of forecast errors.	Review the section "Forecast Error to understand CFE, MSE, σ, MAD, and MAPE. Study Figure 8.2(a) and (b) for an example. Solved Problem 2 shows an example of MAD, and Solved Problem 3 shows MAD and MAPE.	**POM for Windows:** Error Analysis
8.4 Compare and contrast the four approaches to judgmental forecasting.	The section "Judgment Methods explains the differences between salesforce estimates, executive opinion, market research, and the Delphi method.	
8.5 Use regression to make forecasts with one or more independent variables.	The "Causal Methods: Linear Regression" section and Example 8.2 describe how linear regression, when historical data are available, can express demand as a linear function of one or more independent variables. The computer is an essential tool for linear regression. In addition to Example 8.2, Solved Problem 1 provides the statistics on how well the regression equation fits the data.	**Active Model: 8.1:** Linear Regression **OM Explorer Solver:** Regression Analysis **POM for Windows:** Least Squares—Simple and Multiple Regression **POM for Windows:** Regression Projector

Learning Objective	Guidelines for Review	Online Resources
8.6 Make forecasts using the five most common statistical approaches for time-series analysis.	The section "Time-Series Methods" explains the naïve method and the five statistical methods of simple moving average, weighted moving average, exponential smoothing, trend projection with regression, and multiplicative seasonal methods that are used. Examples 8.3 through 8.6 demonstrate the methods, as do Solved Problems 2 through 4. Also see Experiential Learning Exercise 1 for an in-class exercise requiring the use of time-series models to prepare a combination forecast.	**Active Models: 8.2:** Simple Moving Averages; **8.3:** Exponential Smoothing **OM Explorer Tutors:** 8.1: Moving Average Method; 8.2: Weighted Moving Average Method; 8.3: Exponential Smoothing **OM Explorer Solvers:** Time-Series Forecasting; Trend Projection with Regression; Seasonal Forecasting **POM for Windows:** Time-Series Analysis **Student Data File:** Experiential Exercise 8.1 Data
8.7 Describe the big-data approach and the six steps in a typical forecasting process.	See the section "Big Data and the Typical Forecasting Process." Study the big-data approach and the six steps involved in the forecasting process. There is much more complexity when you realize the number of SKUs involved and the need to update the history file. Be sure to understand how combination forecasts and focus forecasting work into step 2 and how CPFR is integral to step 3.	

Key Equations

Forecast Error

1. Forecast error measures:

$$E_t = D_t - F_t$$

$$\text{CFE} = \Sigma E_t$$

$$\bar{E} = \frac{\text{CFE}}{n}$$

$$\text{MSE} = \frac{\Sigma E_t^2}{n}$$

$$\sigma = \sqrt{\frac{\Sigma (E_t - \bar{E})^2}{n-1}}$$

$$\text{MAD} = \frac{\Sigma |E_t|}{n}$$

$$\text{MAPE} = \frac{(\Sigma |E_t|/D_t)(100\%)}{n}$$

Causal Methods: Linear Regression

2. Linear regression:

$$Y = a + bX$$

Time-Series Methods

3. Naïve forecasting:

$$F_{t+1} = D_t$$

4. Simple moving average:

$$F_{t+1} = \frac{D_t + D_{t-1} + D_{t-2} + \cdots + D_{t-n+1}}{n}$$

5. Weighted moving average:

$$F_{t+1} = \text{Weight}_1(D_t) + \text{Weight}_2(D_{t-1}) + \text{Weight}_3(D_{t-2}) + \cdots + \text{Weight}_n(D_{t-n+1})$$

6. Exponential smoothing:

$$F_{t+1} = \alpha D_t + (1 - \alpha)F_t$$

7. Trend projection using regression:

$$F_t = a + bt$$

8. Tracking signal:

$$\frac{\text{CFE}}{\text{MAD}} \text{ or } \frac{\text{CFE}}{\text{MAD}_t}$$

9. Exponentially smoothed error:

$$\text{MAD}_t = \alpha|E_t| + (1 - \alpha)\text{MAD}_{t-1}$$

Key Terms

additive seasonal method 332
aggregation 318
backlog 317
backorder 318
big data 334
causal methods 318
collaborative planning, forecasting, and replenishment (CPFR) 337
combination forecasts 337
complementary products 316
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weighted moving average method 327

Solved Problem 1

Chicken Palace periodically offers carryout five-piece chicken dinners at special prices. Let Y be the number of dinners sold and X be the price. On the basis of the historical observations and calculations in the following table, determine the regression equation, correlation coefficient, and coefficient of determination. How many dinners can Chicken Palace expect to sell at $3.00 each?

Observation	Price (X)	Dinners Sold (Y)
1	$2.70	760
2	$3.50	510
3	$2.00	980
4	$4.20	250
5	$3.10	320
6	$4.05	480
Total	$19.55	3,300
Average	$3.258	550

SOLUTION

We use the computer (*Regression Analysis* Solver of OM Explorer or *Regression Projector* module of POM for Windows) to calculate the best values of a, b, the correlation coefficient, and the coefficient of determination.

$$a = 1{,}454.60$$
$$b = -277.63$$
$$r = -0.84$$
$$r^2 = 0.71$$

The regression line is

$$Y = a + bX = 1{,}454.60 - 277.63X$$

The correlation coefficient ($r = -0.84$) shows a negative correlation between the variables. The coefficient of determination ($r^2 = 0.71$) is not too large, which suggests that other variables (in addition to price) might appreciably affect sales.

If the regression equation is satisfactory to the manager, estimated sales at a price of $3.00 per dinner may be calculated as follows:

$$Y = a + bX = 1{,}454.60 - 277.63(3.00)$$
$$= 621.71 \text{ or } 622 \text{ dinners}$$

Solved Problem 2

The Polish General's Pizza Parlor is a small restaurant catering to patrons with a taste for Eastern European pizza. One of its specialties is Polish Prize pizza. The manager must forecast weekly demand for these special pizzas so that he can order pizza shells weekly. Recently, demand has been as follows:

Week	Pizzas	Week	Pizzas
June 2	50	June 23	56
June 9	65	June 30	55
June 16	52	July 7	60

a. Forecast the demand for pizza for June 23 to July 14 by using the simple moving average method with $n = 3$. Then, repeat the forecast by using the weighted moving average method with $n = 3$ and weights of 0.50, 0.30, and 0.20, with 0.50 applying to the most recent demand.

b. Calculate the MAD for each method.

SOLUTION

a. The simple moving average method and the weighted moving average method give the following results:

Current Week	Simple Moving Average Forecast for Next Week	Weighted Moving Average Forecast for Next Week
June 16	$\frac{52 + 65 + 50}{3} = 55.7$ or 56	$[(0.5 \times 52) + (0.3 \times 65) + (0.2 \times 50)] = 55.5$ or 56
June 23	$\frac{56 + 52 + 65}{3} = 55.7$ or 58	$[(0.5 \times 56) + (0.3 \times 52) + (0.2 \times 65)] = 56.6$ or 57
June 30	$\frac{55 + 56 + 52}{3} = 54.3$ or 54	$[(0.5 \times 55) + (0.3 \times 56) + (0.2 \times 52)] = 54.7$ or 55
July 7	$\frac{60 + 55 + 56}{3} = 57.0$ or 57	$[(0.5 \times 60) + (0.3 \times 55) + (0.2 \times 56)] = 57.7$ or 58

Forecasts in each row are for the next week's demand. For example, the simple moving average and weighted moving average forecasts (both are 56 units) are calculated after learning the demand on June 16 and are used for June 23's demand forecast.

b. The mean absolute deviation is calculated as follows:

		SIMPLE MOVING AVERAGE		WEIGHTED MOVING AVERAGE	
Week	**Actual Demand**	**Forecast for This Week**	**Absolute Errors $\lvert E_t \rvert$**	**Forecast for This Week**	**Absolute Errors $\lvert E_t \rvert$**
June 23	56	56	$\lvert 56 - 56 \rvert = 0$	56	$\lvert 56 - 56 \rvert = 0$
June 30	55	58	$\lvert 55 - 58 \rvert = 3$	57	$\lvert 55 - 57 \rvert = 2$
July 7	60	54	$\lvert 60 - 54 \rvert = 6$	55	$\lvert 60 - 55 \rvert = 5$
			$\text{MAD} = \frac{0 + 3 + 6}{3} = 3.0$		$\text{MAD} = \frac{0 + 2 + 5}{3} = 2.3$

For this limited set of data, the weighted moving average method resulted in a slightly lower mean absolute deviation. However, final conclusions can be made only after analyzing much more data.

Solved Problem 3

The monthly demand for units manufactured by the Acme Rocket Company has been as follows:

Month	Units	Month	Units
May	100	September	105
June	80	October	110
July	110	November	125
August	115	December	120

a. Use the exponential smoothing method to forecast the number of units for June to January. The initial forecast for May was 105 units; $\alpha = 0.2$.

b. Calculate the absolute percentage error for each month from June through December and the MAD and MAPE of forecast error as of the end of December.

c. Calculate the tracking signal as of the end of December. What can you say about the performance of your forecasting method?

SOLUTION

a.

Current Month, t	Calculating Forecast for Next Month $F_{t+1} = \alpha D_t + (1 - \alpha)F_t$	Forecast for Month $t + 1$
May	0.2(100) + 0.8(105) = 104.0 or 104	June
June	0.2(80) + 0.8(104.0) = 99.2 or 99	July
July	0.2(110) + 0.8(99.2) = 101.4 or 101	August
August	0.2(115) + 0.8(101.4) = 104.1 or 104	September
September	0.2(105) + 0.8(104.1) = 104.3 or 104	October
October	0.2(110) + 0.8(104.3) = 105.4 or 105	November
November	0.2(125) + 0.8(105.4) = 109.3 or 109	December
December	0.2(120) + 0.8(109.3) = 111.4 or 111	January

b.

Month, t	Actual Demand, D_t	Forecast, F_t	Error, $E_t = D_t - F_t$	Absolute Error, $\lvert E_t \rvert$	Absolute Percentage Error, $(\lvert E_t \rvert / D_t)(100\%)$
June	80	104	−24	24	30.0%
July	110	99	11	11	10.0
August	115	101	14	14	12.0
September	105	104	1	1	1.0
October	110	104	6	6	5.5
November	125	105	20	0	16.0
December	120	109	11	11	9.2
Total	765		39	87	83.7%

$$\text{MAD} = \frac{\Sigma \lvert E_t \rvert}{n} = \frac{87}{7} = 12.4 \text{ and MAPE} = \frac{(\Sigma \lvert E_t \rvert / D_t)(100\%)}{n} = \frac{83.7\%}{7} = 11.96\%$$

c. As of the end of December, the cumulative sum of forecast errors (CFE) is 39. Using the mean absolute deviation calculated in part (b), we calculate the tracking signal:

$$\text{Tracking signal} = \frac{\text{CFE}}{\text{MAD}} = \frac{39}{12.4} = 3.14$$

The probability that a tracking signal value of 3.14 could be generated completely by chance is small. Consequently, we should revise our approach. The long string of forecasts lower than actual demand suggests use of a trend method.

Solved Problem 4

The Northville Post Office experiences a seasonal pattern of daily mail volume every week. The following data for two representative weeks are expressed in thousands of pieces of mail:

Day	Week 1	Week 2
Sunday	5	8
Monday	20	15
Tuesday	30	32
Wednesday	35	30
Thursday	49	45
Friday	70	70
Saturday	15	10
Total	224	210

a. Calculate a seasonal factor for each day of the week.

b. If the postmaster estimates 230,000 pieces of mail to be sorted next week, forecast the volume for each day of the week.

SOLUTION

a. Calculate the average daily mail volume for each week. Then, for each day of the week, divide the mail volume by the week's average to get the seasonal factor. Finally, for each day, add the two seasonal factors and divide by 2 to obtain the average seasonal factor to use in the forecast (see part [b]).

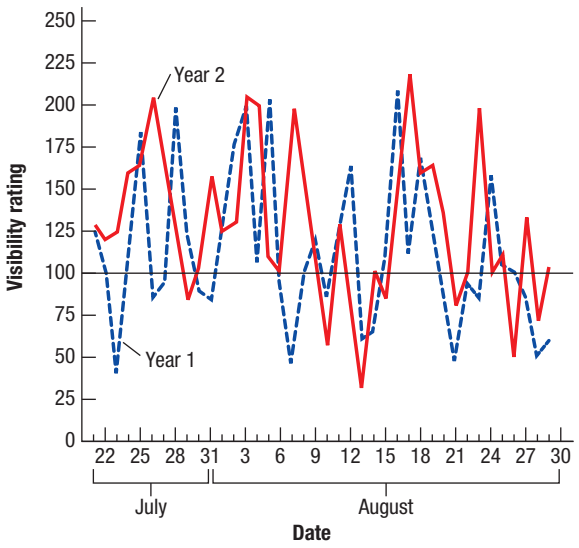
	WEEK 1		WEEK 2		
Day	Mail Volume	Seasonal Factor (1)	Mail Volume	Seasonal Factor (2)	Average Seasonal Factor [(1) + (2)]/2
Sunday	5	5/32 = 0.15625	8	8/30 = 0.26667	0.21146
Monday	20	20/32 = 0.62500	15	15/30 = 0.50000	0.56250
Tuesday	30	30/32 = 0.93750	32	32/30 = 1.06667	1.00209
Wednesday	35	35/32 = 1.09375	30	30/30 = 1.00000	1.04688
Thursday	49	49/32 = 1.53125	45	45/30 = 1.50000	1.51563
Friday	70	70/32 = 2.18750	70	70/30 = 2.33333	2.26042
Saturday	15	15/32 = 0.46875	10	10/30 = 0.33333	0.40104
Total	224		210		
Average	224/7 = 32		210/7 = 30		

b. The average daily mail volume is expected to be 230,000/7 = 32,857 pieces of mail. Using the average seasonal factors calculated in part (a), we obtain the following forecasts:

Day	Calculation		Forecast
Sunday	0.21146(32,857) =		6,948
Monday	0.56250(32,857) =		18,482
Tuesday	1.00209(32,857) =		32,926
Wednesday	1.04688(32,857) =		34,397
Thursday	1.51563(32,857) =		49,799
Friday	2.26042(32,857) =		74,271
Saturday	0.40104(32,857) =		13,177
		Total	230,000

Discussion Questions

1. Figure 8.9 shows summer air visibility measurements for Denver, Colorado. The acceptable visibility standard is 100, with readings above 100 indicating clean air and good visibility, and readings below 100 indicating temperature inversions caused by forest fires, volcanic eruptions, or collisions with comets.
   - **a.** Is a trend evident in the data? Which time-series techniques might be appropriate for estimating the average of these data?
   - **b.** A medical center for asthma and respiratory diseases located in Denver has great demand for its services when air quality is poor. If you were in charge of developing a short-term (say, 3-day) forecast of visibility, which causal factor(s) would you analyze? In other words, which external factors hold the potential to significantly affect visibility in the *short term*?
   - **c.** Tourism, an important factor in Denver's economy, is affected by the city's image. Air quality, as measured by visibility, affects the city's image. If you were responsible for development of tourism, which causal factor(s) would you analyze to forecast visibility for the *medium term* (say, the next two summers)?
   - **d.** The federal government threatens to withhold several hundred million dollars in Department of Transportation funds unless Denver meets visibility standards within 8 years. How would you proceed to generate a *long-term* judgment forecast of technologies that will be available to improve visibility in the next 10 years?
2. Kay and Michael Passe publish *What's Happening?*—a biweekly newspaper to publicize local events. *What's Happening?* has few subscribers; it typically is sold at checkout stands. Much of the revenue comes from advertisers of garage sales and supermarket specials. In an effort to reduce costs associated with printing too many papers or delivering them to the wrong location, Michael implemented a computerized system to collect sales data. Sales-counter scanners accurately record sales data for each location. Since the system was implemented, total sales volume has steadily declined. Selling advertising space and maintaining shelf space at supermarkets are getting more difficult.



Reduced revenue makes controlling costs all the more important. For each issue, Michael carefully makes a forecast based on sales data collected at each location. Then, he orders papers to be printed and distributed in quantities matching the forecast. Michael's forecast reflects a downward trend, which *is* present in the sales data. Now only a few papers are left over at only a few locations. Although the sales forecast accurately predicts the actual sales at most locations, *What's Happening?* is spiraling toward oblivion. Kay suspects that Michael is doing something wrong in preparing the forecast but can find no mathematical errors. Tell her what is happening.

◀ **FIGURE 8.9**
Summer Air Visibility Measurements

Problems

The OM Explorer and POM for Windows software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations.

Causal Methods: Linear Regression

1. Demand for oil changes at Garcia's Garage has been as follows:

Month	Number of Oil Changes
January	41
February	46
March	57
April	52
May	59
June	51
July	60
August	62

a. Use simple linear regression analysis to develop a forecasting model for monthly demand. In this application, the dependent variable, Y, is monthly demand and the independent variable, X, is the month. For January, let $X = 1$; for February, let $X = 2$; and so on.

b. Use the model to forecast demand for September, October, and November. Here, $X = 9$, 10, and 11, respectively.

2. An e-commerce fashion retailer is measuring the productivity of its warehouse employees. Productivity is measured by counting the number of orders picked by employees every hour. Management has gathered performance data of 13 randomly selected warehouse employees with varying months of experience. Management would like to know if prior work experience is related to better performance in the warehouse. The performance data are in the following table:

Work Experience (months)	Number of Orders Picked
30	40
34	45
32	43
37	50
45	52
31	40
28	35
23	30
6	20
35	47
38	48
32	42
31	40

a. Use linear regression to find a relation to forecast Y, which is the number of orders picked up by employees, using the values from the work experience of employees, X.

b. Is there a strong relationship between Y and X? Explain.

3. Management of Erudition, an online learning platform, is keen to motivate students to work hard. In order to quantify the degree of effort put in by each learner, the company has decided to collect data on the amount of time spent by students on their virtual learning environment and the grades obtained by them. The following data have been collected.

a. Develop a regression equation expressing grades as a function of the amount of time spent on the online learning platform.

Student Groups	Grades (%)	Time Spent (hours)
1	20	0
2	25	15
3	40	25
4	50	35
5	55	45
6	60	65
7	65	80
8	70	95
9	75	100

b. What are the correlation coefficient and the coefficient of determination? Comment on your regression equation in light of these measures.

c. Suppose a prospective student could dedicate only 65 hours for this program. What grade can be expected from this student?

4. A manufacturing firm has developed a skills test, the scores from which can be used to predict workers' production rating factors. Data on the test scores of various workers and their subsequent production ratings are shown.

Worker	Test Score	Production Rating	Worker	Test Score	Production Rating
A	53	45	K	54	59
B	36	43	L	73	77
C	88	89	M	65	56
D	84	79	N	29	28
E	86	84	O	52	51
F	64	66	P	22	27
G	45	49	Q	76	76
H	48	48	R	32	34
I	39	43	S	51	60
J	67	76	T	37	32

a. Using POM for Windows's least squares–linear regression module, develop a relationship to forecast production ratings from test scores.

b. If a worker's test score was 80, what would be your forecast of the worker's production rating?

c. Comment on the strength of the relationship between the test scores and production ratings.

5. The materials handling manager of a manufacturing company is trying to forecast the cost of maintenance for the company's fleet of over-the-road tractors. The manager believes that the cost of maintaining the tractors increases with their age. The following data were collected.

Age (years)	Yearly Maintenance Cost ($)	Age (years)	Yearly Maintenance Cost ($)
4.5	619	5.0	1,194
4.5	1,049	0.5	163
4.5	1,033	0.5	182
4.0	495	6.0	764
4.0	723	6.0	1,373
4.0	681	1.0	978
5.0	890	1.0	466
5.0	1,522	1.0	549
5.5	987		

a. Use POM for Windows's least squares–linear regression module to develop a relationship to forecast the yearly maintenance cost based on the age of a tractor.

b. If a section has 20 three-year-old tractors, what is the forecast for the annual maintenance cost?

Time-Series Methods

6. Marianne Schwartz, the owner of Handy Man Rentals, rents carpet cleaners to contractors and walk-in customers. She is interested in arriving at a forecast of rentals so that she can order the correct quantities of supplies that go with the cleaners. Data for the past 10 weeks are shown here.

Week	Rentals	Week	Rentals
1	15	6	20
2	16	7	24
3	24	8	27
4	18	9	18
5	23	10	16

a. Prepare a forecast for weeks 6 through 10 by using a 4-week moving average. What is the forecast for week 11?

b. Calculate the mean absolute deviation as of the end of week 10.

7. Sales for the past 12 months at Computer Success are given here.

Month	Sales ($)	Month	Sales ($)
January	3,000	July	6,300
February	3,400	August	7,200
March	3,700	September	6,400
April	4,100	October	4,600
May	4,700	November	4,200
June	5,700	December	3,900

a. Use a 3-month moving average to forecast the sales for the months May through December.

b. Use a 4-month moving average to forecast the sales for the months May through December.

c. Compare the performance of the two methods by using the mean absolute deviation as the performance criterion. Which method would you recommend?

d. Compare the performance of the two methods by using the mean absolute percent error as the performance criterion. Which method would you recommend?

e. Compare the performance of the two methods by using the mean squared error as the performance criterion. Which method would you recommend?

8. Bradley's Copiers sells and repairs photocopy machines. The manager needs weekly forecasts of service calls so that he can schedule service personnel. Use the actual demand in the first period for the forecast for the first week so error measurement begins in the second week. The manager uses exponential smoothing with $\alpha = 0.20$. Forecast the number of calls for week 6, which is the next week.

Week	Actual Service Calls
1	29
2	27
3	41
4	18
5	33

9. Consider the sales data for Computer Success given in Problem 7.

a. Use a 3-month weighted moving average to forecast the sales for the months April through December. Use weights of (4/8), (3/8), and (1/8), giving more weight to more recent data.

b. Use exponential smoothing with $\alpha = 0.6$ to forecast the sales for the months April through December. Assume that the initial forecast for January was $3,200. Start error measurement in April.

c. Compare the performance of the two methods by using the mean absolute deviation as the performance criterion, with error measurement beginning in April. Which method would you recommend?

d. Compare the performance of the two methods by using the mean absolute percent error as the performance criterion, with error measurement beginning in April. Which method would you recommend?

e. Compare the performance of the two methods by using the mean squared error as the performance criterion, with error measurement beginning in April. Which method would you recommend?

10. A convenience store recently started to carry a new brand of soft drink. Management is interested in estimating future sales volume to determine whether it should continue to carry the new brand or replace it with another brand. The table here provides the number of cans sold per week. Use both the trend projection with regression and the exponential smoothing (let $\alpha = 0.4$ with an initial forecast for week 1 of 617) methods to forecast demand for week 13. Compare these methods by using the mean absolute deviation and mean absolute percent error performance criteria. Does your analysis suggest that sales are trending and, if so, by how much?

Week	1	2	3	4	5	6	7	8	9	10	11	12
Sales	617	617	648	739	659	623	742	704	724	715	668	740

11. Community Federal Bank in Dothan, Alabama, recently increased its fees to customers who use human tellers. Management is interested in whether its new fee policy has increased the number of customers now using its automated teller machines to the point that more machines are required. The table here provides the number of automatic teller transactions by week. Use trend projection with regression to forecast usage for weeks 13 to 16.

Week	1	2	3	4	5	6	7	8	9	10	11	12
Transactions	512	527	631	434	482	539	577	518	526	636	623	461

12. The number of heart surgeries performed at Heartville General Hospital has increased steadily over the past several years. The hospital's administration is seeking the best method to forecast the demand for such surgeries in year 6. The data for the past 5 years are shown.

Year	Demand
1	45
2	50
3	52
4	56
5	58

The hospital's administration is considering the following forecasting methods. Begin error measurement in year 3 so all methods are compared for the same years.

a. Exponential smoothing, with $\alpha = 0.6$. Let the initial forecast for year 1 be 45, the same as the actual demand.

b. Exponential smoothing, with $\alpha = 0.9$. Let the initial forecast for year 1 be 45, the same as the actual demand.

c. Trend projection with regression.

d. Two-year moving average.

e. Two-year weighted moving average, using weights 0.6 and 0.4, with more recent data given more weight.

f. If MAD is the performance criterion chosen by the administration, which forecasting method should it choose?

g. If MSE is the performance criterion chosen by the administration, which forecasting method should it choose?

h. If MAPE is the performance criterion chosen by the administration, which forecasting method should it choose?

13. The following data are for calculator sales in units at an electronics store over the past 9 weeks.

Week	Sales	Week	Sales
1	46	6	58
2	49	7	62
3	43	8	56
4	50	9	63
5	53		

Use trend projection with regression to forecast sales for weeks 10 to 13. What are the error measures (CFE, MSE, σ, MAD, and MAPE) for this forecasting procedure? How about r^2?

14. Nova Limited is a well-known manufacturer of cold-pressed olive oil in Cyprus. The company's unique value proposition is that olives are crushed into a paste by using stone grinders and then pressed to extract oil from the pulp. Olives are harvested during autumn, and oil is extracted at the earliest. They are primarily sold to tourists who visit the island throughout the year. The following table shows the actual sales history for January to October. Generate forecasts for November to December, using the trend projection with regression method. Looking at the accuracy of its forecasts over the historical file, as well as the other statistics provided, how confident are you in these forecasts for November to December?

Month	Sales (liters)	Month	Sales (liters)
January	790	July	610
February	700	August	630
March	725	September	580
April	740	October	570
May	730	November	
June	680	December	

15. Forrest and Dan make boxes of chocolates for which the demand is uncertain. Forrest says, "That's life." In contrast, Dan believes that some demand patterns exist that could be useful for planning the purchase of sugar, chocolate, and shrimp. Forrest insists on placing a surprise chocolate-covered shrimp in some boxes so that "You never know what you're gonna get." Quarterly demand (in boxes of chocolates) for the past 3 years follows:

Quarter	Year 1	Year 2	Year 3
1	3,000	3,300	3,502
2	1,700	2,100	2,448
3	900	1,500	1,768
4	4,400	5,100	5,882
Total	10,000	12,000	13,600

a. Use intuition and judgment to estimate quarterly demand for the fourth year.

b. If the expected sales for chocolates are 14,800 cases for year 4, use the multiplicative seasonal method to prepare a forecast for each quarter of the year. Are any of the quarterly forecasts different from what you thought you would get in part (a)?

16. The manager of Alaina's Garden Center must make the annual purchasing plans for rakes, gloves, and other gardening items. One of the items the company stocks is Fast-Grow, a liquid fertilizer. The sales of this item are seasonal, with peaks in the spring, summer, and

fall months. Quarterly demand (in cases) for the past 2 years follows:

Quarter	Year 1	Year 2
1	45	67
2	339	444
3	299	329
4	222	283
Total	905	1,123

If the expected sales for Fast-Grow are 1,850 cases for year 3, use the multiplicative seasonal method to prepare a forecast for each quarter of the year.

17. The manager of a utility company in the Texas panhandle wants to develop quarterly forecasts of power loads for the next year. The power loads are seasonal, and the data on the quarterly loads in megawatts (MW) for the past 4 years are as follows:

Quarter	Year 1	Year 2	Year 3	Year 4
1	103.5	94.7	118.6	109.3
2	126.1	116.0	141.2	131.6
3	144.5	137.1	159.0	149.5
4	166.1	152.5	178.2	169.0

The manager estimates the total demand for the next year at 600 MW. Use the multiplicative seasonal method to develop the forecast for each quarter.

18. **[D]** Franklin Tooling, Inc., manufactures specialty tooling for firms in the paper-making industry. All of its products are engineer-to-order and so the company never knows exactly what components to purchase for a tool until a customer places an order. However, the company believes that weekly demand for a few components is fairly stable. Component 135.AG is one such item. The past 26 weeks of historical use of component 135.AG is as follows:

Week	Demand	Week	Demand
1	137	14	131
2	136	15	132
3	143	16	124
4	136	17	121
5	141	18	127
6	128	19	118
7	149	20	120
8	136	21	115
9	134	22	106
10	142	23	120
11	125	24	113
12	134	25	121
13	118	26	119

Use OM Explorer's *Time Series Forecasting* Solver to evaluate the following forecasting methods. Start error measurement in the fifth week, so all methods are evaluated over the same time interval. Use the default settings for initial forecasts.

a. Naïve (one-period moving average)

b. Three-period moving average

c. Exponential smoothing, with $\alpha = 0.28$

d. Trend projection with regression

e. Which forecasting method should management use, if the performance criterion it chooses is:

- CFE?
- MSE?
- MAD?
- MAPE?

19. **[D]** Create an Excel spreadsheet on your own that can make combination forecasts for Problem 18. Create a combination forecast using all four techniques from Problem 18. Give each technique an equal weight. Create a second combination forecast by using the three techniques that seem best based on MAD. Give equal weight to each technique. Finally, create a third forecast by equally weighting the two best techniques. Calculate CFE, MAD, MSE, and MAPE for the combination forecast. Are these forecasts better or worse than the forecasting techniques identified in Problem 18?

20. **[D]** The director of a large public library must schedule employees to reshelf books and periodicals checked out of the library. The number of items checked out will determine the labor requirements. The following data reflect the number of items checked out of the library for the past 3 years.

Month	Year 1	Year 2	Year 3
January	1,847	2,045	1,986
February	2,669	2,321	2,564
March	2,467	2,419	2,635
April	2,432	2,088	2,150
May	2,464	2,667	2,201
June	2,378	2,122	2,663
July	2,217	2,206	2,055
August	2,445	1,869	1,678
September	1,894	2,441	1,845
October	1,922	2,291	2,065
November	2,431	2,364	2,147
December	2,274	2,189	2,451

The director needs a time-series method for forecasting the number of items to be checked out during the next month. Find the best simple moving average forecast you can. Decide what is meant by "best" and justify your decision.

[D] = Difficult Problem

21. **[D]** Using the data in Problem 20 and the *Time Series* Solver of OM Explorer, find the best exponential smoothing parameter alpha that minimizes MAD. Let the forecast for period 1 be the actual data for period 1, and begin the error analysis in period 2.

22. **[D]** Using the data in Problem 20, find the trend projection with regression model using the *Time Series Forecasting* Solver of OM Explorer. Compare the performance of this method with the exponential smoothing method from Problem 21. Let the error analysis begin in period 2 (so that both exponential smoothing and trend projection are analyzed over the same time horizon). Which of these two methods would you choose if MAD is the key error measure?

23. **[D]** Cannister, Inc., specializes in the manufacture of plastic containers. The data on the monthly sales of 10-ounce shampoo bottles for the past 5 years are as follows:

Year	1	2	3	4	5
January	742	741	896	951	1,030
February	697	700	793	861	1,032
March	776	774	885	938	1,126
April	898	932	1,055	1,109	1,285
May	1,030	1,099	1,204	1,274	1,468
June	1,107	1,223	1,326	1,422	1,637
July	1,165	1,290	1,303	1,486	1,611
August	1,216	1,349	1,436	1,555	1,608
September	1,208	1,341	1,473	1,604	1,528
October	1,131	1,296	1,453	1,600	1,420
November	971	1,066	1,170	1,403	1,119
December	783	901	1,023	1,209	1,013

a. Using the multiplicative seasonal method, calculate the monthly seasonal indices.

b. Develop a simple linear regression equation to forecast annual sales. For this regression, the dependent variable, Y, is the demand in each year and the independent variable, X, is the index for the year (i.e., $X = 1$ for year 1, $X = 2$ for year 2, and so on until $X = 5$ for year 5).

c. Forecast the annual sales for year 6 by using the regression model you developed in part (b).

d. Prepare the seasonal forecast for each month by using the monthly seasonal indices calculated in part (a).

24. **[D]** The Midwest Computer Company serves a large number of businesses in the Great Lakes region. The company sells supplies and replacements and performs service on all computers sold through seven sales offices. Many items are stocked, so close inventory control is necessary to assure customers of efficient service. Recently, business has been increasing, and management is concerned about stockouts. A forecasting method is needed to estimate requirements several months in advance so that adequate replenishment quantities can be purchased. An example of the sales growth experienced during the past 50 months is the growth in demand for item EP-37, a laser printer cartridge, shown in Table 8.2.

TABLE 8.2 | EP-37 SALES AND LEASE DATA

Month	EP-37 Sales	Leases	Month	EP-37 Sales	Leases
1	80	32	26	1,296	281
2	132	29	27	1,199	298
3	143	32	28	1,267	314
4	180	54	29	1,300	323
5	200	53	30	1,370	309
6	168	89	31	1,489	343
7	212	74	32	1,499	357
8	254	93	33	1,669	353
9	397	120	34	1,716	360
10	385	113	35	1,603	370
11	472	147	36	1,812	386
12	397	126	37	1,817	389
13	476	138	38	1,798	399
14	699	145	39	1,873	409
15	545	160	40	1,923	410
16	837	196	41	2,028	413
17	743	180	42	2,049	439
18	722	197	43	2,084	454
19	735	203	44	2,083	441
20	838	223	45	2,121	470
21	1,057	247	46	2,072	469
22	930	242	47	2,262	490
23	1,085	234	48	2,371	496
24	1,090	254	49	2,309	509
25	1,218	271	50	2,422	522

a. Develop a trend projection with regression solution using OM Explorer. Forecast demand for month 51.

b. A consultant to Midwest's management suggested that new office building leases would be a good leading indicator for company sales. The consultant quoted a recent university study finding that new office building leases precede office equipment and supply sales by 3 months. According to the study findings, leases in month 1 would affect sales in month 4, leases in month 2 would affect sales in month 5, and so on. Use POM for Windows' linear regression module to develop a forecasting model for sales, with leases as the independent variable. Forecast sales for month 51.

c. Which of the two models provides better forecasts? Explain.

25. **[D]** A certain food item at P&Q Supermarkets has the demand pattern shown in the following 24-period table.

a. Use the combination forecasting method of the *Time Series Forecasting* Solver of OM Explorer. Let error analysis begin in month 6, and include (1) a five-period moving average (with a combination weight of 0.33), (2) an exponential smoothing model with $\alpha = 0.20$ (with a combination weight of 0.33), and (3) a trend projection (with a combination weight of 0.33). What is the MAD of this model? What is the forecast for month 25?

b. The need to account for seasonality is apparent if you look at a graph of the trend line. There is a spike in demand in the fifth period of each five-period cycle. Unfortunately, OM *Explorer's Seasonal Forecasting* Solver does not cover the case where there are five periods in a cycle (or seasons in a year). You must do some manual calculations. Begin by calculating the seasonal factor for each period in each of the first four cycles, and then calculating the average seasonal factor for each period (see Example 8.6). Now estimate the total demand for cycle 5 using OM Explorer's Trend Projection routine in the *Time Series* Solver. The dependent variables (see "Trend Patterns Using Regression") are the total demands for the first four cycles. Now multiply the average demand estimate for the fifth cycle by the seasonal factor for the fifth period. This is your forecast for month 25. To calculate the errors (including MAD) for the multiplicative seasonal method for all cycles (except for the fifth month in the fifth cycle), calculate MAD manually. You might instead use the Error Analysis Module of POM for Windows.

c. How do the forecasts by the two methods compare? Which one is likely to give the better forecast, based on MAD?

Period	Demand	Period	Demand
1	33	13	37
2	37	14	43
3	31	15	56
4	39	16	41
5	54	17	36
6	38	18	39
7	42	19	41
8	40	20	58
9	41	21	42
10	54	22	45
11	43	23	41
12	39	24	38

TABLE 8.3 | VISIBILITY DATA

Date	Year 1	Year 2	Date	Year 1	Year 2	Date	Year 1	Year 2
July 22	125	130	Aug 5	105	200	Aug 19	170	160
23	100	120	6	205	110	20	125	165
24	40	125	7	90	100	21	85	135
25	100	160	8	45	200	22	45	80
26	185	165	9	100	160	23	95	100
27	85	205	10	120	100	24	85	200
28	95	165	11	85	55	25	160	100
29	200	125	12	125	130	26	105	110
30	125	85	13	165	75	27	100	50
31	90	105	14	60	30	28	95	135
Aug 1	85	160	15	65	100	29	50	70
2	135	125	16	110	85	30	60	105
3	175	130	17	210	150			
4	200	205	18	110	220			

26. **[D]** The data for the visibility chart in Discussion Question 1 are shown in Table 8.3. The visibility standard is set at 100. Readings below 100 indicate that air pollution has reduced visibility, and readings above 100 indicate that the air is clearer.

a. Use several methods to generate a visibility forecast for August 31 of the second year. Which method seems to produce the best forecast?

b. Use several methods to forecast the visibility index for the summer of the third year. Which method seems to produce the best forecast? Support your choice.

27. **[D]** Tom Glass forecasts electrical demand for the Flatlands Public Power District (FPPD). The FPPD wants to take its Comstock power plant out of service for maintenance when demand is expected to be low. After shutdown, performing maintenance and getting the plant back on line takes 2 weeks. The utility has enough other generating capacity to satisfy 1,550 megawatts (MW) of demand while Comstock is out of service. Table 8.4 shows weekly peak demands (in MW) for the past several autumns. When next in year 6 should the Comstock plant be scheduled for maintenance?

28. **[D]** A manufacturing firm seeks to develop a better forecast for an important product and believes that there is a trend to the data. OM Explorer's *Trend Projection with Regression* Solver has been set up with the 47 demands in the history file. Note the "Load Problem 28 Data" button in the *Trend Projection with Regression* Solver that, when clicked, will automatically input the demand data. Otherwise, you can enter the demand data directly into the Inputs sheet.

Yr	1	2	3	4
Jan	4,507	4,589	4,084	4,535
Feb	4,400	4,688	4,158	4,477
Mar	4,099	4,566	4,174	4,601
Apr	4,064	4,485	4,225	4,648
May	4,002	4,385	4,324	4,860
Jun	3,963	4,377	4,220	4,998
Jul	4,037	4,309	4,267	5,003
Aug	4,162	4,276	4,187	4,960
Sep	4,312	4,280	4,239	4,943
Oct	4,395	4,144	4,352	5,052
Nov	4,540	4,219	4,331	5,107
Dec	4,471	4,052	4,371	

a. What is your forecast for December of year 4, making period 1 as the starting period for the regression?

b. The actual demand for period 48 was just learned to be 5,100. Add this demand to the Inputs file and change the starting period for the regression to period 2 so that the number of periods in the regression remains unchanged. How much or little does the forecast for period 49 change from the one for period 48? The error measures? Are you surprised?

c. Now change the time when the regression starts to period 25 and repeat the process. What differences do you note now? What forecast will you make for period 49?

TABLE 8.4 | WEEKLY PEAK POWER DEMANDS

	AUGUST			SEPTEMBER				OCTOBER				NOVEMBER	
Year	1	2	3	4	5	6	7	8	9	10	11	12	13
1	2,050	1,925	1,825	1,525	1,050	1,300	1,200	1,175	1,350	1,525	1,725	1,575	1,925
2	2,000	2,075	2,225	1,800	1,175	1,050	1,250	1,025	1,300	1,425	1,625	1,950	1,950
3	1,950	1,800	2,150	1,725	1,575	1,275	1,325	1,100	1,500	1,550	1,375	1,825	2,000
4	2,100	2,400	1,975	1,675	1,350	1,525	1,500	1,150	1,350	1,225	1,225	1,475	1,850
5	2,275	2,300	2,150	1,525	1,350	1,475	1,475	1,175	1,375	1,400	1,425	1,550	1,900

EXPERIENTIAL LEARNING 8.1 Forecasting a Vital Energy Statistic

The following time-series data capture the weekly average of East Coast crude oil imports in thousands of barrels per day.

QUARTER 2 YEAR 1		QUARTER 3 YEAR 1		QUARTER 4 YEAR 1		QUARTER 1 YEAR 2	
Week	**Data**	**Week**	**Data**	**Week**	**Data**	**Week**	**Data**
1	1,160	14	1,116	27	1,073	40	994
2	779	15	1,328	28	857	41	1,307
3	1,134	16	1,183	29	1,197	42	997
4	1,275	17	1,219	30	718	43	1,082
5	1,355	18	1,132	31	817	44	887
6	1,513	19	1,094	32	946	45	1,067
7	1,394	20	1,040	33	725	46	890
8	1,097	21	1,053	34	748	47	865
9	1,206	22	1,232	35	1,031	48	858
10	1,264	23	1,073	36	1,061	49	814
11	1,153	24	1,329	37	1,074	50	871
12	1,424	25	1,096	38	941	51	1,255
13	1,274	26	1,125	39	994	52	980

Your instructor has a "holdout" sample representing the values for week 53 and beyond. Your task is to use the POM for Windows *Time Series Forecasting* module and the history file to project this statistic into the future. You can enter the demand data directly into the Data Table. Prior to your next class meeting:

a. Use the POM for Windows *Time Series Forecasting* module to locate the best naïve, moving average, weighted moving average, and trend projection with regression models that you think will most accurately forecast demand during the holdout sample. *Begin your error calculations with week 5.*

b. Create an Excel spreadsheet that begins with inputs of the four forecasts from the *Time Series Forecasting* module. Its purpose is to develop a combination forecast that will serve as your team's forecasts for each period. Assign a weight to each forecast model (the sum of all four forecast weights for one period should equal 1.0) and develop a "combination forecast" by multiplying each forecast by its weight. Keep the weights constant for the whole history file as you search for the best set of weights. If you do not like a particular model, give it a weight of 0. Calculate appropriate forecast error measures for your combination forecast in your Excel spreadsheet.

c. Create a management report that shows your period-by-period forecasts and their overall historical CFE and MAPE performance for each model and your combination forecast.

In-Class Exercise—Part 1

a. Input into your Excel spreadsheet the forecasts from the POM for Windows *Time Series Forecasting* module to get the combination forecast for the first period (week 53) in the holdout sample. The combination forecast is considered your team's forecast.

b. Enter the actual data announced by your instructor, and have Excel compute appropriate forecast error measures for your four models and the combination forecast. Decide on any revisions of weights for the combination forecast.

c. Update the POM for Windows *Time Series Forecasting* module with the actual demand for the new period and get the new forecasts.

In-Class Exercise—Part 2

a. Input the forecasts from the POM for Windows *Time Series Forecasting* module into your Excel spreadsheet to get the final combination forecast for the next period (week 54). At this point, you may change this period's weights on each forecasting technique going into the combination forecast. You have no contextual information but may observe that one model has been performing particularly well in the past few periods. Your team might have different opinions, but you must reach a consensus.

b. Enter the actual data announced by your instructor, with Excel computing appropriate forecast error measures for your four models and the combination forecast.

c. Update the POM for Windows *Time Series Forecasting* module with the actual demand for the new period and get the new forecasts.

In-Class Exercise—Parts 3 and Beyond

Continue in the fashion of Parts 1 and 2 to produce forecasts as directed by your instructor. At the end of the exercise, create a second management report that shows for the holdout sample your period-by-period forecasts, their individual forecast errors, and percent deviations for each model and your combination forecast. Explain your logic regarding any changes made to your combination forecast weights over the holdout period.[5]

[5] *Source:* This experiential exercise was prepared as an in-class exercise by Dr. John Jensen, University of South Carolina, as a basis for classroom discussion. By permission of John B. Jensen.

CASE Yankee Fork and Hoe Company

The Yankee Fork and Hoe Company is a leading producer of garden tools ranging from wheelbarrows, mortar pans, and hand trucks to shovels, rakes, and trowels. The tools are sold in four different product lines, ranging from the top-of-the-line Hercules products, which are rugged tools for the toughest jobs, to the Garden Helper products, which are economy tools for the occasional user. The market for garden tools is extremely competitive because of the simple design of the products and the large number of competing producers. In addition, more people are using power tools, such as lawn edgers, hedge trimmers, and thatchers, reducing demand for their manual counterparts. These factors compel Yankee to maintain low prices while retaining high quality and dependable delivery.

Garden tools represent a mature industry. Unless new manual products can be developed or a sudden resurgence occurs in home gardening, the prospects for large increases in sales are not bright. Keeping ahead of the competition is a constant battle. No one knows this better than Alan Roberts, president of Yankee.

The types of tools sold today are, by and large, the same ones sold 30 years ago. The only way to generate new sales and retain old customers is to provide superior customer service and produce a product with high customer value. This approach puts pressure on the manufacturing system, which has been having difficulties lately. Recently, Roberts has been receiving calls from long-time customers, such as Sears and True Value Hardware Stores, complaining about late shipments. These customers advertise promotions for garden tools and require on-time delivery.

Roberts knows that losing customers like Sears and True Value would be disastrous. He decides to ask consultant Sharon Place to look into the matter and report to him in 1 week. Roberts suggests that she focus on the bow rake as a case in point because it is a high-volume product and has been a major source of customer complaints of late.

Planning Bow Rake Production

A bow rake consists of a head with 12 teeth spaced 1 inch apart, a hardwood handle, a bow that attaches the head to the handle, and a metal ferrule that reinforces the area where the bow inserts into the handle. The bow is a metal strip that is welded to the ends of the rake head and bent in the middle to form a flat tab for insertion into the handle. The rake is about 64 inches long.

Place decides to find out how Yankee plans bow rake production. She goes straight to Phil Stanton, who gives the following account:

> Planning is informal around here. To begin, marketing determines the forecast for bow rakes by month for the next year. Then they pass it along to me. Quite frankly, the forecasts are usually inflated—must be their big egos over there. I have to be careful because we enter into long-term purchasing agreements for steel, and having it just sitting around is expensive. So, I usually reduce the forecast by 10 percent or so. I use the modified forecast to generate a monthly final-assembly schedule, which determines what I need to have from the forging and woodworking areas. The system works well if the forecasts are good. But when marketing comes to me and says they are behind on customer orders, as they often do near the end of the year, it wreaks havoc with the schedules. Forging gets hit the hardest. For example, the presses that stamp the rake heads from blanks of steel can handle only 7,000 heads per day, and the bow rolling machine can do only 5,000 per day. Both operations are also required for many other products.

Because the marketing department provides crucial information to Stanton, Place decides to see the marketing manager, Ron Adams. Adams explains how he arrives at the bow rake forecasts.

TABLE 8.5 | FOUR-YEAR DEMAND HISTORY FOR THE BOW RAKE

	DEMAND			
Month	Year 1	Year 2	Year 3	Year 4
1	55,220	39,875	32,180	62,377
2	57,350	64,128	38,600	66,501
3	15,445	47,653	25,020	31,404
4	27,776	43,050	51,300	36,504
5	21,408	39,359	31,790	16,888
6	17,118	10,317	32,100	18,909
7	18,028	45,194	59,832	35,500
8	19,883	46,530	30,740	51,250
9	15,796	22,105	47,800	34,443
10	53,665	41,350	73,890	68,088
11	83,269	46,024	60,202	68,175
12	72,991	41,856	55,200	61,100

Things do not change much from year to year. Sure, sometimes we put on a sales promotion of some kind, but we try to give Phil enough warning before the demand kicks in—usually a month or so. I meet with several managers from the various sales regions to go over shipping data from last year and discuss anticipated promotions, changes in the economy, and shortages we experienced last year. Based on these meetings, I generate a monthly forecast for the next year. Even though we take a lot of time getting the forecast, it never seems to help us avoid customer problems.

The Problem

Place ponders the comments from Stanton and Adams. She understands Stanton's concerns about costs and keeping inventory low and Adams' concern about having enough rakes on hand to make timely shipments. Both are also somewhat concerned about capacity. Yet she decides to check actual customer demand for the bow rake over the past 4 years (in Table 8.5) before making her final report to Roberts.

QUESTIONS

1. Comment on the forecasting system being used by Yankee. Suggest changes or improvements that you believe are justified.
2. Develop your own forecast for bow rakes for each month of the next year (year 5). Justify your forecast and the method you used.

VIDEO CASE

Forecasting and Supply Chain Management at Deckers Outdoor Corporation

Deckers Outdoor Corporation's footwear products are among some of the most well-known brands in the world. From UGG sheepskin boots and Teva sport sandals to Simple shoes, Deckers flip-flops, and Tsubo footwear, Deckers is committed to building niche footwear brands into global brands with market leadership positions. Annual revenue for 2019 was $2 billion. In addition to traditional retail store outlets for Deckers's footwear styles, the company maintains an active and growing "direct to consumer" e-commerce business. Since most retail stores cannot carry every style in every color and size, the company offers the full line for each of its brands directly to consumers through the brands' individual websites. Online sales at its virtual store are handled by its e-commerce group. Customers who want a pair of shoes not available at the retail store can always buy from the virtual store.

Founded in 1973, the company manufactured a single line of sandals in a small factory in southern California. The challenges of managing the raw materials and finished goods inventories were small compared to today's global sourcing and sales challenges for the company's various brands. Today, each brand has its own development team and brand managers who generate, develop, and test-market the seasonal styles that appear on the shelves of retailers such as Nordstrom, Lord & Taylor, REI, The Walking Company, and the company's own UGG brand retail stores in the United States and Japan.

At Deckers, forecasting is the starting point for inventory management, sales and operations planning, resource planning, and scheduling—in short, managing its supply chain. It carries a considerable amount of seasonal stock. Shoes with seasonal demand that are left over at the end of their season must be sold at heavily discounted prices. Its products fall into three categories: (1) carryover items that were sold in prior years, (2) new items that look similar to past models, and (3) completely new designs that are fashionable with no past history.

Twice a year, the brand development teams work on the fall and spring product lines. They come up with new designs about a year in advance of each season. Each brand (UGG, Teva, Simple, Tsubo, and Deckers) contains numerous products. The materials for new designs are selected and tested in prototypes. Approved designs are put into the seasonal lineup. Forecasts must be made at both the product and aggregate levels months before the season begins. "Bottoms-up" forecasts for each product begin by analyzing any available history files of past demand. Judgment forecasts are also important inputs, particularly for the second and third categories of shoes that are not carryovers. For example, Char



Astrid Stawiarz/Getty Images for POPSUGAR

Deckers' popular UGG brand is sold all over the world. Here Koolaburra boots by UGG are on display at POPSUGAR's first-ever Sugar Chalet Winter Wonderland in Bryant's Park on November 23, 2019 in New York City.

Nicanor-Kimball is an expert in spotting trends in shoe sales and makes forecasts for the virtual store. For new designs, historical sales on similar items are used to make a best guess on demand for those items. This process is facilitated by a forecasting and inventory system on the company's intranet. At the same time, the sales teams for each brand call on their retail accounts and secure customer orders of approved designs for the coming season. Then, the virtual store forecasts are merged with orders from the retail store orders to get the total seasonal demand forecasted by product. Next, the product forecasts are "rolled up" by category, and "top down" forecasts are also made.

These forecasts then go to top management, where some adjustments may be made to account for financial market conditions, consumer credit, weather, demographic factors, and customer confidence. The impact of public relations and advertising must also be considered.

Actually, forecasting continues on throughout the year on a daily and weekly basis to "get a handle" on demand. Comparing actual demand with what was forecasted for different parts of the season also helps the forecasters make better forecasts for the future and better control inventories.

On the basis of initial demand forecasts, the company must begin sourcing the materials needed to produce the footwear. The company makes most of its products in China and sources many of the raw materials there as well. For UGG products sheepskin sourcing occurs in Australia with top-grade producers, but the rawhide tanning still takes places in China. With potential suppliers identified and assurance from internal engineering that the footwear can be successfully made, the engineering and material data are handed over to the manufacturing department to determine how best to make the footwear in mass quantities. At this point, Deckers places a seasonal "buy" with its suppliers.

The orders for each product are fed into the manufacturing schedules at the Chinese factories. All the products for a given brand are manufactured at the same factory. While Deckers's agents negotiate the raw materials contracts early in the development process, the factories place the orders for the raw materials only when the company sends in the actual orders for the finished goods. No footwear is made by the factories until orders are received.

At the factories, finished goods footwear is inspected and packaged for the month-long ocean voyage from Hong Kong to ports in the United States. Deckers ships 50 containers a week from its Chinese manufacturing sources, each holding approximately 5,000 pairs of shoes. Ownership of the finished goods transfers from the factories to Deckers in Hong Kong.

When the shipping containers arrive in the United States, the footwear is transferred to Deckers's distribution centers in Southern California. Teva products are warehoused in Ventura, California; all other products are handled by the company's state-of-the-art facility in Camarillo, California. Typically, Deckers brings product into the distribution centers 2 to 3 months in advance of expected needs so that the production at the suppliers' factories and the labor activities at the distribution centers are leveled. There are definitive spikes in the demand for footwear, with Teva spiking in quarter 1 and UGG spiking in quarter 4. The leveling approach works to keep costs low in the supply chain. However, it also means that Deckers must maintain sizable inventories. Most shipments from suppliers come in to the distribution centers and are stored in inventory for 1 to 2 months, awaiting a customer order. By the time the footwear is stocked in the distribution center, the company knows which retail customers will be getting the various products, based on the orders booked months earlier. Then, according to delivery schedules negotiated with the customers, the company begins filling orders and shipping products to retail locations. The warehouse tracks incoming shipments, goods placed on the shelves for customers, and outgoing orders. The inventory system helps manage the customer order filling process.

Because the booked orders are a relatively large proportion of the total orders from retailers, and the number of unanticipated orders is very small, only small safety stocks are needed to service the retailers. Occasionally, the purchase order from Deckers to one of its suppliers matches the sales order from the customer. In such a case, Deckers uses a "cross-dock" system. When the shipment is received at the distribution center, it is immediately checked in and loaded on another truck for delivery to customers. Cross docking reduces the need to store vast quantities of product for long periods of time and cuts down on warehousing expenses for Deckers. The company has been successful in turning its inventory over about four times a year, which is in line with footwear industry standards.

The online sales traffic is all managed centrally. In fact, for ordering and inventory management purposes, the online side of the business is treated just like another major retail store account. As forecasted seasonal orders are generated by each brand's sales team, a manufacturing order for the online business is placed by the e-commerce sales team at the same time. However, unlike the retail outlets that take delivery of products on a regular schedule, the inventory pledged to the online business is held in the distribution center until a website order is received. Only then is it shipped directly to the consumer who placed the online order. If actual demand exceeds expected demand, Char Nicanor-Kimball checks if more inventory can be secured from other customer orders that have scaled back.

The forecasting and supply chain management challenges now facing Deckers are twofold. First, the company plans to grow the brands that have enjoyed seasonal sales activity into year-round footwear options for consumers by expanding the number of products for those brands. For example, most sales for UGG footwear occur in the fall/winter season. Sales for Teva historically have been in the spring and summer. Product managers are now working to develop styles that will allow the brands to cross over the seasons. Second, the company plans to expand internationally, and will have retail outlets in Europe, China, and other Asian locations in the very near future. Company managers are well aware of the challenges and opportunities such global growth will bring, and are taking steps now to ensure that the entire supply chain is prepared to forecast and handle the demand when the time comes.

QUESTIONS

1. How much does the forecasting process at Deckers correspond with the "typical forecasting process" described at the end of this chapter?
2. Based on what you see in the video, what kinds of information technology are used to make forecasts, maintain accurate inventory records, and project future inventory levels?
3. What factors make forecasting at Deckers particularly challenging? How can forecasts be made for seasonal, fashionable products for which there is no history file? What are the costs of overforecasting demand for such items? Underforecasting?
4. What are the benefits of leveling aggregate demand by having a portfolio of products that create a 365-day demand?
5. Deckers has expanded internationally over the past few years, thereby increasing the volume of shoes it must manage in the supply chain and the pattern of material flows. What implications does this strategy have on forecasting, order quantities, logistics, and relationships with its suppliers and customers?

9

INVENTORY MANAGEMENT

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

- **9.1** Identify the trade-offs involving small versus large inventories.
- **9.2** Define the different types of inventory and the roles they play in supply chains.
- **9.3** Explain the tactics for reducing inventories in supply chains.
- **9.4** Use ABC analysis to determine the items deserving most attention and tightest inventory control.
- **9.5** Calculate the economic order quantity and apply it to various situations.
- **9.6** Determine the order quantity and reorder point for a continuous review inventory control system.
- **9.7** Determine the review interval and target inventory level for a periodic review inventory control system.

Ford's Smart Inventory Management System (SIMS)



Jonathan Weiss/Alamy Stock Photo

Display of Ford Explorers at a Ford dealership.

As you pass a large car dealership and see the hundreds of new cars neatly arranged in the lot, have you ever wondered how it was decided to stock those particular units in the dealership's inventory? According to Bryan Goodman, a research scientist at Ford, it really matters what is on the lot at the

moment a customer arrives. Having the wrong models, colors, or options could have a big effect on sales. The answer, however, is not larger inventories. One problem is figuring out what the customers want, and the number of possibilities can be mind boggling. On a given vehicle, customers may have multiple choices on features such as exterior color, trim, interior seating, entertainment, navigation, and the like. The number of combinations on some models could be in the millions. Another problem with large inventories is that inventory holding costs can be prohibitive; it costs about $10 per vehicle per day.

Ford's answer was to employ a *big-data approach* (see Chapter 8, "Forecasting"). A team of 200 big-data and analytics experts from a range of disciplines focused on three areas: ascertaining what customers want, managing vehicle complexity, and delivering the right cars with the right features to individual dealers. To do that, Ford integrates and analyzes several data streams, including data on what has already been built and sold at a dealership, what has been sold in the context of what was in inventory at the time of the sale, sales patterns of other Ford dealerships in the area, plus what customers are searching for and configuring on company websites. These data are then combined with economic data to predict vehicle sales relative to housing starts, employment rates, and the like. The system, called the Smart Inventory Management System, or SIMS, requires the support of supercomputers with 1.5 terabytes of RAM to analyze all of that data on a timely basis. Relevant data are sent to dealers on a weekly basis, and it is up to them whether to follow the order recommendations. Dealers are in the best position to fine-tune orders because they can better evaluate additional information on the ground using their experience and intuition. Nonetheless, there is a 98 percent match between what SIMS recommends and what is actually ordered. Each week, 50,000 vehicle orders are placed in North America alone.

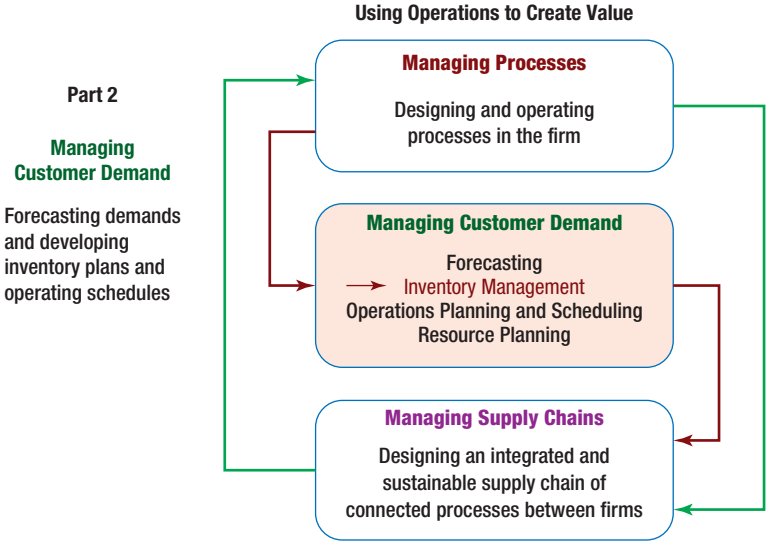
The new system was rolled out in 2009 and has become a major success. Its recommendations saved dealers $90 per vehicle. By reducing the time a vehicle spends on the lots, dealers have enjoyed quicker inventory turnover. However, the value of SIMS goes beyond new car inventories. By tailoring the bulk of the company's production to customers' preferences, assembly plant schedules and parts forecasts have been significantly improved. It is estimated that SIMS is worth more than $100 million a year to Ford.

Pre-owned vehicle inventories can also be expensive. Ford Motor Company, along with other car manufacturers, uses CarStory, an artificial intelligence platform built on a database of millions of used vehicles and shopper insights from across the country. CarStory, which touches 15 million consumers a month and has inventory data from more than 10,000 franchised and independent dealerships, provides details to consumers about the condition of vehicles along with how pricing measures up against market averages. In essence, a dealership's inventory of cars is made available to a much larger market, thereby helping to increase inventory turnover and revenues.[1]

[1] *Sources*: Julia King, "How Analytics Helped Ford Turn Its Fortunes," http://www.computerworld.com (December 2, 2013); Kathleen Burke, "Ford Data Crunchers Help Dealers Fine-Tune Inventory," http://www.autonews.com (August 18, 2014); Chanelle Bessette, "Ford's $100 Million Data Machine," http://fortune.com (June 2, 2014); Vince Bond, Jr., "Ford Dealers Gain Access to AI Tool for Used-Car Sales," https://www.auronews.com (February 19, 2018).

Inventory management, the planning and controlling of inventories to meet the competitive priorities of the organization, is an important concern for managers in all types of businesses. We have seen in Chapter 8, "Forecasting", how forecasting can help us determine the sizing and timing of customer demands for goods or services. **Inventory management** is the first of the tools we discuss in Part 2 of this text that is focused on how to satisfy that demand. Effective inventory management is essential for realizing the full potential of any supply chain. The challenge is not to pare inventories to the bone to reduce costs or to have plenty around to satisfy all demands, but to have the right amount to achieve the competitive priorities of the business most efficiently. This type of efficiency can happen only if the right amount of inventory is flowing through the supply chain—through suppliers, the firm, warehouses or distribution centers, and customers. Much of inventory management involves **lot sizing**, which is the determination of how frequently and in what quantity to order inventory. We make ample reference to the term **lot size**, which is the quantity of an inventory item that management either buys from a supplier or manufactures using internal processes. In this chapter, we focus on the decision-making aspects of inventory management.

inventory management
The planning and controlling of inventories to meet the competitive priorities of the organization.



Inventories are important to all types of organizations, their employees, and their supply chains. Inventories profoundly affect everyday operations because they must be counted, paid for, used in operations, used to satisfy customers, and managed. Inventories require an investment of funds, as does the purchase of a new machine. Monies invested in inventory are not available for investment in other things; thus, they represent a drain on the cash flows of an organization. Nonetheless, companies realize that the availability of products is a key selling point in many markets and downright critical in many more.

So, is inventory a boon or a bane? Certainly, too much inventory on hand reduces profitability, and too little inventory on hand creates shortages in the supply chain and ultimately damages customer confidence. Inventory management, therefore, involves trade-offs. Let us discover how companies can effectively manage inventories across the organization.

lot sizing
The determination of how frequently and in what quantity to order inventory.

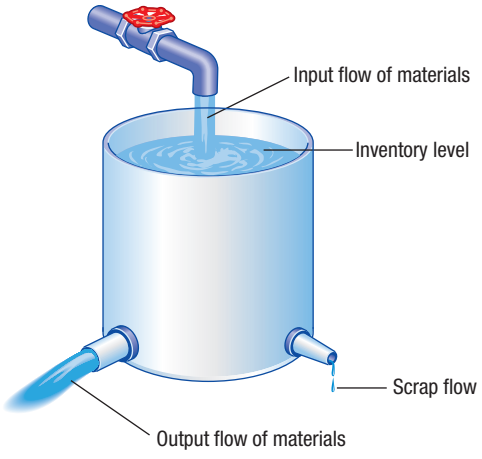
lot size
The quantity of an inventory item that management either buys from a supplier or manufactures using internal processes.

Inventory Trade-Offs

The value of inventory management becomes apparent when the complexity of the supply chain is recognized. The performance of numerous suppliers determines the inward flow of materials and services to a firm. The performance of the firm determines the outward flow of services or products to the next stage of the supply chain. The flow of materials, however, determines inventory levels. **Inventory** is a stock of materials used to satisfy customer demand or to support the production of services or goods. Figure 9.1 shows how inventories are created at one node in a supply chain through the analogy of a water tank. The flow of water into the tank raises the water level. The inward flow of water represents input materials, such as steel, component parts, office supplies, or a finished product. The water level represents the amount of inventory held at a plant, service facility, warehouse, or retail outlet. The flow of water from the tank lowers the water level in the tank. The outward flow of water represents the demand for materials in inventory, such as customer orders for a Huffy bicycle or service requirements for supplies such as soap, food, or furnishings. The rate of the outward flow also reflects the ability of the firm to match the demand for services or products. Another possible outward flow is that of scrap, which also lowers the level of usable inventory. Together, the difference between input flow rate and the output flow rate determines the level of inventory. Inventories rise when more material flows into the tank than flows out; they fall when more material flows out than flows in. Figure 9.1 also shows clearly why firms utilize Six Sigma and total quality management (TQM) to reduce defective materials: The larger the scrap flows, the larger the input flow of materials required for a given level of output.

inventory
A stock of materials used to satisfy customer demand or to support the production of services or goods.

▼ **FIGURE 9.1**
Creation of Inventory



A fundamental question in supply chain management is how much inventory to have. The answer to this question involves a trade-off between the advantages and disadvantages of holding inventory. Depending on the situation, the pressures for having small inventories may or may not exceed the pressures for having large inventories.

Pressures for Small Inventories

inventory holding cost

The sum of the cost of capital and the variable costs of keeping items on hand, such as storage and handling, taxes, insurance, and shrinkage.

An inventory manager's job is to balance the advantages and disadvantages of both small and large inventories and find a happy medium between the two levels. The primary reason for keeping inventories small is that inventory represents a temporary monetary investment. As such, the firm incurs an opportunity cost, which we call the cost of capital, arising from the money tied up in inventory that could be used for other purposes. The **inventory holding cost** (or *carrying cost*) is the sum of the cost of capital plus the variable costs of keeping items on hand, such as storage and handling costs and taxes, insurance, and shrinkage costs. When these components change with inventory levels, so does the holding cost.

Companies usually state an item's holding cost per period of time as a percent of its value. The annual cost to maintain one unit in inventory typically ranges from 15 to 35 percent of its value. Suppose that a firm's holding cost is 20 percent. If the average value of total inventory is 20 percent of sales, the average annual cost to hold inventory is 4 percent [0.20(0.20)] of total sales. This cost is sizable in terms of gross profit margins, which often are less than 10 percent. Thus, the components of holding cost create pressures for small inventories.

Cost of Capital The cost of capital is the opportunity cost of investing in an asset relative to the expected return on assets of similar risk. Inventory is an asset; consequently, we should use a cost measure that adequately reflects the firm's approach to financing assets. Most firms use the *weighted average cost of capital (WACC)*, which is the average of the required return on a firm's stock equity and the interest rate on its debt, weighted by the proportion of equity and debt in its portfolio. The cost of capital usually is the largest component of holding cost, as high as 15 percent of inventory value, depending on the particular capitalization portfolio of the firm. Firms typically update the WACC on an annual basis because it is used to make many financial decisions.

Storage and Handling Costs Inventory takes up space and must be moved into and out of storage. Storage and handling costs may be incurred when a firm rents space on either a long- or short-term basis. An inventory holding cost is incurred when a firm could use storage space productively in some other way.

Taxes, Insurance, and Shrinkage More taxes are paid if end-of-year inventories are high, and the cost of insuring the inventories increases, too. Shrinkage takes three forms. The first, *pilferage*, or theft of inventory by customers or employees, is a significant percentage of sales for some businesses. The second form of shrinkage, called *obsolescence*, occurs when inventory cannot be used or sold at full value, owing to model changes, engineering modifications, or unexpectedly low demand. Obsolescence is a big expense in the retail clothing industry. Drastic discounts on seasonal clothing frequently must be offered on many of these products at the end of a season. Finally, *deterioration* through physical spoilage or damage due to rough or excessive material handling results in lost value. Food and beverages, for example, lose value and might even have to be discarded when their shelf life is reached. When the rate of deterioration is high, building large inventories may be unwise.

Pressures for Large Inventories

Given the costs of holding inventory, why not eliminate it altogether? Let us look briefly at the pressures related to maintaining large inventories.

Customer Service Creating inventory can speed delivery and improve the firm's on-time delivery of goods. High inventory levels reduce the potential for stockouts and backorders, which are key concerns of wholesalers and retailers. A *stockout* is an order that cannot be satisfied, resulting in loss of the sale. A *backorder* is a customer order that cannot be filled when promised or demanded but is filled later. Customers do not like waiting for backorders to be filled. Many of them will take their business elsewhere. Sometimes, customers are given discounts for the inconvenience of waiting.

ordering cost

The cost of preparing a purchase order for a supplier or a production order for manufacturing.

Ordering Cost Each time a firm places a new order, it incurs an **ordering cost**, or the cost of preparing a purchase order for a supplier or a production order for manufacturing. For the same item, the ordering cost is the same, regardless of the order size. The purchasing agent must take the time to decide how much to order and, perhaps, select a supplier and negotiate terms. Time also is spent on paperwork, follow-up, and receiving the item(s). In the case of a production order for a manufactured item, a blueprint and routing instructions often must accompany the order. However, in many situations, technology can be used to determine when to place orders and actually place them, greatly reducing the ordering cost for an item.

setup cost

The cost involved in changing over a machine or workspace to produce a different item.

Setup Cost The cost involved in changing over a machine or workspace to produce a different item is the **setup cost**. It includes labor and time to make the changeover, cleaning, and sometimes new tools or equipment. Scrap or rework costs are also higher at the start of the production run.

Setup cost also is independent of order size, which creates pressure to make or order a large supply of the items and hold them in inventory rather than order smaller batches. Once again, in some situations, technology can be used to make machines flexible in the products they manufacture, thereby greatly reducing the cost to changeover between product runs. (See Chapter 2, "Process Strategy and Analysis.")

Labor and Equipment Utilization By creating more inventory, management can increase workforce productivity and facility utilization in three ways. First, placing larger, less frequent production orders reduces the number of unproductive setups, which add no value to a service or product. Second, holding inventory reduces the chance of the costly rescheduling of production orders because the components needed to make the product are not in inventory. Third, building inventories improves resource utilization by stabilizing the output rate when demand is cyclical or seasonal. The firm uses inventory built during slack periods to handle extra demand in peak seasons. This approach minimizes the need for extra shifts, hiring, layoffs, overtime, and additional equipment.

Transportation Cost Sometimes, outbound transportation cost can be reduced by increasing inventory levels. Having inventory on hand allows more full-carload shipments to be made and minimizes the need to expedite shipments by more expensive modes of transportation. Inbound transportation costs can also be reduced by creating more inventory. Sometimes, several items are ordered from the same supplier. Placing these orders at the same time will increase inventories because some items will be ordered before they are actually needed; nonetheless, it may lead to rate discounts, thereby decreasing the costs of transportation and raw materials.

Payments to Suppliers A firm often can reduce total payments to suppliers if it can tolerate higher inventory levels. Suppose that a firm learns that a key supplier is about to increase its prices. In this case, it might be cheaper for the firm to order a larger quantity than usual—in effect delaying the price increase—even though inventory will increase temporarily. A firm can also take advantage of quantity discounts this way. A **quantity discount**, whereby the price per unit drops when the order is sufficiently large, is an incentive to order larger quantities. Supplement C, "Special Inventory Models," shows how to determine order quantities in such a situation.

quantity discount
A drop in the price per unit when an order is sufficiently large.

Although serious considerations are involved in deciding the amount of inventory to retain, one unavoidable fact remains: Inventories cost money. Every organization that retains inventories must find a way to finance them. The following Managerial Challenge shows how inventories can grab the attention of executives at the top level and become a problem to be solved by managers at the lower levels.

MANAGERIAL CHALLENGE Finance

Raphael Sanchez is the chief financial officer (CFO) of Medco, a manufacturer of medical technologies. The company has multiple manufacturing facilities located throughout the Western Hemisphere. In his role he is responsible for his company's business plan, which drives the planning process; consequently, to assemble the plan, he must secure information from the different divisions within the organization. Recently, Raphael noticed that a key financial measure in the plan, return on assets (net income divided by total assets), has been slipping. Key investors are getting nervous. He realized that a number of factors could be in play; however, the need for working capital, a key element of total assets, has been increasing. Inventory is financed by working capital. Raphael suspected that Medco could be more efficient with respect to its inventory investment. He gave Sara Kowalski, financial analyst in the corporate office, the task of reporting to him how inventories can be reduced without affecting the customers of Medco.

Sara immediately realized the need to get inputs from those closely involved with inventory decision making. She contacted Roy Smith, Information Systems, Julie Fawcett, Accounting, and Antonio Tagliani, Operations, who all agreed to discuss inventories and help with the report. Roy knows the programs Medco uses to control inventories (place replenishment orders and manage backorders) and the reports generated for management use. Julie can shed light on the costs attributed to various types of inventory. Antonio is directly involved in selecting the ordering policies and the systems for managing inventory as well as organizing the resources needed to meet the goals placed on inventory levels. Sara needs answers to some questions for her report to Mr. Sanchez. How are the inventory decisions being made?

How does the cost of capital, which is largely under the purview of Finance, affect inventory decisions? What are the tactics for reducing inventories, and which ones are viable for Medco? What systems are being used for managing inventories, and can they be used to lower inventories while maintaining customer service? Before meeting with the others, Sara could benefit from a general understanding of this topic, which is provided in the remainder of this chapter.

Types of Inventory

Inventories can be classified in several ways. In this section we discuss accounting inventories and operational inventories.

Accounting Inventories

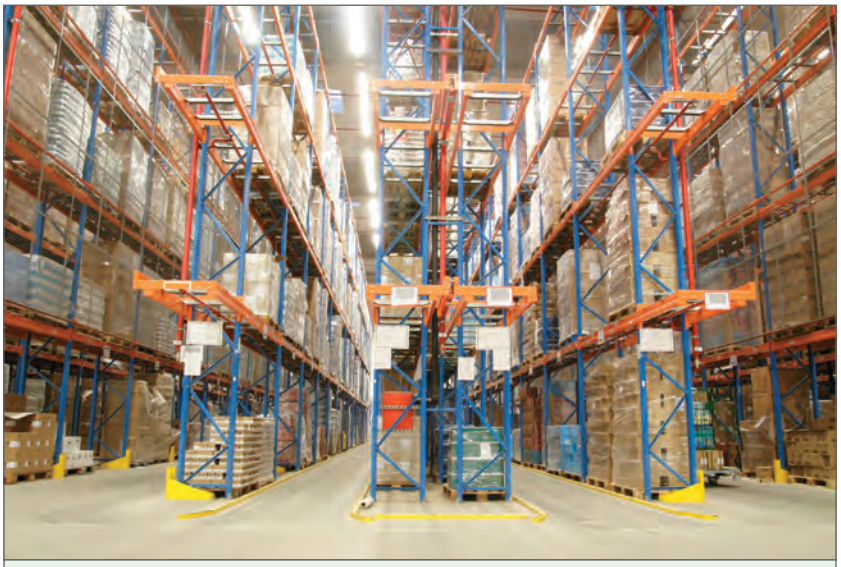
raw materials (RM)
The inventories needed for the production of services or goods.

work-in-process (WIP)
Items, such as components or assemblies, needed to produce a final product in manufacturing or service operations.

finished goods (FG)
The items in manufacturing plants, warehouses, and retail outlets that are sold to the firm's customers.

Inventory exists in three aggregate categories that are useful for accounting purposes. **Raw materials (RM)** are the inventories needed for the production of services or goods. They are considered to be inputs to the transformation processes of the firm. **Work-in-process (WIP)** consists of items, such as components or assemblies, needed to produce a final product in manufacturing. WIP is also present in some service operations, such as repair shops, restaurants, check-processing centers, and package delivery services. **Finished goods (FG)** in manufacturing plants, warehouses, and retail outlets are the items sold to the firm's customers. The finished goods of one firm may actually be the raw materials for another.

Figure 9.2 shows how inventory can be held in different forms and at various stocking points. In this example, raw materials—the finished goods of the supplier—are held by both the supplier and the manufacturer. Raw materials at the plant pass through one or more processes, which transform them into various levels of WIP inventory. Final processing of this inventory yields finished goods inventory. Finished goods can be held at the plant, the distribution center (which may be a warehouse owned by the manufacturer or the retailer), and retail locations.



Marcin Balcerzak/Shutterstock

Raw materials, work-in-progress, and finished goods inventories can all be stocked in the same facility. Modern warehouses allow for efficient inventory access.

An important distinction regarding the three categories of inventories is the nature of the demand they experience. For example, take finished goods, which are **independent demand items**—that is, items for which demand is influenced by market conditions and is not related to the inventory decisions for any other item held in stock or produced. Retailers, such as JCPenney and Dillard's, deal with finished goods. Examples of independent demand items include:

- Wholesale and retail merchandise
- Service support inventory, such as stamps and mailing labels for post offices, office supplies for law firms, and laboratory supplies for research universities

independent demand items
Items for which demand is influenced by market conditions and is not related to the inventory decisions for any other item held in stock or produced.

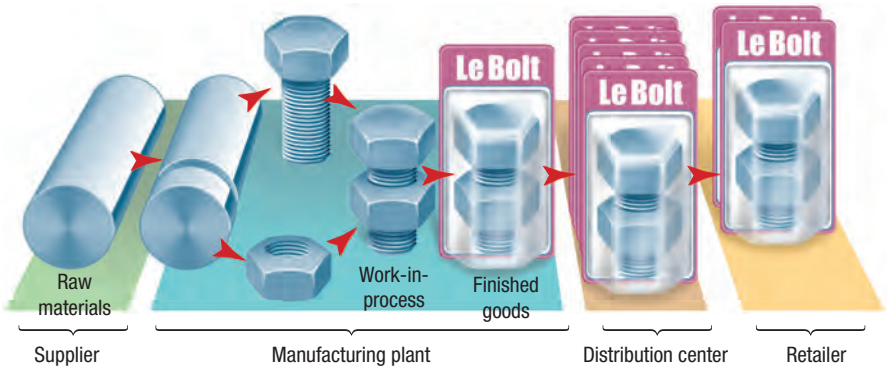


FIGURE 9.2 ▶
Inventory of Successive Stocking Points

- Product and replacement-part distribution inventories
- Maintenance, repair, and operating (MRO) supplies—that is, items that do not become part of the final service or product, such as employee uniforms, fuel, paint, and machine repair parts

Managing an independent demand inventory can be tricky because demand is influenced by external factors. For example, the owner of a bookstore may not be sure how many copies of the latest bestselling novel customers will purchase during the coming month. As a result, the manager may decide to stock extra copies as a safeguard. Independent demand, such as the demand for various book titles, must be *forecasted* using the techniques we discussed in Chapter 8, "Forecasting." There is, however, a whole different type of demand for certain items that must be considered. **Dependent demand items**, consisting of raw materials and WIP inventories, are those items whose required quantity varies with the production plans for other items held in the firm's inventory. These items are required as components or inputs to a service or product. Dependent demand should be calculated, not forecasted, and exhibits a pattern very different from that of independent demand (see Chapter 11, "Resource Planning").

dependent demand items
Items whose required quantity varies with the production plans for other items held in the firm's inventory.

Operational Inventories

Inventories can also be classified by how they are created. In this context, inventory takes four forms: (1) cycle, (2) safety stock, (3) anticipation, and (4) pipeline. They cannot be identified physically; that is, an inventory manager cannot look at a pile of widgets and identify which ones are cycle inventory and which ones are safety stock inventory. However, conceptually, each of the four types comes into being in an entirely different way. Once you understand these differences, you can prescribe different ways to reduce inventory.

Cycle Inventory The portion of total inventory that varies directly with lot size is called **cycle inventory**. Two principles apply:

1. The lot size, Q, varies directly with the elapsed time (or cycle) between orders. If a lot is ordered every 5 weeks, the average lot size must equal 5 weeks' demand.
2. The longer the time between orders for a given item, the greater the cycle inventory must be.

cycle inventory
The portion of total inventory that varies directly with lot size.

At the beginning of the interval, the cycle inventory is at its maximum, or Q. At the end of the interval, just before a new lot arrives, cycle inventory drops to its minimum, or 0. The average cycle inventory is the average of these two extremes:

$$\text{Average cycle inventory} = \frac{Q + 0}{2} = \frac{Q}{2}$$

This formula is exact only when the demand rate is constant and uniform. However, it does provide a reasonably good estimate even when demand rates are not constant. Factors other than the demand rate (e.g., scrap losses) also may cause estimating errors when this simple formula is used.

Safety Stock Inventory To avoid customer service problems and the hidden costs of unavailable components, companies hold safety stock. **Safety stock inventory** is surplus inventory that protects against uncertainties in demand, lead time, and supply changes. Safety stocks are desirable when suppliers fail to deliver either the desired quantity on the specified date or items of acceptable quality, or when manufactured items require significant amounts of scrap or rework. Safety stock inventory ensures that operations are not disrupted when such problems occur, allowing subsequent operations to continue.

safety stock inventory
Surplus inventory that a company holds to protect against uncertainties in demand, lead time, and supply changes.

To create safety stock, a firm places an order for delivery earlier than when the item is typically needed.[2] The replenishment order therefore arrives ahead of time, giving a cushion against uncertainty. For example, suppose that the average lead time from a supplier is 3 weeks, but a firm orders 5 weeks in advance just to be safe. This policy creates a safety stock equal to a 2-week supply ($5 - 3 = 2$).

Anticipation Inventory Inventory used to absorb uneven rates of demand or supply, which businesses often face, is referred to as **anticipation inventory**. Predictable, seasonal demand patterns lend themselves to the use of anticipation inventory. Uneven demand can motivate a manufacturer to stockpile anticipation inventory during periods of low demand so that output levels do not have to be increased much when demand peaks. Anticipation inventory also can help when suppliers are threatened with a strike or have severe capacity limitations.

anticipation inventory
Inventory used to absorb uneven rates of demand or supply.

Pipeline Inventory Inventory that is created when an order for an item is issued but not yet received is called **pipeline inventory**. This form of inventory exists because the firm must commit

pipeline inventory
Inventory that is created when an order for an item is issued but not yet received.

[2]When orders are placed at fixed intervals, a second way to create safety stock is used. Each new order placed is larger than the quantity typically needed through the next delivery date.



Mike Danneman/Moment/Getty Images

Pipeline inventories result from moving items and materials from one location to another. Because trains offer an economical way to transport large quantities of goods, they are a favorite choice to reduce the costs of pipeline inventories.

to enough inventory (on-hand plus in-transit) to cover the lead time for the order. Longer lead times or higher demands per week create more pipeline inventory. As such, the average pipeline inventory between two stocking points can be measured as the average demand during lead time, $\overline{D}_L$, which is the average demand for the item per period ($\overline{d}$) multiplied by the number of periods in the item's lead time (L) to move between the two points, or

$$\text{Pipeline inventory} = \overline{D}_L = \overline{d}L$$

The equation assumes that both $\overline{d}$ and L are constants and that L is not affected by the order or lot size, Q. Changing an item's lot size does not directly affect the average level of the pipeline inventory. Nonetheless, the lot size can *indirectly* affect pipeline inventory if it is related to the lead time. In such a case, pipeline inventory will change depending on the relationship of L to Q. Example 9.1 shows how this can happen.

EXAMPLE 9.1 Estimating Inventory Levels

Online Resource
Tutor 9.1 in OM Explorer provides a new example to practice the estimation of inventory levels.

A plant makes monthly shipments of electric drills to a wholesaler in average lot sizes of 280 drills. The wholesaler's average demand is 70 drills a week, and the lead time from the plant is 3 weeks. The wholesaler must pay for the inventory from the moment the plant makes a shipment. If the wholesaler is willing to increase its purchase quantity to 350 units, the plant will give priority to the wholesaler and guarantee a lead time of only 2 weeks. What is the effect on the wholesaler's cycle and pipeline inventories?

SOLUTION

The wholesaler's current cycle and pipeline inventories are

$$\text{Cycle inventory} = \frac{Q}{2} = \frac{280}{2} = 140 \text{ drills}$$

$$\text{Pipeline inventory} = \overline{D}_L = \overline{d}L = (70 \text{ drills/week})(3 \text{ weeks}) = 210 \text{ drills}$$

Figure 9.3 shows the cycle and pipeline inventories if the wholesaler accepts the new proposal.

FIGURE 9.3 ▶
Estimating Inventory Levels Using Tutor 9.1

1. Enter the average lot size, average demand during a period, and the number of periods of lead time:

Average lot size	350
Average demand	70
Lead time	2

2. To compute cycle inventory, simply divide average lot size by 2. To compute pipeline inventory, multiply average demand by lead time:

Cycle inventory	175
Pipeline inventory	140

DECISION POINT

The effect of the new proposal on cycle inventories is to increase them by 35 units, or 25 percent. The reduction in pipeline inventories, however, is 70 units, or 33 percent. The proposal would reduce the total investment in cycle and pipeline inventories. Also, it is advantageous to have shorter lead times because the wholesaler has to commit to purchases only 2 weeks in advance, rather than 3 weeks.

Inventory Reduction Tactics

Managers are always eager to find cost-effective ways to reduce inventory in supply chains. In this section we discuss the basic tactics (which we call *levers*) for reducing cycle, safety stock, anticipation, and pipeline inventories in supply chains. A primary lever is one that must be activated if inventory is to be reduced. A secondary lever reduces the penalty cost of applying the primary lever and the need for having inventory in the first place.

Cycle Inventory

The primary lever to reduce cycle inventory is simply to reduce the lot sizes of items moving in the supply chain. However, making such reductions in Q without making any other changes can be devastating. For example, setup costs or ordering costs can skyrocket. If these changes occur, two secondary levers can be used:

1. Streamline the methods for placing orders and making setups to reduce ordering and setup costs and allow Q to be reduced. This may involve redesigning the infrastructure for information flows or improving manufacturing processes.
2. Increase repeatability to eliminate the need for changeovers. **Repeatability** is the degree to which the same work can be done again. Repeatability can be increased through high product demand; the use of specialization; the devotion of resources exclusively to a product; the use of the same part in many different products; the use of *flexible automation*; the use of the *one-worker, multiple-machines* concept; or through *group technology*. Increased repeatability may justify new setup methods, reduce transportation costs, and allow quantity discounts from suppliers.

repeatability
The degree to which the same work can be done again.

Safety Stock Inventory

The primary lever to reduce safety stock inventory is to place orders closer to the time when they must be received. However, this approach can lead to unacceptable customer service unless demand, supply, and delivery uncertainties can be minimized. Four secondary levers can be used in this case:

1. Improve demand forecasts so that fewer surprises come from customers. Design the mechanisms to increase collaboration with customers to get advance warnings for changes in demand levels.
2. Cut the lead times of purchased or produced items to reduce demand uncertainty. For example, local suppliers with short lead times could be selected when possible.
3. Reduce supply uncertainties. Suppliers are likely to be more reliable if production plans are shared with them. Put in place the mechanisms to increase collaboration with suppliers. Surprises from unexpected scrap or rework can be reduced by improving manufacturing processes. Preventive maintenance can minimize unexpected downtime caused by equipment failure.
4. Rely more on equipment and labor buffers, such as *capacity cushions* and cross-trained workers. These buffers are important to businesses in the service sector because they generally cannot inventory their services.

Anticipation Inventory

The primary lever to reduce anticipation inventory is simply to match demand rate with production rate. Secondary levers can be used to even out customer demand in one of the following ways:

1. Add new products with different demand cycles so that a peak in the demand for one product compensates for the seasonal low for another.
2. Provide off-season promotional campaigns.
3. Offer seasonal pricing plans.

Pipeline Inventory

An operations manager has direct control over lead times but not demand rates. Because pipeline inventory is a function of demand during the lead time, the primary lever is to reduce the lead time. Two secondary levers can help managers cut lead times:

1. Find more responsive suppliers and select new carriers for shipments between stocking locations or improve materials handling within the plant. Improving the information system could overcome information delays between a distribution center and retailer.
2. Change Q in those cases where the lead time depends on the lot size.

Inventories in supply chains are managed with the help of inventory control systems. These systems manage the levels of cycle, safety stock, anticipation, and pipeline inventories in a firm. Regardless of whether an item experiences independent or dependent demand, three important questions must be answered: (1) What degree of control should we impose on an item? (2) How much should we order? (3) When should we place the order? An approach called ABC analysis, which we address in the next section, helps with the first question. Inventory control systems respond to the last two questions. In selecting an inventory control system for a particular application, the nature of the demands imposed on the inventory items is crucial. In this chapter, we focus on inventory control systems for independent demand items, which is the type of demand the bookstore owner, other retailers, service providers, and distributors face. Even though demand from any one customer is difficult to predict, low demand from some customers for a particular item often is offset by high demand from others. Thus, total demand for any independent demand item may follow a relatively smooth pattern, with some random fluctuations. For items facing dependent demands, such as raw materials and WIP inventories, material requirements planning (MRP) systems are useful. We devote Chapter 11, "Resource Planning", to this important inventory control system.

In the remainder of this chapter, we first address the question of what degree of control to impose on an item and then answer the question of how much to order. In the last two sections we discuss and compare two inventory control systems: (1) the continuous review system, called a *Q* system, and (2) the periodic review system, called a *P* system.

ABC Analysis

stock-keeping unit (SKU)
An individual item or product that has an identifying code and is held in inventory somewhere along the supply chain.

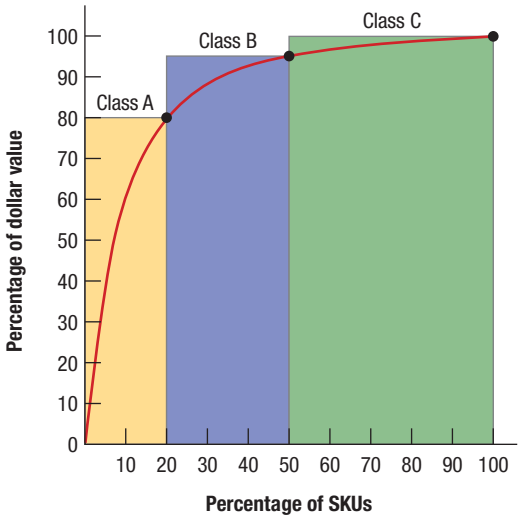
ABC analysis
The process of dividing SKUs into three classes, according to their dollar usage, so that managers can focus on items that have the highest dollar value.

Thousands of items, often referred to as stock-keeping units, are held in inventory by a typical organization, but only a small percentage of them deserve management's closest attention and tightest control. A **stock-keeping unit (SKU)** is an individual item or product that has an identifying code and is held in inventory somewhere along the supply chain. **ABC analysis** is the process of dividing SKUs into three classes according to their dollar usage so that managers can focus on items that have the highest dollar value. This method is the equivalent of creating a *Pareto chart* except that it is applied to inventory rather than to process errors. As Figure 9.4 shows, class A items typically represent only about 20 percent of the SKUs but account for 80 percent of the dollar usage. Class B items account for another 30 percent of the SKUs but only 15 percent of the dollar usage. Finally, 50 percent of the SKUs fall into class C, representing a mere 5 percent of the dollar usage. The goal of ABC analysis is to identify the class A SKUs so management can closely control their inventory levels.

The analysis begins by multiplying the annual demand rate for a SKU by the dollar value (cost) of one unit of that SKU to determine its dollar usage. After ranking the SKUs on the basis of dollar usage and creating the Pareto chart, the analyst looks for "natural" changes in slope. The dividing lines in Figure 9.4 between classes are inexact. Class A SKUs could be somewhat higher or lower than 20 percent of all SKUs but normally account for the bulk of the dollar usage.

Class A SKUs are reviewed frequently to reduce the average lot size and to ensure timely deliveries from suppliers. It is important to maintain high inventory turnover for these items. By contrast, class B SKUs require an intermediate level of control. Here, less frequent monitoring of suppliers coupled with adequate safety stocks can provide cost-effective coverage of demands. For class C SKUs, much looser control is appropriate. While a stockout of a class C SKU can be as crucial as for a class A SKU, the inventory holding cost of class C SKUs tends to be low. These features suggest that higher inventory levels can be tolerated and that more safety stock and larger lot sizes may suffice for class C SKUs. See Solved Problem 2 for a detailed example of ABC analysis.

FIGURE 9.4 ▶
Typical Chart Using ABC Analysis



Creating ABC inventory classifications is useless unless inventory records are accurate. Technology can help; many companies are tracking inventory wherever it exists in the supply chain. Chips imbedded in product packaging contain information on the product and send signals that can be accessed by sensitive receivers and transmitted to a central location for processing. There are other, less sophisticated

approaches of achieving accuracy that can be used. One way is to assign responsibility to specific employees for issuing and receiving materials and accurately reporting each transaction. Another method is to secure inventory behind locked doors or gates to prevent unauthorized or unreported withdrawals. This method also guards against accidentally storing newly received inventory in the wrong locations, where it can be lost for months. **Cycle counting** can also be used, whereby storeroom personnel physically count a small percentage of the total number of SKUs each day, correcting errors that they find. Class A SKUs are counted most frequently. A final method is to make logic error checks on each transaction reported and fully investigate any discrepancies. The discrepancies can include (1) actual receipts when no receipts are scheduled, (2) disbursements that exceed the current on-hand inventory balance, and (3) receipts with an inaccurate (nonexistent) SKU number.

cycle counting

An inventory control method whereby storeroom personnel physically count a small percentage of the total number of items each day, correcting errors that they find.

Now that we have identified the inventory items deserving of most attention, we turn to the decision of how much to order.

Economic Order Quantity

Supply chain managers face conflicting pressures to keep inventories low enough to avoid excess inventory holding costs but high enough to reduce ordering and setup costs. *Inventory holding cost* is the sum of the cost of capital and the variable costs of keeping items on hand, such as storage and handling, taxes, insurance, and shrinkage. *Ordering cost* is the cost of preparing a purchase order for a supplier or a production order for the shop, while *setup cost* is the cost of changing over a machine to produce a different item. In this section, we will address the *cycle inventory*, which is that portion of total inventory that varies directly with lot size. A good starting point for balancing these conflicting pressures and determining the best cycle-inventory level for an item is finding the **economic order quantity (EOQ)**, which is the lot size that minimizes total annual cycle-inventory holding and ordering costs. The approach to determining the EOQ is based on the following assumptions:

economic order quantity (EOQ)

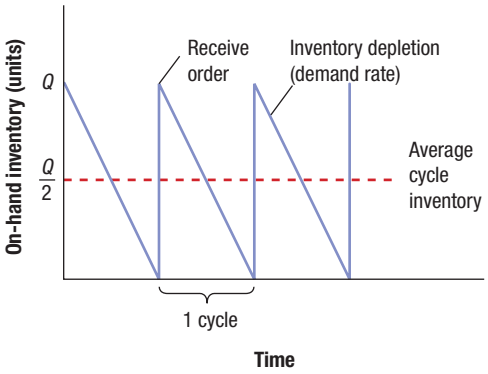
The lot size that minimizes total annual cycle-inventory holding and ordering costs.

1. The demand rate for the item is constant (e.g., always 10 units per day) and known with certainty.
2. No constraints are placed (such as truck capacity or materials handling limitations) on the size of each lot.
3. The only two relevant costs are the inventory holding cost and the fixed cost per lot for ordering or setup.
4. Decisions for one item can be made independently of decisions for other items. In other words, no advantage is gained in combining several orders going to the same supplier.
5. The lead time is constant (e.g., always 14 days) and known with certainty. The amount received is exactly what was ordered, and it arrives all at once rather than piecemeal.

The economic order quantity will be optimal when all five assumptions are satisfied. In reality, few situations are so simple. Nonetheless, the EOQ is often a reasonable approximation of the appropriate lot size, even when several of the assumptions do not quite apply. Here are some guidelines on when to use or modify the EOQ.

- **Do not use the EOQ**
  - If you use the "make-to-order" strategy and your customer specifies that the entire order be delivered in one shipment
  - If the order size is constrained by capacity limitations such as the size of the firm's ovens, amount of testing equipment, or number of delivery trucks
- **Modify the EOQ**
  - If significant quantity discounts are given for ordering larger lots
  - If replenishment of the inventory is not instantaneous, which can happen if the items must be used or sold as soon as they are finished without waiting until the entire lot has been completed (see Supplement C, "Special Inventory Models," for several useful modifications to the EOQ)
- **Use the EOQ**
  - If you follow a "make-to-stock" strategy and the item has relatively stable demand
  - If your carrying costs per unit and setup or ordering costs are known and relatively stable

The EOQ was never intended to be an optimizing tool. Nonetheless, if you need to determine a reasonable lot size, it can be helpful in many situations.



▲ **FIGURE 9.5**
Cycle-Inventory Levels

Calculating the EOQ

We begin by formulating the total cost for any lot size Q for a given SKU. Next, we derive the EOQ, which is the Q that minimizes total annual cycle-inventory cost. Finally, we describe how to convert the EOQ into a companion measure, the elapsed time between orders.

When the EOQ assumptions are satisfied, cycle inventory behaves as shown in Figure 9.5. A cycle begins with Q units held in inventory, which happens when a new order is received. During the cycle, on-hand inventory is used at a constant rate and, because demand is known with certainty and the lead time is a constant, a new lot can be ordered so that inventory falls to 0 precisely when the new lot is received. Because inventory varies uniformly between Q and 0, the average cycle inventory equals half the lot size, Q.

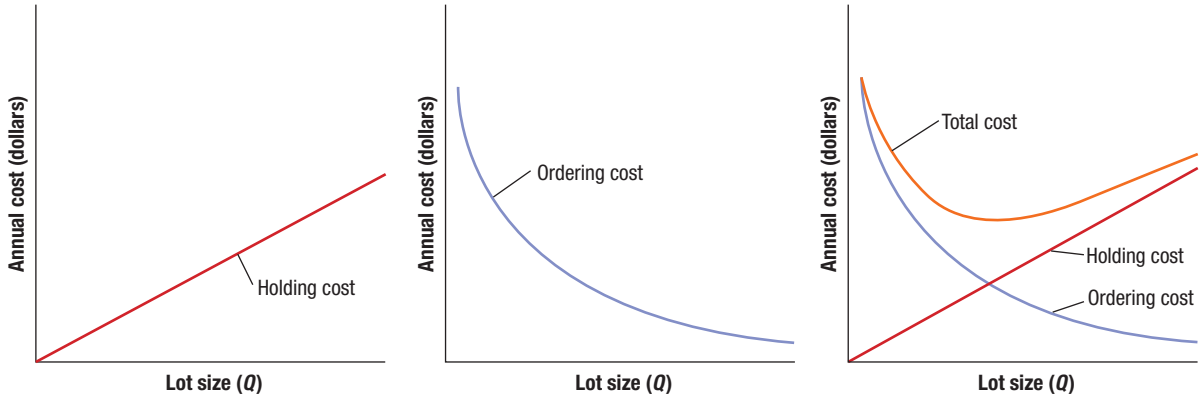
The annual holding cost for this amount of inventory, which increases linearly with Q, as Figure 9.6(a) shows, is

$$\text{Annual holding cost} = (\text{Average cycle inventory})(\text{Unit holding cost})$$

The annual ordering cost is

$$\text{Annual ordering cost} = (\text{Number of orders/Year})(\text{Ordering or setup cost})$$

The average number of orders per year equals annual demand divided by Q. For example, if 1,200 units must be ordered each year and the average lot size is 100 units, then 12 orders will be placed during the year. The annual ordering or setup cost decreases nonlinearly as Q increases, as shown in Figure 9.6(b), because fewer orders are placed.



▲ **FIGURE 9.6**
Graphs of Annual Holding, Ordering, and Total Costs

The total annual cycle-inventory cost,[3] as graphed in Figure 9.6(c), is the sum of the two cost components:

$$\text{Total cost} = \text{Annual holding cost} + \text{Annual ordering or setup cost}^{4}$$

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S)$$

where
C = total annual cycle-inventory cost
Q = lot size, in units
H = cost of holding one unit in inventory for a year, often expressed as a percentage of the item's value
D = annual demand, in units per year
S = cost of ordering or setting up one lot, in dollars per lot

In Example 9.2, we show how to calculate the cost of a lot-sizing policy.

[3]Expressing the total cost on an annual basis usually is convenient (although not necessary). Any time horizon can be selected as long as D and H cover the same time period. If the total cost is calculated on a monthly basis, D must be monthly demand and H must be the cost of holding a unit for 1 month.

[4]The number of orders actually placed in any year is always a whole number, although the formula allows for the use of fractional values. However, rounding is not needed because what is being calculated is an average of multiple years. Such averages often are nonintegers.

EXAMPLE 9.2 The Cost of a Lot-Sizing Policy

A museum of natural history opened a gift shop 2 years ago. Managing inventories has become a problem. Low inventory turnover is squeezing profit margins and causing cash flow problems.

One of the top-selling SKUs in the container group at the museum's gift shop is a bird feeder. Sales are 18 units per week, and the supplier charges $60 per unit. The cost of placing an order with the supplier is $45. Annual holding cost is 25 percent of a feeder's value, and the museum operates 52 weeks per year. Management chose a 390-unit lot size so that new orders could be placed less frequently. What is the annual cycle-inventory cost of the current policy of using a 390-unit lot size? Would a lot size of 468 be better?

Online Resource

Tutor 9.2 in OM Explorer provides a new example of the application of ABC analysis.

SOLUTION

We begin by computing the annual demand and holding cost as

$$D = (18 \text{ units/week})(52 \text{ weeks/year}) = 936 \text{ units}$$
$$H = 0.25(\$60/\text{unit}) = \$15$$

The total annual cycle-inventory cost for the current policy is

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S)$$
$$= \frac{390}{2}(\$15) + \frac{936}{390}(\$45) = \$2{,}925 + \$108 = \$3{,}033$$

The total annual cycle-inventory cost for the alternative lot size is

$$C = \frac{468}{2}(\$15) + \frac{936}{468}(\$45) = \$3{,}510 + \$90 = \$3{,}600$$

DECISION POINT

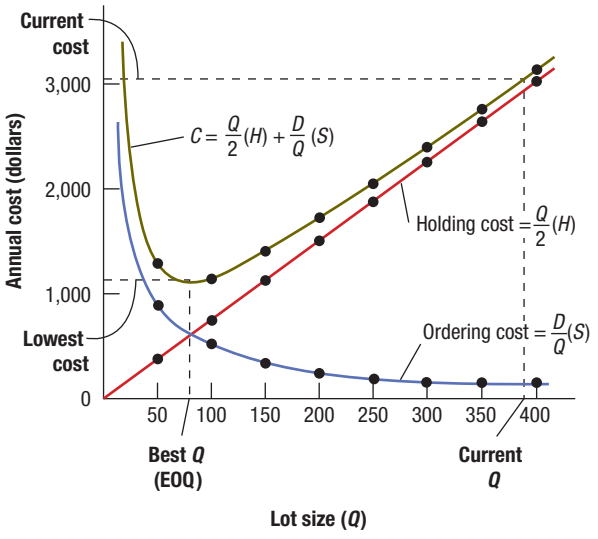
The lot size of 468 units, which is a half-year supply, would be a more expensive option than the current policy. The savings in ordering costs are more than offset by the increase in holding costs. Management should use the total annual cycle-inventory cost function to explore other lot-size alternatives.

Figure 9.7 displays the impact of using several Q values for the bird feeder in Example 9.2. Eight different lot sizes were evaluated in addition to the current one. Both holding and ordering costs were plotted, but their sum—the total annual cycle-inventory cost curve—is the important feature. The graph shows that the best lot size, or EOQ, is the lowest point on the total annual cost curve, or between 50 and 100 units. Obviously, reducing the current lot-size policy $Q = 390$ can result in significant savings.

A more efficient approach is to use the EOQ formula:

$$\text{EOQ} = \sqrt{\frac{2DS}{H}}$$

We use calculus to obtain the EOQ formula from the total annual cycle-inventory cost function. We take the first derivative of the total annual cycle-inventory cost function with respect to Q, set it equal to 0, and solve for Q. As Figure 9.7 indicates, the EOQ is the order quantity for which annual holding cost equals annual ordering cost. Using this insight, we can also obtain the EOQ formula by equating the formulas for annual ordering cost and annual holding cost and solving for Q. The graph in Figure 9.7 also reveals that when the annual holding cost for any Q exceeds the annual ordering cost, as with the 390-unit order, we can immediately conclude that Q is too high. A lower Q reduces holding cost and increases ordering cost, bringing them into balance. Similarly, if the annual ordering cost exceeds the annual holding cost, Q should be increased.



▲ **FIGURE 9.7**
Total Annual Cycle-Inventory Cost Function for the Bird Feeder

Sometimes, inventory policies are based on the time between replenishment orders, rather than on the number of units in the lot size. The **time between orders (TBO)** for a particular lot size is the average elapsed time between receiving (or placing) replenishment orders of Q units. Expressed as a fraction of a year, the TBO is simply Q divided by annual demand. When we use the EOQ and express time in terms of months, the TBO is

time between orders (TBO)

The average elapsed time between receiving (or placing) replenishment orders of Q units for a particular lot size.

$$\text{TBO}_{\text{EOQ}} = \frac{\text{EOQ}}{D}(12 \text{ months/year})$$

In Example 9.3, we show how to calculate TBO for years, months, weeks, and days.

EXAMPLE 9.3 Finding the EOQ, Total Cost, and TBO

Online Resource
Tutor 9.3 in OM Explorer provides a new example to practice the application of the EOQ model.

Online Resource
Active Model 9.1 provides additional insight on the EOQ model and its uses.

For the bird feeder in Example 9.2, calculate the EOQ and its total annual cycle-inventory cost. How frequently will orders be placed if the EOQ is used?

SOLUTION

Using the formulas for EOQ and annual cost, we get

$$\text{EOQ} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(936)(45)}{15}} = 74.94, \text{ or } 75 \text{ units}$$

Parameters

Current Lot Size (Q)	390	Economic Order Quantity	75
Demand (D)	936		
Order Cost (S)	$45		
Unit Holding Cost (H)	$15		

Annual Costs		Annual Costs based on EOQ	
Orders per Year	2.4	Orders per Year	12.48
Annual Ordering Cost	$108.00	Annual Ordering Cost	$561.60
Annual Holding Cost	$2,925.00	Annual Holding Cost	$562.50
Annual Inventory Cost	$3,033.00	Annual Inventory Cost	$1,124.10

FIGURE 9.8 ▶
Total Annual Cycle-Inventory Costs Based on EOQ Using Tutor 9.3

Figure 9.8 shows that the total annual cost is much less than the $3,033 cost of the current policy of placing 390-unit orders.

When the EOQ is used, the TBO can be expressed in various ways for the same time period:

$$\text{TBO}_{\text{EOQ}} = \frac{\text{EOQ}}{D} = \frac{75}{936} = 0.080 \text{ year}$$

$$\text{TBO}_{\text{EOQ}} = \frac{\text{EOQ}}{D}(12 \text{ months/year}) = \frac{75}{936}(12) = 0.96 \text{ month}$$

$$\text{TBO}_{\text{EOQ}} = \frac{\text{EOQ}}{D}(52 \text{ weeks/year}) = \frac{75}{936}(52) = 4.17 \text{ weeks}$$

$$\text{TBO}_{\text{EOQ}} = \frac{\text{EOQ}}{D}(365 \text{ days/year}) = \frac{75}{936}(365) = 29.25 \text{ days}$$

DECISION POINT

Using the EOQ, about 12 orders per year will be required. Using the current policy of 390 units per order, an average of 2.4 orders will be needed each year (every 5 months). The current policy saves on ordering costs but incurs a much higher cost for carrying the cycle inventory. Although it is easy to see which option is best on the basis of total ordering and holding costs, other factors may affect the final decision. For example, if the supplier would reduce the price per unit for large orders, it may be better to order the larger quantity.

Managerial Insights from the EOQ

Subjecting the EOQ formula to *sensitivity analysis* can yield valuable insights into the management of inventories. Sensitivity analysis is a technique for systematically changing crucial parameters to determine the effects of a change. Table 9.1 shows the effects on the EOQ when we substitute different values into the numerator or denominator of the formula.

TABLE 9.1 | SENSITIVITY ANALYSIS OF THE EOQ

Parameter	EOQ	Parameter Change	EOQ Change	Comments
Demand	$\sqrt{\frac{2DS}{H}}$	↑	↑	Increase in lot size is in proportion to the square root of *D*.
Order/Setup Costs	$\sqrt{\frac{2DS}{H}}$	↓	↓	Weeks of supply decreases and inventory turnover increases because the lot size decreases.
Holding Costs	$\sqrt{\frac{2DS}{H}}$	↓	↑	Larger lots are justified when holding costs decrease.

As Table 9.1 shows, the EOQ provides support for some of the intuition you may have about inventory management. However, the effect of ordering or setup cost changes on inventories is especially important for *lean systems*. This relationship explains why manufacturers are so concerned about reducing setup time and costs; it makes small lot production economic. Actually, lean systems provide an environment conducive to the use of the EOQ. For example, yearly, monthly, daily, or hourly demand rates are known with reasonable certainty in lean systems, and the rate of demand is relatively uniform. Lean systems (see Chapter 4, "Lean Systems") may have few process constraints if the firm practices *constraint management* (see Chapter 6, "Constraint Management"). In addition, lean systems strive for constant delivery lead times and dependable delivery quantities from suppliers, both of which are assumptions of the EOQ. Consequently, the EOQ as a lot-sizing tool is quite compatible with the principles of lean systems.

We now turn to a discussion of the two most common independent demand inventory control systems: the continuous review (Q) system and the periodic review (P) system.



Mike Stewart/AP/Shutterstock

Retailers typically face independent demands for the products on their shelves. Thousands of customers may shop at a large warehouse retailer, each looking for a different selection of products. The products must be restocked from a distribution center in the region.

Continuous Review System

A **continuous review (Q) system**, sometimes called a **reorder point (ROP) system** or *fixed order-quantity system*, tracks the remaining inventory of a SKU each time a withdrawal is made to determine whether it is time to reorder. In practice, these reviews are done frequently (e.g., daily) and often continuously (after each withdrawal). The advent of computers and electronic cash registers linked to inventory records has made continuous reviews easy. At each review, a decision is made about a SKU's inventory position. If it is judged to be too low, the system triggers a new order. The **inventory position (IP)** measures the SKU's ability to satisfy future demand. It includes **scheduled receipts (SR)**, which are orders that have been placed but have not yet been received, plus on-hand inventory (OH) minus backorders (BO). Sometimes, scheduled receipts are called **open orders**. More specifically,

$$\text{Inventory position} = \text{On-hand inventory} + \text{Scheduled receipts} - \text{Backorders}$$
$$\text{IP} = \text{OH} + \text{SR} - \text{BO}$$

When the inventory position reaches a predetermined minimum level, called the **reorder point (R)**, a fixed quantity Q of the SKU is ordered. In a continuous review system, although the order quantity Q is fixed, the time between orders can vary. Hence, Q can be based on the EOQ, a price break quantity (the minimum lot size that qualifies for a quantity discount), a container size (such as a truckload), or some other quantity selected by management.

continuous review (Q) system
A system designed to track the remaining inventory of a SKU each time a withdrawal is made to determine whether it is time to reorder.

reorder point (ROP) system
See continuous review (Q) system.

inventory position (IP)
The measurement of a SKU's ability to satisfy future demand.

scheduled receipts (SR)
Orders that have been placed but have not yet been received.

open orders
See scheduled receipts (SR).

reorder point (R)
The predetermined minimum level that an inventory position must reach before a fixed quantity Q of the SKU is ordered.

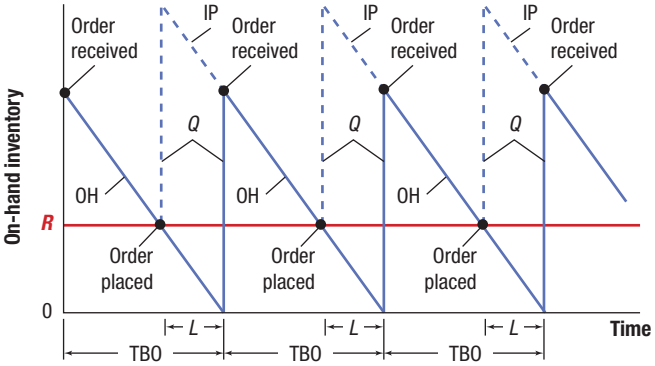
Selecting the Reorder Point When Demand and Lead Time Are Constant

To demonstrate the concept of a reorder point, suppose that the demand for feeders at the museum gift shop in Example 9.3 is always 18 per week, the lead time is a constant 2 weeks, and the supplier always ships the exact number ordered on time. With both demand and lead time constant, the museum's buyer can wait until the inventory position drops to 36 units, or (18 units/week) (2 weeks), to place a new order. Thus, in this case, the reorder point, R, equals the *total demand during lead time*, with no added allowance for safety stock.

Figure 9.9 shows how the system operates when demand and lead time are constant. The downward-sloping line represents the on-hand inventory, which is being depleted at a constant rate. When it reaches the reorder point R (the horizontal line), a new order for Q units is placed. The on-hand inventory continues to drop throughout lead time L until the order is received. At that time, which marks the end of the lead time, on-hand inventory jumps by Q units. A new order arrives just when inventory drops to 0. The TBO is the same for each cycle.

The inventory position, IP, shown in Figure 9.9 corresponds to the on-hand inventory, except during the lead time. Just after a new order is placed, at the start of the lead time,

▼ **FIGURE 9.9**
Q System When Demand and Lead Time Are Constant and Certain



IP increases by Q, as shown by the dashed line. The IP exceeds OH by this same margin throughout the lead time.[5] At the end of the lead time, when the scheduled receipts convert to on-hand inventory, IP = OH once again. The key point here is to compare IP, not OH, with R in deciding whether to reorder. A common error is to ignore scheduled receipts or backorders.

In Example 9.4, we show how to determine the time to place a new order when both the demand and lead time are constant.

EXAMPLE 9.4 Placing a New Order When Demand and Lead Time Are Constant

Demand for chicken soup at a supermarket is always 25 cases a day, and the lead time is always 4 days. The shelves were just restocked with chicken soup, leaving an on-hand inventory of only 10 cases. No backorders currently exist, but there is one open order in the pipeline for 200 cases. What is the inventory position? Should a new order be placed?

SOLUTION

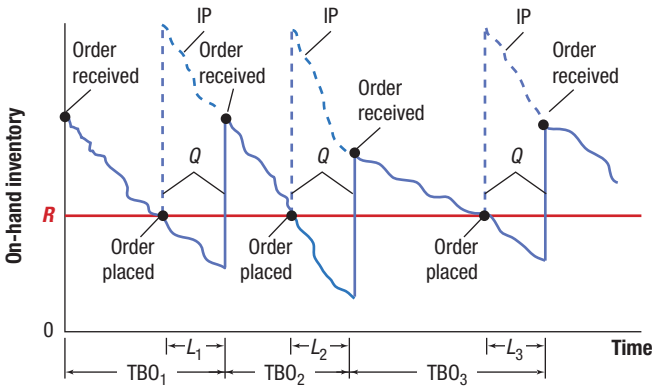
$$R = \text{Total demand during lead time} = (25)(4) = 100 \text{ cases}$$

$$\text{IP} = \text{OH} + \text{SR} - \text{BO}$$

$$= 10 + 200 - 0 = 210 \text{ cases}$$

DECISION POINT

Because IP exceeds R (210 versus 100), do not reorder. Inventory is almost depleted, but a new order need not be placed because the scheduled receipt is in the pipeline.



▲ **FIGURE 9.10**
Q System When Demand Is Uncertain

Selecting the Reorder Point When Demand Is Variable and Lead Time Is Constant

In reality, demand is not always predictable. Figure 9.10 shows how the Q system operates when demand is variable and lead time is constant. The wavy downward-sloping line indicates that demand varies from day to day. Its slope is steeper in the second cycle, which means that the demand rate is higher during this time period. The changing demand rate means that the time between orders changes, so $TBO_1 \neq TBO_2 \neq TBO_3$. Example 9.5 shows the mechanics of the continuous review system when demand is variable and the lead time is constant.

EXAMPLE 9.5 Placing a New Order When Demand Is Variable and Lead Time Is Constant

A distribution center (DC) in Wisconsin stocks Sony plasma TV sets. The center receives its inventory from a mega warehouse in Kansas with a lead time (L) of 5 days. The DC uses a reorder point (R) of 300 sets and a fixed order quantity (Q) of 250 sets. The current on-hand inventory (OH) at the end of Day 1 is 400 sets, there are no scheduled receipts (SR), and there are no backorders (BO). Assume that all demands and receipts occur at the end of the day. The inventory position is compared to the reorder point after demands and receipts are accounted for. If necessary, an order is placed and the inventory position is updated. Given the demand schedule in the table provided, determine when to order using a (Q) system.

[5] A possible exception is the situation when more than one scheduled receipt is open at the same time because of long lead times or larger than average demands during the lead time. Such is the case in Example 9.5.

SOLUTION

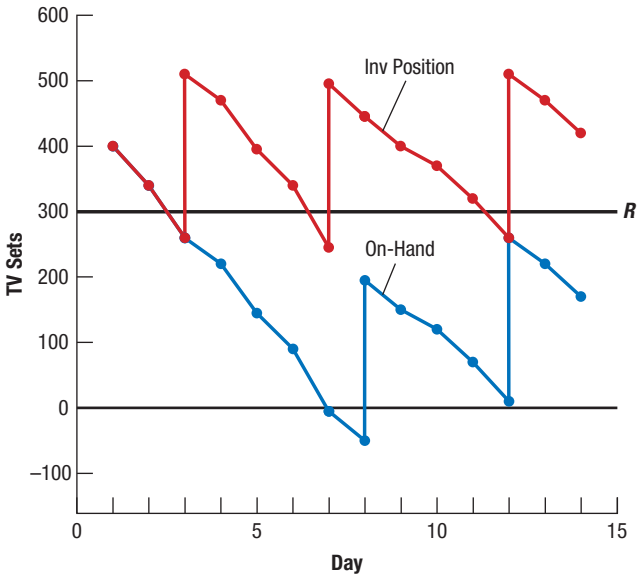
We use the following equation:

Inventory position (*IP*) = OH + SR − BO

Day	Demand	OH	SR	BO	IP	*Q*
1	50	400			400 + 0 = 400	
2	60	340			340 + 0 = 340	
3	80	260	**250** after ordering		260 < *R* before ordering 260 + **250** = 510 after ordering	**250** (due Day 8)
4	40	220	**250**		220 + **250** = 470	
5	75	145	**250**		145 + **250** = 395	
6	55	90	**250**		90 + **250** = 340	
7	95	0	**250** + **250** = 500 after ordering	5	0 + **250** − 5 = 245 < *R* before ordering 245 + **250** = 495 after ordering	**250** (due Day 12)
8	50	0 + **250** − 50 − 5 = 195	**250**		195 + **250** = 445	
9	45	195 − 45 = 150	**250**		150 + **250** = 400	
10	30	120	**250**		120 + **250** = 370	
11	50	70	**250**		70 + **250** = 320	
12	60	70 − 60 + **250** = 260	**250** after ordering		260 < *R* before ordering 260 + **250** = 510 after ordering	**250** (due Day 17)
13	40	260 − 40 = 220	**250**		220 + **250** = 470	
14	50	170	**250**		170 + **250** = 420	

DECISION POINT

The figure shows the relationship between the on-hand quantity of TV sets and the inventory position. The IP at the DC drops below the reorder point of 300 sets for the first time on Day 3, triggering an order for 250 sets. On Day 7, demand exceeded the supply of TVs, generating a backorder of 5 sets. Notice that the calculation for IP accounts for the backorder as well as the fact that there are two scheduled receipts on the books once the new order is placed. This situation occurred because the reorder point was breached one day before the open order for 250 sets was received. On Day 8, the shipment of 250 sets arrives and the backorders are satisfied. Note that the on-hand inventory satisfies the demand for that day, as well as the backorders, from the shipment of 250 sets, leaving only 195 sets for inventory. The demands at the DC are fairly volatile and can cause the reorder point to be breached quite dramatically at times. This often happens with continuous review systems when customers place orders in large quantities, rather than one unit at a time. The customers of the DC could be large retailers who purchase large volumes of TV sets for sales promotions. Another possible reason is that the DC in this example performs all inventory transactions at the end of the day; even if shipments to customers were only one unit at a time, they were treated as one large shipment for purposes of inventory control. With today's technology and the use of product bar codes, the DC could continuously monitor inventory and place replenishment orders just as the reorder point was reached.



As shown in Example 9.5, because of uncertainty, demands during the lead time are unpredictable and backorders or stockouts can occur. That is why managers add safety stock to hedge against lost sales. Consequently, R is higher in Figure 9.10 than in Figure 9.9. It also explains why the on-hand inventory usually does not drop to 0 by the time a replenishment order arrives for well-designed continuous review systems. The greater the safety stock and thus the higher reorder point R, the less likely a stockout. In general

$$\text{Reorder point} = \text{Average demand during lead time} + \text{Safety stock}$$
$$= \bar{d}L + \text{safety stock}$$

where

$\bar{d}$ = average demand per week or day or month

L = constant lead time in weeks or days or months

Because the average demand during lead time is variable, the real decision to be made when selecting R concerns the safety stock level. Deciding on a small or large safety stock is a trade-off between customer service and inventory holding costs. Cost minimization models can be used to find the best safety stock, but they require estimates of stockout and backorder costs, which are usually difficult to make with any precision because it is hard to estimate the effect of lost sales, lost customer confidence, future loyalty of customers, and market share because the customer went to a competitor. The usual approach for determining R is for management—based on judgment—to set a reasonable service level policy for the inventory and then determine the safety stock level that satisfies this policy. There are three steps to arrive at a reorder point:

1. Choose an appropriate service level policy.
2. Determine the distribution of demand during lead time.
3. Determine the safety stock and reorder point levels.

service level
The desired probability of not running out of stock in any one ordering cycle, which begins at the time an order is placed and ends when it arrives in stock.

cycle-service level
See service level.

protection interval
The period over which safety stock must protect the user from running out of stock.

Step 1: Service Level Policy Select a **service level**, or **cycle-service level** (the desired probability of not running out of stock in any one ordering cycle), which begins at the time an order is placed and ends when it arrives in stock. The intent is to provide coverage over the **protection interval**, or the period over which safety stock must protect the user from running out of stock. For the Q system, the lead time is the protection interval. For example, in a bookstore the manager may select a 90 percent cycle-service level for a book. In other words, the probability is 90 percent that demand will not exceed the supply during the lead time. The probability of running short *during the protection interval*, creating a stockout or backorder, is only 10 percent (100 − 90) in our example. This stockout risk, which occurs only during the lead time in the Q system, is greater than the overall risk of a stockout because the risk is nonexistent outside the ordering cycle.

Step 2: Distribution of Demand during Lead Time Determine the distribution of demand during lead time, which requires the specification of its mean and standard deviation. To translate a cycle-service level policy into a specific safety stock level, we must know how demand during the lead time is distributed. If demand and lead times vary little around their averages, the safety stock can be small. Conversely, if they vary greatly from one order cycle to the next, the safety stock must be large. Variability is measured by the distribution of demand during lead time. Sometimes, average demand during the lead time and the standard deviation of demand during the lead time are not directly available and must be calculated by combining information on the demand rate with information on the lead time. Suppose that lead time is constant and demand is variable, but records on demand are not collected for a time interval that is exactly the same as the lead time. The same inventory control system may be used to manage thousands of different SKUs, each with a different lead time. For example, if demand is reported *weekly*, these records can be used directly to compute the average and the standard deviation of demand during the lead time if the lead time is exactly 1 week. However, if the lead time is 3 weeks, the computation is more difficult.

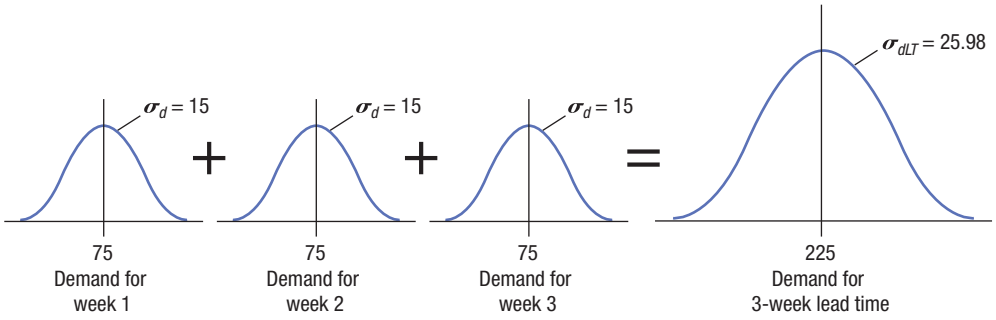
We can determine the demand during the lead time distribution by making some reasonable assumptions. Suppose that the average demand, $\bar{d}$ is known along with the standard deviation of demand, σ_d, over some time interval such as days or weeks. Also, suppose that the probability distributions of demand for each time interval are identical and independent of each other. For example, if the time interval is a week, the probability distributions of demand are assumed to be the same each week (identical $\bar{d}$ and σ_d), and the total demand in 1 week does not affect the total demand in another week. Let L be the constant lead time, expressed in the same time units as the demand. Under these assumptions, average demand during the lead time will be the sum of the averages for each of the L identical and independent distributions of demand, or $\bar{d} + \bar{d} + \bar{d} + \ldots = \bar{d}L$. In addition, the variance of the distribution of demand during lead time will be the sum of the variances of the L identical and independent distributions of demand, or

$$\sigma_d^2 + \sigma_d^2 + \sigma_d^2 + \ldots = \sigma_d^2 L$$

Finally, the standard deviation of the distribution of demand during lead time is

$$\sigma_{dLT} = \sqrt{\sigma_d^2 L} = \sigma_d \sqrt{L}$$

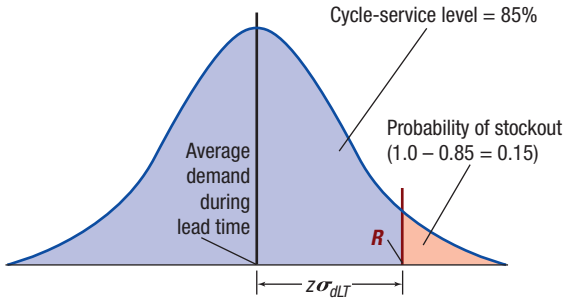
Figure 9.11 shows how the demand distribution of the lead time is developed from the individual distributions of weekly demands, where $\bar{d} = 75$, $\sigma_d = 15$, and $L = 3$. In this example, average demand during the lead time is (75)(3) = 225 units and $\sigma_{dLT} = 15\sqrt{3} = 25.98$.



◀ **FIGURE 9.11**
Development of Distribution of Demand During Lead Time

Step 3: Safety Stock and Reorder Point When selecting the safety stock, the inventory planner often assumes that demand during the lead time is normally distributed, as shown in Figure 9.12.

The average demand during the lead time is the centerline of the graph, with 50 percent of the area under the curve to the left and 50 percent to the right. Thus, if a cycle-service level of 50 percent were chosen, the reorder point R would be the quantity represented by this centerline. Because R equals the average demand during the lead time plus the safety stock, the safety stock is 0 when R equals this average demand. Demand is less than average 50 percent of the time and, thus, having no safety stock will be sufficient only 50 percent of the time.



▲ **FIGURE 9.12**
Finding Safety Stock with Normal Probability Distribution for an 85 Percent Cycle-Service Level

To provide a service level above 50 percent, the reorder point must be higher than the average demand during the lead time. As Figure 9.12 shows, that requires moving the reorder point to the right of the centerline so that more than 50 percent of the area under the curve is to the left of R. An 85 percent cycle-service level is achieved in Figure 9.12, with 85 percent of the area under the curve to the left of R (in **blue**) and only 15 percent to the right (in **pink**). We compute the safety stock as follows:

$$\text{Safety stock} = z\sigma_{dLT}$$

where

z = the number of standard deviations needed to achieve the cycle-service level
σ_{dLT} = standard deviation of demand during the lead time

The reorder point becomes

$$R = \bar{d}L + \text{safety stock}$$

The higher the value of z, the higher the safety stock and the cycle-service level should be. If $z = 0$, there is no safety stock, and stockouts will occur during 50 percent of the order cycles. For a cycle-service level of 85 percent, $z = 1.04$. Example 9.6 shows how to use the appendix on the normal distribution to find the appropriate z-value, safety stock, and reorder point.

EXAMPLE 9.6 Reorder Point for Variable Demand and Constant Lead Time

Let us return to the bird feeder in Example 9.3. The EOQ is 75 units. Suppose that the average demand is 18 units per week with a standard deviation of 5 units. The lead time is constant at 2 weeks. Determine the safety stock and reorder point if management wants a 90 percent cycle-service level.

Online Resource

Tutor 9.4 in OM Explorer provides a new example to determine the safety stock and the reorder point for a *Q* system.

SOLUTION

In this case, $\sigma_d = 5, \bar{d} = 18$ units, and $L = 2$ weeks, so $\sigma_{dLT} = \sigma_d\sqrt{L} = 5\sqrt{2} = 7.07$. Consult the body of the table in the appendix on the normal distribution for 0.9000, which corresponds to a 90 percent cycle-service level. The closest number is 0.8997, which corresponds to 1.2 in the row heading and 0.08 in the column heading. Adding these values gives a *z*-value of 1.28. With this information, we calculate the safety stock and reorder point as follows:

$$\text{Safety stock} = z\sigma_{dLT} = 1.28(7.07) = 9.05, \text{ or } 9 \text{ units}$$

$$\text{Reorder point} = \bar{d}L + \text{Safety stock}$$

$$= 2(18) + 9 = 45 \text{ units}$$

DECISION POINT

The *Q* system for the bird feeder operates as follows: Whenever the inventory position reaches 45 units, order the EOQ of 75 units. Various order quantities and safety stock levels can be used in a *Q* system. For example, management could specify a different order quantity (because of shipping constraints) or a different safety stock (because of storage limitations).

Selecting the Reorder Point When Both Demand and Lead Time Are Variable

In practice, it is often the case that both the demand and the lead time are variable. Unfortunately, the equations for the safety stock and reorder point become more complicated. In the equation for safety stock below, we make two simplifying assumptions. First, the demand distribution and the lead time distribution are measured in the same time units. For example, both demand and lead time are measured in weeks. Second, demand and lead time are *independent*. That is, demand per week is not affected by the length of the lead time.

$$\text{Safety stock} = z\sigma_{dLT}$$

$$R = (\text{Average weekly demand} \times \text{Average lead time in weeks}) + \text{Safety stock}$$

$$= \bar{d}\bar{L} + \text{Safety stock}$$

where

$\bar{d}$ = Average weekly or daily or monthly demand

$\bar{L}$ = Average weekly or daily or monthly lead time

σ_d = Standard deviation of weekly or daily or monthly demand

σ_{LT} = Standard deviation of the lead time, and

$\sigma_{dLT} = \sqrt{\bar{L}\sigma_d^2 + \bar{d}^2\sigma_{LT}^2}$

Now that we have determined the mean and standard deviation of the distribution of demand during lead time under these more complicated conditions, we can determine the safety stock and then select the reorder point as we did before for the case where the lead time was constant, as shown in Example 9.7.

EXAMPLE 9.7 Reorder Point for Variable Demand and Variable Lead Time

The Office Supply Shop estimates that the average demand for a popular ball-point pen is 12,000 pens per week with a standard deviation of 3,000 pens. The current inventory policy calls for replenishment orders of 156,000 pens. The average lead time from the distributor is 5 weeks, with a standard deviation of 2 weeks. If management wants a 95 percent cycle-service level, what should the reorder point be?

SOLUTION

We have $\bar{d} = 12{,}000$ pens, $\sigma_d = 3{,}000$ pens, $\bar{L} = 5$ weeks, and $\sigma_{LT} = 2$ weeks.

$$\sigma_{dLT} = \sqrt{\bar{L}\sigma_d^2 + \bar{d}^2\sigma_{LT}^2} = \sqrt{(5)(3{,}000)^2 + (12{,}000)^2(2)^2} = 24{,}919.87 \text{ pens}$$

Consult the body of the appendix on the normal distribution for 0.9500, which corresponds to a 95 percent cycle-service level. That value falls exactly in the middle of the tabular values of 0.9495 (for a z-value of 1.64) and 0.9505 (for a z-value of 1.65). Consequently, we will use the more conservative value of 1.65. We calculate the safety stock and reorder point as follows:

$$\text{Safety stock} = z\sigma_{dLT} = (1.65)(24{,}919.87) = 41{,}117.79, \text{ or } 41{,}118 \text{ pens}$$

$$\text{Reorder point} = \overline{dL} + \text{Safety stock} = (12{,}000)(5) + 41{,}118 = 101{,}118 \text{ pens}$$

DECISION POINT

Whenever the stock of ball-point pens drops to 101,118, management should place another replenishment order of 156,000 pens to the distributor.

Sometimes, the theoretical distributions for demand and lead time are not known. In those cases, we can use simulation to find the distribution of demand during lead time using discrete distributions for demand and lead times. Simulation can also be used to estimate the performance of an inventory system.

Systems Based on the *Q* System

Two systems based on the Q system are the two-bin system and the base-stock system.

Two-Bin System The concept of a Q system can be incorporated into a **visual system**, that is, a system that allows employees to place orders when inventory visibly reaches a certain marker. Visual systems are easy to administer because records are not kept on the current inventory position. The historical usage rate can simply be reconstructed from past purchase orders. Visual systems are intended for use with low-value SKUs that have a steady demand, such as nuts and bolts or office supplies. Overstocking is common, but the extra inventory holding cost is minimal because the items have relatively little value.

visual system

A system that allows employees to place orders when inventory visibly reaches a certain marker.

A visual system version of the Q system is the **two-bin system** in which a SKU's inventory is stored at two different locations. Inventory is first withdrawn from one bin. If the first bin is empty, the second bin provides backup to cover demand until a replenishment order arrives. An empty first bin signals the need to place a new order. Premade order forms placed near the bins let workers send one to purchasing or even directly to the supplier. When the new order arrives, the second bin is restored to its normal level and the rest is put in the first bin. The two-bin system operates like a Q system, with the normal level in the second bin being the reorder point R. The system also may be implemented with just one bin by marking the bin at the reorder point level.

two-bin system

A visual system version of the Q system in which a SKU's inventory is stored at two different locations.

Base-Stock System In its simplest form, the **base-stock system** issues a replenishment order, Q, each time a withdrawal is made, for the same amount as the withdrawal. This one-for-one replacement policy maintains the inventory position at a base-stock level equal to expected demand during the lead time plus safety stock. The base-stock level, therefore, is equivalent to the reorder point in a Q system. However, order quantities now vary to keep the inventory position at R at all times. Because this position is the lowest IP possible that will maintain a specified service level, the base-stock system may be used to minimize cycle inventory. More orders are placed, but each order is smaller. This system is appropriate for expensive items, such as replacement engines for jet airplanes. No more inventory is held than the maximum demand expected until a replacement order can be received.

base-stock system

An inventory control system that issues a replenishment order, Q, each time a withdrawal is made, for the same amount of the withdrawal.

Calculating Total *Q* System Costs

Total costs for the continuous review (Q) system is the sum of three cost components:

$$\text{Total cost} = \text{Annual cycle-inventory holding cost} + \text{annual ordering cost} + \text{annual safety stock holding cost}$$

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S) + (H)(\text{Safety stock})$$

The annual cycle-inventory holding cost and annual ordering cost are the same equations we used for computing the total annual cycle-inventory cost in Example 9.2. The annual cost of holding the safety stock is computed under the assumption that the safety stock is on hand at

all times. Referring to Figure 9.10 in each order cycle, we will sometimes experience a demand greater than the average demand during lead time, and sometimes we will experience less. On average over the year, we can assume the safety stock will be on hand. See Solved Problems 4 and 6 at the end of this chapter for an example of calculating the total costs for a Q system.

Advantages of the *Q* System

Primary advantages of Q systems are the following:

1. The review frequency of each SKU may be individualized. Tailoring the review frequency to the SKU can reduce total ordering and holding costs.
2. Fixed lot sizes, if large enough, can result in quantity discounts. The firm's physical limitations, such as its truckload capacities, materials handling methods, and shelf space, might also necessitate a fixed lot size.
3. The system requires low levels of safety stock for the amount of uncertainty in demands during the lead time.

Periodic Review System

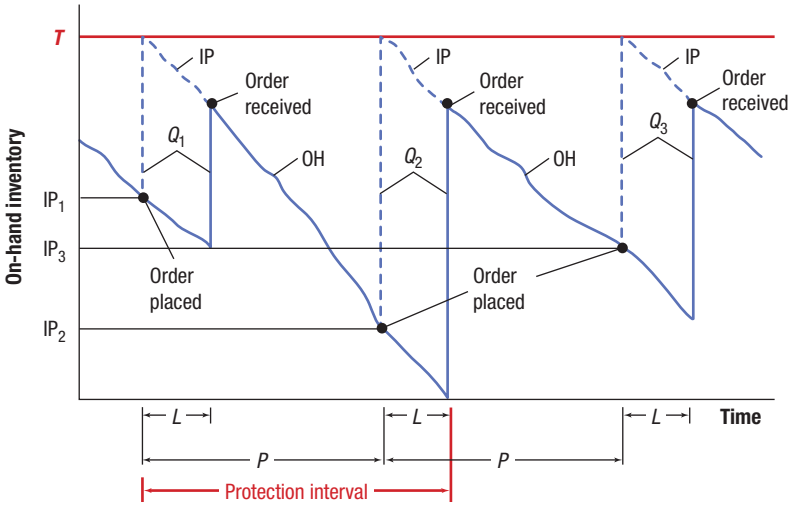
periodic review (*P*) system
A system in which an item's inventory position is reviewed periodically rather than continuously.

An alternative inventory control system is the **periodic review (*P*) system**, sometimes called a *fixed interval reorder system* or *periodic reorder system*, in which an item's inventory position is reviewed periodically rather than continuously. Such a system can simplify delivery scheduling because it establishes a routine. A new order is always placed at the end of each review, and the time between orders (TBO) is fixed at P. Demand is a random variable, so total demand between reviews varies. In a P system, the lot size, Q, may change from one order to the next, but the time between orders is fixed. An example of a periodic review system is that of a soft-drink supplier making weekly rounds of grocery stores. Each week, the supplier reviews the store's inventory of soft drinks and restocks the store with enough items to meet demand and safety stock requirements until the next week.

Under a P system, four of the original EOQ assumptions are maintained: (1) no constraints are placed on the size of the lot, (2) the relevant costs are holding and ordering costs, (3) decisions for one SKU are independent of decisions for other SKUs, and (4) lead times are certain and supply is known. However, demand uncertainty is again allowed for. Figure 9.13 shows the periodic review system under these assumptions. The downward-sloping line again represents on-hand inventory. When the predetermined time, P, has elapsed since the last review, an order is placed to bring the inventory position, represented by the dashed line, up to the target inventory level, T. The lot size for the first review is Q_1, or the difference between inventory position IP_1 and T. As with the continuous review system, IP and OH differ only during the lead time. When the order arrives at the end of the lead time, OH and IP again are identical. Figure 9.13 shows that lot sizes vary from one order cycle to the next. Because the inventory position is lower at the second review, a greater quantity is needed to achieve an inventory level of T.

Example 9.8 shows how to determine the order quantity in a P system.

▼ **FIGURE 9.13**
P System When Demand Is Uncertain



EXAMPLE 9.8 **Determining How Much to Order in a *P* System**

Return to the distribution center (DC) in Example 9.5. Suppose that management wants to use a periodic review system for the Sony TV sets. The first review of the inventory is scheduled for the end of Day 2. Assume that all demands and receipts occur at the end of the day. On the scheduled review day, inventory replenishment orders are placed after the demands and receipts have been accounted for. The lead time is 5 days, and management has set $T = 620$ and $P = 6$ days. Given the demand schedule in the table provided, determine the order quantity (Q) using a P system.

SOLUTION

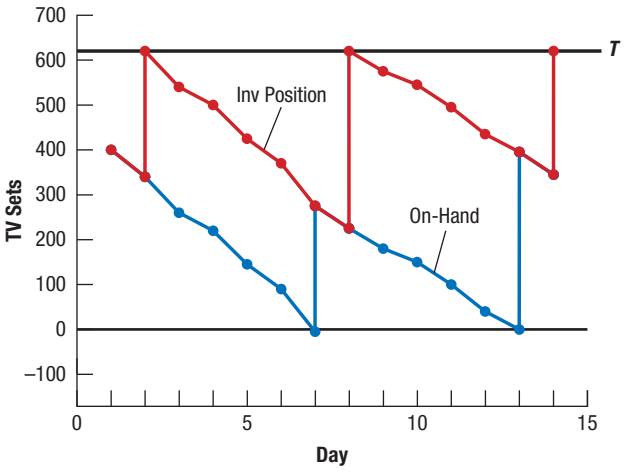
We use the following equations:

$$\text{Inventory Position (IP)} = \text{OH} + \text{SR} - \text{BO}$$
$$\text{Order Quantity } (Q) = T - \text{IP}$$

Day	Demand	OH	SR	BO	IP	*Q*
1	50	400			400	
2	60	340	**280** after ordering		340 before ordering 340 + **280** = 620 after ordering	620 − 340 = **280** (due Day 7)
3	80	260	**280**		260 + **280** = 540	
4	40	220	**280**		220 + **280** = 500	
5	75	145	**280**		145 + **280** = 425	
6	55	90	**280**		90 + **280** = 370	
7	95	90 + **280** − 95 = 275			275 + 0 = 275	
8	50	225	**395** after ordering		225 + 0 = 225 before ordering 225 + **395** = 620 after ordering	620 − 225 = **395** (due Day 13)
9	45	180	**395**		180 + **395** = 575	
10	30	150	**395**		150 + **395** = 545	
11	50	100	**395**		100 + **395** = 495	
12	60	40	**395**		40 + **395** = 435	
13	40	40 + **395** − 40 = 395			395 + 0 = 395	
14	50	345	**275** after ordering		345 + 0 = 345 before ordering 345 + **275** = 620 after ordering	620 − 345 = **275** (due Day 19)

DECISION POINT

The figure shows the relationship between on-hand inventory and the inventory position. The DC did not experience any backorders because on Day 7 the replenishment order arrived in the nick of time. Notice that the order quantities vary in size, while the time between orders remains a constant. Compare the operation of the *P* system in this example to the *Q* system in Example 9.5. The *Q* system requires constant monitoring to determine when the order point is reached. However, the average daily inventory is only 188 sets, compared to 226 sets for the *P* system. Granted, the *Q* system experienced backorders because of some unexpectedly large orders. Nonetheless, it is a general rule that to gain the benefits of periodic ordering, the *P* system requires more inventory for the same level of protection against stockouts or backorders. We will see why this is the case as we develop the parameters for the *P* system.



Selecting the Time Between Reviews

To run a *P* system, managers must make two decisions: the length of time between reviews, *P*, and the target inventory level, *T*. Let us first consider the time between reviews, *P*. It can be any convenient interval, such as each Friday or every other Friday. Another option is to base *P* on the cost trade-offs of the EOQ. In other words, *P* can be set equal to the average time between orders for the economic order quantity, or TBO_{EOQ}. Because demand is variable, some orders will be larger than the EOQ and some will be smaller. However, over an extended period of time, the average lot size



Aleksandr Papichev/Alamy Stock Photo

Large, fixed-capacity modes of transportation require defined schedules of operation. Such a situation supports the use of periodic review systems. Here a tanker ship awaits a load of oil at a pump station in a large port with railway infrastructure.

should be close to the EOQ. If other models are used to determine the lot size (e.g., those described in Supplement C, "Special Inventory Models"), we divide the lot size chosen by the annual demand, D, and use this ratio as P. It will be expressed as the fraction of a year between orders, which can be converted into months, weeks, or days as needed.

Selecting the Target Inventory Level When Demand Is Variable and Lead Time Is Constant

Now, let us calculate the target inventory level, T, when demand is variable but the lead time is constant. Figure 9.13 reveals that an order must be large enough to make the inventory position, IP, last beyond the next review, which is P time periods away. The checker must wait P periods to revise, correct, and reestablish the inventory position. Then, a new order is placed, but it does not arrive until after the lead time, L. Therefore, as Figure 9.13 shows, a protection interval of $P + L$ periods is needed. A fundamental difference between the Q and P systems is the length of time needed for stockout protection. A Q system needs stockout protection only during the lead time because orders can be placed as soon as they are needed and will be received L periods later. A P system, however, needs stockout protection for the longer $P + L$ protection interval because orders are placed only at fixed intervals, and the inventory is not checked until the next designated review time.

As with the Q system, we need to develop the appropriate distribution of demand during the protection interval to specify the system fully. In a P system, we must develop the distribution of demand for $P + L$ time periods. The target inventory level T must equal the expected demand during the protection interval of $P + L$ periods, plus enough safety stock to protect against demand uncertainty over this same protection interval. We assume that lead time is constant and that demand in one period is independent of demand in the next period. Thus, the average demand during the protection interval is $\bar{d}\ (P + L)$, or

$$T = \bar{d}\ (P + L) + \text{Safety stock for the protection interval}$$

We compute safety stock for a P system much as we did for the Q system. However, the safety stock must cover demand uncertainty for a longer period of time. When using a normal probability distribution, we multiply the desired standard deviations to implement the cycle-service level, z, by the standard deviation of demand during the protection interval, σ_{P+L}. The value of z is the same as for a Q system with the same cycle-service level. Thus,

$$\text{Safety stock} = z\sigma_{P+L}$$

Based on our earlier logic for calculating σ_{dLT} we know that the standard deviation of the distribution of demand during the protection interval is

$$\sigma_{P+L} = \sigma_d\sqrt{P + L}$$

Because a P system requires safety stock to cover demand uncertainty over a longer time period than a Q system, a P system requires more safety stock; that is, σ_{P+L} exceeds σ_{dLT}. Hence, to gain the convenience of a P system requires that overall inventory levels be somewhat higher than those for a Q system. Example 9.9 demonstrates the calculation of P and T for the bird feeder example.

EXAMPLE 9.9 Calculating *P* and *T*

Online Resource

Tutor 9.5 in OM Explorer provides a new example to determine the review interval and the target inventory for a *P* system.

Again, let us return to the bird feeder example. Recall that demand for the bird feeder is normally distributed with a mean of 18 units per week and a standard deviation in weekly demand of 5 units. The lead time is 2 weeks, and the business operates 52 weeks per year. The Q system developed in Example 9.6 called for an EOQ of 75 units and a safety stock of 9 units for a cycle-service level of 90 percent. What is the equivalent *P* system? Answers are to be rounded to the nearest integer.

SOLUTION

We first define D and then P. Here, P is the time between reviews, expressed in weeks because the data are expressed as demand *per week*:

$$D = (18 \text{ units/week})(52 \text{ weeks/year}) = 936 \text{ units}$$

$$P = \frac{\text{EOQ}}{D}(52) = \frac{75}{936}(52) = 4.2, \text{ or 4 weeks}$$

With $\bar{d} = 18$ units per week, an alternative approach is to calculate P by dividing the EOQ by $\bar{d}$ to get 75/18 = 4.2, or 4 weeks. Either way, we would review the bird feeder inventory every 4 weeks. We now find the standard deviation of demand over the protection interval ($P + L = 6$):

$$\sigma_{P+L} = \sigma_d\sqrt{P + L} = 5\sqrt{6} = 12.25 \text{ units}$$

Before calculating T, we also need a z-value. For a 90 percent cycle-service level, $z = 1.28$ (see the appendix on the normal distribution). The safety stock becomes

$$\text{Safety stock} = z\sigma_{P+L} = 1.28(12.25) = 15.68, \text{ or 16 units}$$

We now solve for T:

$$\begin{aligned} T &= \text{Average demand during the protection interval} + \text{Safety stock} \\ &= \bar{d}(P + L) + \text{Safety stock} \\ &= (18 \text{ units/week})(6 \text{ weeks}) + 16 \text{ units} = 124 \text{ units} \end{aligned}$$

DECISION POINT

Every 4 weeks we would order the number of units needed to bring inventory position IP (counting the new order) up to the target inventory level of 124 units. The P system requires 16 units in safety stock, while the Q system only needs 9 units. If cost were the only criterion, the Q system would be the choice for the bird feeder. As we discuss later, other factors may sway the decision in favor of the P system.

Selecting the Target Inventory Level When Demand and Lead Time Are Variable

A useful approach for finding P and T in practice is simulation. Given discrete probability distributions for demand and lead time, simulation can be used to estimate the demand during the protection interval distribution. The *Demand During the Protection Interval Simulator* in OM Explorer can be used to determine the distribution. Once determined, the distribution can be used to select a value for T, given a desired cycle-service level.

Calculating Total *P* System Costs

The total costs for the P system are the sum of the same three cost elements for the Q system. The differences are in the calculation of the order quantity and the safety stock. As shown in Figure 9.13, the average order quantity will be the average consumption of inventory during the P periods between orders. Consequently, $Q = \bar{d}P$. Total costs for the P system are

$$C = \frac{\bar{d}P}{2}(H) + \frac{D}{\bar{d}P}(S) + (H)(\text{Safety stock})$$

See Solved Problem 5 at the end of this chapter for an example of calculating total P system costs.

Advantages of the *P* System

Primary advantages of P systems are the following:

1. The system is convenient because replenishments are made at fixed intervals. Fixed replenishment intervals allow for standardized pickup and delivery times. In contrast, individual items are ordered on their own best intervals with the Q system, which can differ widely.
2. Orders for multiple items from the same supplier can be combined into a single purchase order. This approach reduces ordering and transportation costs and can result in a price break from the supplier.

3. The inventory position, IP, needs to be known only when a review is made (not continuously, as in a Q system). However, this advantage is moot for firms using computerized record-keeping systems, in which a transaction is reported upon each receipt or withdrawal. When inventory records are always current, the system is called a **perpetual inventory system**.

perpetual inventory system
A system of inventory control in which the inventory records are always current.

Both the Q system and the P system have their advantages. Indeed, the advantages for one system become the disadvantages for the other. In conclusion, the choice between Q and P systems is not clear cut. Which system is better depends on the relative importance of its advantages in various situations.

Systems Based on the *P* System

Two systems based on the P system are the single-bin system and the optional replenishment system.

Single-Bin System The concept of a P system can be translated into a simple visual system of inventory control. In the **single-bin system**, a maximum level is marked on the storage shelf or bin, and the inventory is brought up to the mark periodically—say, once a week. The single bin may be, for example, a gasoline storage tank at a service station or a storage bin for small parts at a manufacturing plant.

single-bin system
A system of inventory control in which a maximum level is marked on the storage shelf or bin, and the inventory is brought up to the mark periodically.

Optional Replenishment System Sometimes called the optional review, min–max, or (s, S) system, the **optional replenishment system** is much like the P system. It is used to review the inventory position at fixed time intervals and, if the position has dropped to (or below) a predetermined level, to place a variable-sized order to cover expected needs. The new order is large enough to bring the inventory position up to a target inventory, similar to T for the P system. However, orders are not placed after a review unless the inventory position has dropped to the predetermined minimum level. The minimum level acts as the reorder point R does in a Q system. If the target is 100 and the minimum level is 60, the minimum order size is 40 (or 100 − 60). As we discuss in Managerial Practice 9.1, IKEA uses this system to manage its massive inventories in stores worldwide.

optional replenishment system
A system used to review the inventory position at fixed time intervals and, if the position has dropped to (or below) a predetermined level, to place a variable-sized order to cover expected needs.

MANAGERIAL PRACTICE 9.1 Inventory Management at IKEA

You just bought a new TV, and now you need a TV bench with cabinets and adjustable shelves for your equipment. In response to an online ad, you go to your nearest IKEA store and begin shopping in the massive showroom. This may take a while, given that a typical store has as many as 9,500 products! But there it is, exactly what you want. You record the item you selected and find that it is located in Aisle 5, Bin 7, in the warehouse directly below the showroom. The TV bench is in three flat boxes in a rack that you can easily access. After loading your bench on a push cart, you proceed to the checkout station, load your vehicle, and head home to assemble it in your living room. Congratulations—you just purchased furniture from the world's largest furniture retailer!

IKEA is a $45 billion company with 433 stores in 52 countries and 211,000 employees. IKEA competes on the basis of low prices and good quality, and inventory management plays a key role. There are three elements to its strategy: low inventory costs, linking volume to warehouse assignment, and the inventory management system.

Inventory Cost

IKEA recognized that inventory costs, such as storage and handling, customer service, ordering, labor and equipment utilization, and transportation, are a function of process design. To this end, it utilizes an inventory management tactic called *cost-per-touch*. The more hands that touch the product (that is, the more steps in a process), the more costs associated with it. Every time a product is touched, shipped, moved, loaded, assembled, or shifted, it costs the company money, even if it's as simple as an employee moving the product from one rack to another. Competitors who offer their customers "full service" often have high inventory costs. At IKEA, customers select their products, pick them up at the warehouse, take them home, and then assemble them. Through careful process design, customers can easily navigate the warehouse located at the retail store, load their product, and move to the checkout station, largely without help. The warehouse consists of meticulously stacked flat boxes as high as a person can reach, not only assisting the customer but also making it easier to restock the warehouse. The flat boxes allow for more room in the warehouse to stock additional items. Also, the company cuts down on inventory cost by designing products that are at least 50 percent made from sustainable or recycled products, thereby reducing the value of the inventory and lowering the opportunity cost associated with capital tied up in inventory. Further, the products are designed to use fewer materials while not compromising on quality or durability, enabling IKEA to cut down on transportation costs. Less fuel, fewer trips, and less labor are used to ship its products. All of this supports the competitive priority of low-cost operations, and an order winner of low price.

Warehouse Assignment

To support the *cost-per-touch* tactic, IKEA uses its retail locations for warehousing. Warehouse operations are split between high-flow and low-flow products.

Following the precepts of ABC analysis, in which 20 percent of the SKUs that represent 80 percent of the dollar usage are called "class A" items, IKEA assigns the class A items to that part of the warehouse devoted to high-flow items. That is where most customers go to get their items, as you did when you picked up your TV bench. Here automatic storage and retrieval systems, supported by automated software, are used to reduce the amount of labor time. IKEA's storage system has to be accurate during store hours so efficient self-service is possible. Slower-selling products are stocked in the low-flow area of the warehouse and do not require employees to move them too much, also supporting the *cost-per-touch* tactic. Manual procedures for warehouse operations can be used for the slower-selling products. By aligning operations with volume in the warehouse, IKEA can maximize the value of its labor resources.

Inventory Management System

IKEA employs an in-store logistics manager for the ordering process and a store goods manager for material handling in each store. The in-store logistics manager uses an inventory management system IKEA calls "Minimum/Maximum Settings," which we refer to as an *optional replenishment system* or, more precisely, an (s, S) system. The minimum setting (s) is the amount of product that triggers the need to place an order—that is, the reorder point as in a Q system. The maximum setting (S) is the target inventory level, or the maximum amount of product that should be ordered if inventory is zero. Consequently, the order quantity becomes the difference between S and the on-hand inventory at the time the order is placed. The system operates much like a P system except the stock has to be at, or below, s to trigger the order, and not a specified time between orders. Because demand for any given product varies by location, each store has its own set of min–max settings. Logistics managers know how much product is sold each day from point-of-sale data, and therefore they can determine when replenishment orders must be placed.

IKEA provides a clear example of how a large retailer can use operations to compete in a very competitive market.[6]

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
9.1 Identify the trade-offs involving small versus large inventories.	We cover these important aspects of inventories in the section "Inventory Trade-Offs." Focus on the pressures for small or large inventories and Figure 9.1.	
9.2 Define the different types of inventory and the roles they play in supply chains.	The section "Types of Inventory" explains each type of inventory and provides an example in Figure 9.2. Example 9.1 and Solved Problem 1 show how to estimate inventory levels. Be sure to understand the distinction between independent and dependent inventories.	**OM Explorer Tutor:** 9.1: Estimating Inventory Levels
9.3 Explain the tactics for reducing inventories in supply chains.	See the section "Inventory Reduction Tactics" for important approaches to managing inventory levels. The main tools for eliminating unneeded inventories are inventory control systems.	
9.4 Use ABC analysis to identify the items deserving most attention and tightest inventory control.	The section "ABC Analysis" shows a simple approach to categorizing inventory items for ease of management oversight. Figure 9.4 provides an example. Solved Problem 2 demonstrates the calculations.	**OM Explorer Tutor:** 9.2: ABC Analysis **POM for Windows:** ABC Analysis
9.5 Calculate the economic order quantity and apply it to various situations.	See the section "Economic Order Quantity" for a complete discussion of the EOQ model. Focus on Figures 9.5, 9.6, and 9.7 to see how the EOQ model affects inventory levels under the standard assumptions and how the EOQ provides the lowest cost solution. Review Examples 9.2 and 9.3 and Solved Problem 3 for help in calculating the total costs of various lot-size choices. Table 9.1 reveals important managerial insights from the EOQ. See also the Active Model Exercise.	**Active Model:** 9.1: Economic Order Quantity **OM Explorer Tutor:** 9.3: Finding EOQ and Total Cost **POM for Windows:** Economic Order Quantity (EOQ) Model **Tutor Exercise:** 9.1: Finding EOQ; Safety Stock; *R, P, T* at Bison College Bookstore

[6] *Sources:* Jay Schofield, "How IKEA Keeps Track of Their Massive Inventory," www.systemid.com/learn/ikea (August 2, 2016); "3 Ways IKEA Aces Inventory Management (and You Can Too)," https://clearspider.net/blog/ikea-inventory-management/ (April 24, 2018); "IKEA Supply Chain: How Does IKEA Manage Its Inventory?" www.tradegecko.com/blog/supply-chain-management/ (July 2, 2018).

Learning Objective	Guidelines for Review	Online Resources
9.6 Determine the order quantity and reorder point for a continuous review inventory control system.	The section "Continuous Review System" builds the essence of the *Q* system from basic principles to more realistic assumptions. Be sure to understand Figures 9.10 and 9.12. Examples 9.4, 9.5, and 9.6 and Solved Problems 4 and 6 show how to determine the parameters *Q* and *R* under various assumptions.	**OM Explorer Solvers:** Inventory Systems Designer; Demand During Protection Interval Simulator; *Q* System Simulator **OM Explorer Tutor:** 9.4: Finding the Safety Stock and *R* **Tutor Exercise:** 9.1: Finding EOQ; Safety Stock; *R, P, T* at Bison College Bookstore **Tutorial on Inventory Management Systems:** Using Simulation to Develop Inventory Management Systems **Advanced Problems:** Office Supply Shop Simulation; Floral Shop Simulation; Simquick Simulation Exercise
9.7 Determine the review interval and target inventory level for a periodic review inventory control system.	We summarize the key concepts in the section "Periodic Review System." Figure 9.13 shows how a *P* system operates, while Examples 9.8 and 9.9 and Solved Problem 5 demonstrate how to calculate the parameters *P* and *T*.	**OM Explorer Solver:** Inventory Systems Designer; Demand During Protection Interval Simulator **OM Explorer Tutor:** 9.5: Calculating *P* and *T* **Tutor Exercise:** 9.1: Finding EOQ; Safety Stock; *R, P, T* at Bison College Bookstore **Tutorial on Inventory Management Systems:** Using Simulation to Develop Inventory Management Systems **Advanced Problem:** Grocery Store Simulation; Simquick Simulation Exercise

Key Equations

Types of Inventory

1. Average cycle inventory: $\frac{Q}{2}$
2. Pipeline inventory: $\bar{D}_L = \bar{d}L$

Economic Order Quantity

3. Total annual cycle-inventory cost = Annual holding cost + Annual ordering or setup cost:

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S)$$

4. Economic order quantity:

$$\text{EOQ} = \sqrt{\frac{2DS}{H}}$$

5. Time between orders, expressed in weeks:

$$\text{TBO}_{\text{EOQ}} = \frac{\text{EOQ}}{D}(52 \text{ weeks/year})$$

Continuous Review System

6. Inventory position = On-hand inventory + Scheduled receipts − Backorders:

$$IP = OH + SR - BO$$

7. Continuous review system:

Protection interval = Lead time (L)

Standard deviation of demand during the lead time (constant L) = $\sigma_{dLT} = \sigma_d\sqrt{L}$

Standard deviation of demand during the lead time (variable L) = $\sigma_{dLT} = \sqrt{\bar{L}\,\sigma_d^2 + \bar{d}^{\,2}\sigma_{LT}^2}$

Safety stock = $z\sigma_{dLT}$

Reorder point R for constant lead time = $\bar{d}L$ + Safety stock

Reorder point R for variable lead time = $\bar{d}\bar{L}$ + Safety stock

Order quantity = EOQ

Replenishment rule: Order EOQ units when IP $\leq R$

Total Q system cost: $C = \frac{Q}{2}(H) + \frac{D}{Q}(S) + (H)(\text{Safety stock})$

Periodic Review System

8. Periodic review system:

Review interval = Time between orders = P

Protection interval = Time between orders + Lead time = $P + L$

Standard deviation of demand during the protection interval $\sigma_{P+L} = \sigma_d\sqrt{P + L}$

Safety stock = $z\sigma_{P+L}$

Target inventory level (T) = Average demand during the protection interval + Safety stock

$= \bar{d}\,(P + L)$ + Safety stock

Order quantity: Target inventory level − Inventory position = T − IP

Replenishment rule: Every P time periods, order T − IP units

Total P system cost: $C = \frac{\bar{d}P}{2}(H) + \frac{D}{\bar{d}P}(S) + (H)(\text{Safety stock})$

Key Terms

ABC analysis 366
anticipation inventory 363
base-stock system 377
continuous review (Q) system 371
cycle counting 367
cycle inventory 363
cycle-service level 374
dependent demand items 363
economic order quantity (EOQ) 367
finished goods (FG) 362
independent demand items 362
inventory 359
inventory holding cost 360
inventory management 359
inventory position (IP) 371
lot size 359
lot sizing 359
open orders 371
optional replenishment system 382
ordering cost 360
periodic review (P) system 378
perpetual inventory system 382
pipeline inventory 363
protection interval 374
quantity discount 361
raw materials (RM) 362
reorder point (R) 371
reorder point (ROP) system 371
repeatability 365
safety stock inventory 363
scheduled receipts (SR) 371
service level 374
setup cost 360
single-bin system 382
stock-keeping unit (SKU) 366
time between orders (TBO) 369
two-bin system 377
visual system 377
work-in-process (WIP) 362

Solved Problem 1

A distribution center experiences an average weekly demand of 50 units for one of its items. The product is valued at $650 per unit. Inbound shipments from the factory warehouse average 350 units. Average lead time (including ordering delays and transit time) is 2 weeks. The distribution center operates 52 weeks per year; it carries a 1-week supply of inventory as safety stock and no anticipation inventory. What is the value of the average aggregate inventory being held by the distribution center?

SOLUTION

Type of Inventory	Calculation of Aggregate Average Inventory	
Cycle	$\frac{Q}{2} = \frac{350}{2}$	= 175 units
Safety stock	1-week supply	= 50 units
Anticipation	None	
Pipeline	$\bar{d}L$ = (50 units/week) (2 weeks)	= 100 units
	Average aggregate inventory	= 325 units
	Value of aggregate inventory	= $650(325)
		= $211,250

Solved Problem 2

Online Resource

Tutor 9.2 in OM Explorer provides a new example of the application of ABC analysis.

Booker's Book Bindery divides SKUs into three classes according to their dollar usage. Calculate the usage values of the following SKUs and determine which is most likely to be classified as class A.

SOLUTION

The annual dollar usage for each SKU is determined by multiplying the annual usage quantity by the value per unit. As shown in Figure 9.14, the SKUs are then sorted by annual dollar usage, in declining order. Finally, A–B and B–C class lines are drawn roughly, according to the guidelines presented in the text. Here, class A includes only one SKU (signatures), which represents only 1/7, or 14 percent, of the SKUs but accounts for 83 percent of annual dollar usage. Class B includes the next two SKUs, which taken together represent 28 percent of the SKUs and account for 13 percent of annual dollar usage. The final four SKUs, class C, represent over half the number of SKUs but only 4 percent of total annual dollar usage.

SKU Number	Description	Quantity Used per Year	Unit Value
1	Boxes	500	$3.00
2	Cardboard (square feet)	18,000	$0.02
3	Cover stock	10,000	$0.75
4	Glue (gallons)	75	$40.00
5	Inside covers	20,000	$0.05
6	Reinforcing tape (meters)	3,000	$0.15
7	Signatures	150,000	$0.45

SKU Number	Description	Quantity Used per Year		Unit Value ($)		Annual Dollar Usage
1	Boxes	500	×	3.00	=	$1,500
2	Cardboard (square feet)	18,000	×	0.02	=	$360
3	Cover stock	10,000	×	0.75	=	$7,500
4	Glue (gallons)	75	×	40.00	=	$3,000
5	Inside covers	20,000	×	0.05	=	$1,000
6	Reinforcing tape (meters)	3,000	×	0.15	=	$450
7	Signatures	150,000	×	0.45	=	$67,500
					Total	$81,310

SKU #	Description	Qty Used/Year	Value	Dollar Usage	Pct of Total	Cumulative % of Dollar Value	Cumulative % of SKU	Class
7	Signatures	150,000	$0.45	$67,500	83.0%	83.0%	14.3%	A
3	Cover stock	10,000	$0.75	$7,500	9.2%	92.2%	28.6%	B
4	Glue	75	$40.00	$3,000	3.7%	95.9%	42.9%	B
1	Boxes	500	$3.00	$1,500	1.8%	97.8%	57.1%	C
5	Inside covers	20,000	$0.05	$1,000	1.2%	99.0%	71.4%	C
6	Reinforcing tape	3,000	$0.15	$450	0.6%	99.6%	85.7%	C
2	Cardboard	18,000	$0.02	$360	0.4%	100.0%	100.0%	C
Total				$81,310				

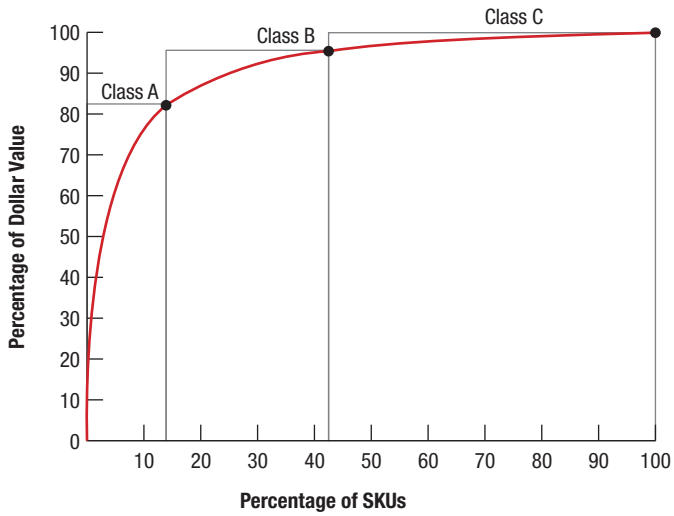


FIGURE 9.14
Annual Dollar Usage for Class A, B, and C SKUs Using Tutor 9.2

Solved Problem 3

Nelson's Hardware Store stocks a 19.2-volt cordless drill that is a popular seller. Annual demand is 5,000 units, the ordering cost is $15, and the inventory holding cost is $4/unit/year.

a. What is the economic order quantity?
b. What is the total annual cost for this inventory item?

SOLUTION

a. The order quantity is

$$\text{EOQ} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(5{,}000)(\$15)}{\$4}} = \sqrt{37{,}500}$$

$$= 193.65, \text{ or } 194 \text{ drills}$$

b. The total annual cost is

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S) = \frac{194}{2}(\$4) + \frac{5{,}000}{194}(\$15) = \$774.60$$

Solved Problem 4

A regional distributor purchases discontinued appliances from various suppliers and then sells them on demand to retailers in the region. The distributor operates 5 days per week, 52 weeks per year. Only when it is open for business can orders be received. The following data are estimated for a countertop mixer:

Average daily demand ($\bar{d}$) = 100 mixers

Standard deviation of daily demand (σ_d) = 30 mixers

Lead time (L) = 3 days

Holding cost (H) = \$9.40/unit/year

Ordering cost (S) = \$35/order

Cycle-service level = 92 percent

The distributor uses a continuous review Q system.

a. What order quantity, Q, and reorder point, R, should be used?

b. What is the total annual cost of the system?

c. If on-hand inventory is 40 units, one open order for 440 mixers is pending, and no backorders exist, should a new order be placed?

SOLUTION

a. Annual demand is

$$D = (5 \text{ days/week})(52 \text{ weeks/year})(100 \text{ mixers/day}) = 26{,}000 \text{ mixers/year}$$

The order quantity is

$$\text{EOQ} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(26{,}000)(\$35)}{\$9.40}} = \sqrt{193{,}167} = 440.02, \text{ or } 440 \text{ mixers}$$

The standard deviation of the distribution of demand during lead time is

$$\sigma_{dLT} = \sigma_d\sqrt{L} = 30\sqrt{3} = 51.96$$

A 92 percent cycle-service level corresponds to $z = 1.41$ (see the appendix on the normal distribution). Therefore,

$$\text{Safety stock} = z\sigma_{dLT} = 1.41(51.96 \text{ mixers}) = 73.26, \text{ or } 73 \text{ mixers}$$

$$\text{Average demand during the lead time} = \bar{d}L = 100(3) = 300 \text{ mixers}$$

$$\text{Reorder point } R = \text{Average demand during the lead time} + \text{Safety stock}$$

$$= 300 \text{ mixers} + 73 \text{ mixers} = 373 \text{ mixers}$$

With a continuous review system, $Q = 440$ and $R = 373$.

b. The total annual cost for the Q systems is

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S) + (H)(\text{Safety stock})$$

$$C = \frac{440}{2}(\$9.40) + \frac{26{,}000}{440}(35) + (\$9.40)(73) = \$4{,}822.38$$

c. Inventory position = On-hand inventory + Scheduled receipts − Backorders

$$IP = OH + SR - BO = 40 + 440 - 0 = 480 \text{ mixers}$$

Because IP (480) exceeds R (373), do not place a new order.

Solved Problem 5

Suppose that a periodic review (P) system is used at the distributor in Solved Problem 4, but otherwise the data are the same.

a. Calculate the P (in workdays, rounded to the nearest day) that gives approximately the same number of orders per year as the EOQ.

b. What is the target inventory level, T? Compare the P system to the Q system in Solved Problem 4.

c. What is the total annual cost of the P system?

d. It is time to review the item. On-hand inventory is 40 mixers; receipt of 440 mixers is scheduled, and no backorders exist. How much should be reordered?

SOLUTION

a. The time between orders is

$$P = \frac{\text{EOQ}}{D}(260 \text{ days/year}) = \frac{440}{26{,}000}(260) = 4.4, \text{ or } 4 \text{ days}$$

b. Figure 9.15 shows that $T = 812$ and safety stock $= (1.41)(79.37) = 111.91$, or about 112 mixers. The corresponding Q system for the countertop mixer requires less safety stock.

c. The total annual cost of the P system is

$$C = \frac{\bar{d}P}{2}(H) + \frac{D}{\bar{d}P}(S) + (H)(\text{Safety stock})$$

$$C = \frac{(100)(4)}{2}(\$9.40) + \frac{26{,}000}{(100)(4)}(\$35) + (\$9.40)(1.41)(79.37)$$

$$= \$5{,}207.80$$

d. Inventory position is the amount on hand plus scheduled receipts minus backorders, or

$$IP = OH + SR - BO = 40 + 440 - 0 = 480 \text{ mixers}$$

The order quantity is the target inventory level minus the inventory position, or

$$Q = T - IP = 812 \text{ mixers} - 480 \text{ mixers} = 332 \text{ mixers}$$

An order for 332 mixers should be placed.

Continuous Review (Q) System

z	1.41
Safety Stock	73
Reorder Point	373
Annual Cost	$4,822.38

Periodic Review (P) System

Time Between Reviews (P)	4.00 Days
☑ Enter manually	
Standard Deviation of Demand During Protection Interval	79.37
Safety Stock	112
Average Demand During Protection Interval	700
Target Inventory Level (T)	812
Annual Cost	$5,207.80

◀ **FIGURE 9.15**
OM Explorer Solver for Inventory Systems

Solved Problem 6

Grey Wolf Lodge is a popular 500-room hotel in the North Woods. Managers need to keep close tabs on all room service items, including a special pine-scented bar soap. The daily demand for the soap is 275 bars, with a standard deviation of 30 bars. Ordering cost is $10 and the inventory holding cost is $0.30/bar/year. The lead time from the supplier is 5 days, with a standard deviation of 1 day. The lodge is open 365 days a year.

a. What is the economic order quantity for the bar of soap?

b. What should the reorder point be for the bar of soap if management wants to have a 99 percent cycle-service level?

c. What is the total annual cost for the bar of soap, assuming a Q system will be used?

SOLUTION

a. We have $D = (275)(365) = 100{,}375$ bars of soap; $S = \$10$; and $H = \$0.30$. The EOQ for the bar of soap is

$$\text{EOQ} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(100{,}375)(\$10)}{\$0.30}} = \sqrt{6{,}691{,}666.7}$$

$$= 2{,}586.83, \text{ or } 2{,}587 \text{ bars}$$

b. We have $\bar{d} = 275$ bars/day, $\sigma_d = 30$ bars, $\bar{L} = 5$ days, and $\sigma_{LT} = 1$ day.

$$\sigma_{dLT} = \sqrt{\bar{L}\sigma_d^2 + \bar{d}^{\,2}\sigma_{LT}^2} = \sqrt{(5)(30)^2 + (275)^2(1)^2} = 283.06 \text{ bars}$$

Consult the body of the appendix on the normal distribution for 0.9900, which corresponds to a 99 percent cycle-service level. The closest value is 0.9901, which corresponds to a z-value of 2.33. We calculate the safety stock and reorder point as follows:

$$\text{Safety stock} = z\sigma_{dLT} = (2.33)(283.06) = 659.53, \text{ or } 660 \text{ bars}$$

$$\text{Reorder point} = \bar{d}\bar{L} + \text{Safety stock} = (275)(5) + 600 = 2{,}035 \text{ bars}$$

c. The total annual cost for the Q system is

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S) + (H)(\text{Safety stock})$$

$$C = \frac{2{,}587}{2}(\$0.30) + \frac{100{,}375}{2{,}587}(\$10) + (\$0.30)(660) = \$974.05$$

Discussion Questions

1. What is the relationship between inventory and the nine competitive priorities we discussed in Chapter 1, "Using Operations to Create Value"? Suppose that two competing manufacturers, Company H and Company L, are similar except that Company H has much higher investments in raw materials, work-in-process, and finished goods inventory than Company L. In which of the nine competitive priorities will Company H have an advantage?
2. Car manufacturers such as BMW and Toyota are also known as original equipment manufacturers (OEMs). They perform the final assembly and installation of components delivered by suppliers. For ease of communication and information transfer, their systems can be accessed by suppliers. In certain cases, these OEMs dictate their suppliers to use a specific information system for compatibility purposes. How will this impact inventory performance across the supply chain? What issues do you think may arise from this approach?
3. Will organizations ever get to the point where they will no longer need inventories? Why or why not?

Problems

The OM Explorer, POM for Windows, and Active Models software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download the software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software replaces entirely the manual calculations.

Types of Inventory

1. A part is produced in lots of 1,000 units. It is assembled from two components worth $50 total. The value added in production (for labor and variable overhead) is $60 per unit, bringing total costs per completed unit to $110. The average lead time for the part is 6 weeks and annual demand is 3,800 units, based on 50 business weeks per year.
   - **a.** How many units of the part are held, on average, in cycle inventory? What is the dollar value of this inventory?
   - **b.** How many units of the part are held, on average, in pipeline inventory? What is the dollar value of this inventory? (*Hint:* Assume that the typical part in pipeline inventory is 50 percent completed. Thus, half the labor and variable overhead cost has been added, bringing the unit cost to $80, or $50 + $60/2).
2. Prince Electronics, a manufacturer of consumer electronic goods, has five distribution centers in different regions of the country. For one of its products, a high-speed modem priced at $350 per unit, the average weekly demand at *each* distribution center is 75 units. Average shipment size to each distribution center is 400 units, and average lead time for delivery is 2 weeks. Each distribution center carries 2 weeks' supply as safety stock but holds no anticipation inventory.
   - **a.** On average, how many dollars of pipeline inventory will be in transit to each distribution center?
   - **b.** How much total inventory (cycle, safety, and pipeline) does Prince hold for all five distribution centers?
3. Terminator, Inc., manufactures a motorcycle part in lots of 250 units. The raw materials cost for the part is $150, and the value added in manufacturing 1 unit from its components is $300, for a total cost per completed unit of $450. The lead time to make the part is 3 weeks, and the annual demand is 4,000 units. Assume 50 working weeks per year.
   - **a.** How many units of the part are held, on average, as cycle inventory? What is its value?
   - **b.** How many units of the part are held, on average, as pipeline inventory? What is its value?

Inventory Reduction Tactics

4. Ruby-Star Incorporated is considering two different vendors for one of its top-selling products, which has an average weekly demand of 50 units and is valued at $75 per unit. Inbound shipments from vendor 1 will average 350 units with an average lead time (including ordering delays and transit time) of 2 weeks. Inbound shipments from vendor 2 will average 500 units with an average lead time of 1 week. Ruby-Star operates 52 weeks per year; it carries a 2-week supply of inventory as safety stock and no anticipation inventory.
   - **a.** What would be the average aggregate inventory value of this product if Ruby-Star used vendor 1 exclusively?
   - **b.** What would be the average aggregate inventory value of this product if Ruby-Star used vendor 2 exclusively?
   - **c.** How would your analysis change if average weekly demand increased to 100 units per week?
5. Haley Photocopying purchases paper from an out-of-state vendor. Average weekly demand for paper is 150 cartons per week, for which Haley pays $15 per carton. Inbound shipments from the vendor average 1,000 cartons with an average lead time of 3 weeks. Haley operates 52 weeks per year; it carries a 4-week supply of inventory as safety stock and no anticipation inventory. The vendor has recently announced that it will be building a facility near Haley Photocopying that will reduce lead time to 1 week. Further, the vendor will be able to reduce shipments to 200 cartons. Haley believes that it will be able to reduce safety stock to a 1-week supply. What impact will these changes make to Haley's average inventory level and its average aggregate inventory value?

ABC Analysis

6. Oakwood Hospital is considering using ABC analysis to classify laboratory SKUs into three categories: those that will be delivered daily from its supplier (Class A items), those that will be controlled using a continuous review system (B items), and those that will be held in a two-bin system (C items). The following table shows the annual dollar usage for a sample of eight SKUs. Rank the SKUs, and assign them to their appropriate category.

SKU Code	Dollar Value	Annual Usage
1	$0.01	1,200
2	$0.03	120,000
3	$0.45	100
4	$1.00	44,000
5	$4.50	900
6	$0.90	350
7	$0.30	70,000
8	$1.50	200

7. Southern Markets, Inc., is considering the use of ABC analysis to focus on the most critical SKUs in its inventory. Currently, there are approximately 20,000 different SKUs with a total dollar usage of $10,000,000 per year.

a. What would you expect to be the number of SKUs and the total annual dollar usage for A items, B items, and C items at Southern Markets, Inc.?

b. The following table provides a random sample of the unit values and annual demands of eight SKUs. Categorize these SKUs as A, B, and C items.

SKU Code	Unit Value	Demand (Units)
A104	$2.10	2,500
D205	$2.50	30
X104	$0.85	350
U404	$0.25	250
L205	$4.75	20
S104	$0.02	4,000
X205	$0.35	1,020
L104	$4.25	50

8. New Wave Shelving's inventory manager would like to start using an ABC inventory classification system. The following table shows the annual inventory usage of all the 19 component items that the company holds. Assign them to their appropriate category.

SKU #	Description	Quantity Used per Year	Dollar Value per Unit
a-1	Steel panel	500	$ 25.00
a-2	Steel bumper	750	$ 135.00
a-3	Steel clamp	3,500	$ 5.00
a-4	Steel brace	200	$ 20.00
b-1	Copper coil	1,250	$ 260.00
b-2	Copper panel	1,250	$ 50.00
b-3	Copper brace 1	250	$ 75.00
b-4	Copper brace 2	150	$ 125.00
c-1	Rubber bumper	8,500	$ 0.75
c-2	Rubber foot	6,500	$ 0.75
c-3	Rubber seal 1	1,500	$ 1.00
c-4	Rubber seal 2	3,500	$ 1.00
c-5	Rubber seal 3	1,200	$ 2.25
d-1	Plastic fastener kit	1,500	$ 3.50
d-2	Plastic handle	2,000	$ 0.75
d-3	Plastic panel	1,000	$ 6.50
d-4	Plastic bumper	2,000	$ 1.25
d-5	Plastic coil	450	$ 6.00
d-6	Plastic foot	6,000	$ 0.25

Economic Order Quantity

9. Yellow Press, Inc., buys paper in 1,500-pound rolls for printing. Annual demand is 2,500 rolls. The cost per roll is $800, and the annual holding cost is 15 percent of the cost. Each order costs $50 to process.

a. How many rolls should Yellow Press, Inc., order at a time?

b. What is the time between orders?

10. A supermarket in London sells 750 kg of rice per month from Thailand. The ordering cost is £250 and the holding cost is £0.75 per kg per year.

a. How much rice should the supermarket order at a time?

b. What is the time between orders?

11. At Dot Com, a large retailer of popular books, demand is constant at 32,000 books per year. The cost of placing an order to replenish stock is $10, and the annual cost of holding is $4 per book. Stock is received 5 working

days after an order has been placed. No backordering is allowed. Assume 300 working days a year.

a. What is Dot Com's optimal order quantity?

b. What is the optimal number of orders per year?

c. What is the optimal interval (in working days) between orders?

d. What is demand during the lead time?

e. What is the reorder point?

f. What is the inventory position immediately after an order has been placed?

12. Big Builder (BB) sells construction equipment such as concrete mixer, wheelbarrow, and angle grinders to highway agencies who use them for road construction. BB receives orders from multiple agencies via email and post. It costs BB £25 to process an order and the combined demand from multiple agencies is 3,000 units per year. The holding cost is £55 per item per year and unit cost is £1,100. Items are imported from Germany and stock is received 7 working days after an order is placed. No backordering is allowed. Assume 220 working days a year.

a. What is BB's optimal order quantity?

b. What is the optimal number of orders per year?

c. What is the optimal interval (in working days) between orders?

d. What is the demand during the lead time?

e. What is the reorder point?

f. What are the total annual costs?

Continuous Review System

13. Sam's Pet Hotel operates 52 weeks per year, 6 days per week, and uses a continuous review inventory system. It purchases kitty litter for $11.70 per bag. The following information is available about these bags.

Demand = 90 bags/week

Order cost = $54/order

Annual holding cost = 27 percent of cost

Desired cycle-service level = 80 percent

Lead time = 3 weeks (18 working days)

Standard deviation of weekly demand = 15 bags

Current on-hand inventory is 320 bags, with no open orders or backorders.

a. What is the EOQ? What would be the average time between orders (in weeks)?

b. What should R be?

c. An inventory withdrawal of 10 bags was just made. Is it time to reorder?

d. The store currently uses a lot size of 500 bags (i.e., $Q = 500$). What is the annual holding cost of this policy? Annual ordering cost? Without calculating the EOQ, how can you conclude from these two calculations that the current lot size is too large?

e. What would be the annual cost saved by shifting from the 500-bag lot size to the EOQ?

14. Consider again the kitty litter ordering policy for Sam's Pet Hotel in Problem 13.

a. Suppose that the weekly demand forecast of 90 bags is incorrect and actual demand averages only 60 bags per week. How much higher will total costs be, owing to the distorted EOQ caused by this forecast error?

b. Suppose that actual demand is 60 bags but that ordering costs are cut to only $6 by using the Internet to automate order placing. However, the buyer does not tell anyone, and the EOQ is not adjusted to reflect this reduction in S. How much higher will total costs be, compared to what they could be if the EOQ were adjusted?

15. In a Q system, the demand rate for strawberry ice cream is normally distributed, with an average of 300 pints *per week*. The lead time is 9 weeks. The standard deviation of *weekly* demand is 15 pints.

a. What is the standard deviation of demand during the 9-week lead time?

b. What is the average demand during the 9-week lead time?

c. What reorder point results in a cycle-service level of 99 percent?

16. Petromax Enterprises uses a continuous review inventory control system for one of its SKUs. The following information is available on the item. The firm operates 50 weeks in a year.

Demand = 50,000 units/year

Ordering cost = $35/order

Holding cost = $2/unit/year

Average lead time = 3 weeks

Standard deviation of weekly demand = 125 units

a. What is the economic order quantity for this item?

b. If Petromax wants to provide a 90 percent cycle-service level, what should be the safety stock and the reorder point?

17. You are a manufacturer of precision components for the automotive industry. Your supplier reviews stock every 4 weeks and replenishes it instantaneously. The standard deviation of demand during the lead time is 130 units. The supplier has streamlined its operations and promised a cycle-service level of 99 percent. If the supplier has decided to undertake weekly audits, how much can safety stock be reduced without reducing the 99 percent cycle-service level?

18. In a two-bin inventory system, the demand for 3-inch lag bolts during the 2-week lead time is normally distributed, with an average of 53 units per week. The standard deviation of weekly demand is 5 units.

a. What is the probability of demand exceeding the reorder point when the normal level in the second bin is set at 130 units?

b. What is the probability of demand exceeding the 130 units in the second bin if it takes 3 weeks to receive a replenishment order?

19. An e-commerce retailer is trading a successful haircare product imported from overseas suppliers. It takes 6 weeks for the item to reach the warehouse from suppliers. Due to various import documentation requirements, placing an order costs £45 per unit. Weekly demand for this item varies, with an average of 350 units and a standard deviation of 25 units. It is purchased from suppliers at a cost of £30 per unit, and the warehousing cost amounts to 15 percent of the item cost. Being an e-commerce retailer, the firm operates throughout the year.

a. What is the optimal order quantity for this item?

b. How many units of the item should be maintained as safety stock for 99 percent protection against stockouts during an order cycle?

c. If supply lead time can be reduced to 4 weeks, what is the reduction in the number of units maintained as safety stock for the same 99 percent stockout protection?

d. If through appropriate sales promotions, the demand variability is reduced so that the standard deviation of weekly demand is 15 units instead of 25, what is the percent reduction in the number of units maintained as safety stock for the same 99 percent stockout protection?

20. Your firm uses a continuous review system and operates 52 weeks per year. One of the SKUs has the following characteristics.

Demand (D) = 20,000 units/year

Ordering cost (S) = \$40/order

Holding cost (H) = \$2 unit/year

Lead time (L) = 2 weeks

Cycle-service level = 95 percent

Demand is normally distributed, with a standard deviation of *weekly* demand of 100 units.

Current on-hand inventory is 1,040 units, with no scheduled receipts and no backorders.

a. Calculate the item's EOQ. What is the average time, in weeks, between orders?

b. Find the safety stock and reorder point that provide a 95 percent cycle-service level.

c. For these policies, what are the annual costs of (i) holding the cycle inventory and (ii) placing orders?

d. A withdrawal of 15 units just occurred. Is it time to reorder? If so, how much should be ordered?

21. A company begins a review of ordering policies for its continuous review system by checking the current policies for a sample of SKUs. Following are the characteristics of one item.

Demand (D) = 64 units/week (Assume 52 weeks per year)

Ordering or setup cost (S) = \$50/order

Holding cost (H) = \$13/unit/year

Lead time (L) = 2 weeks

Standard deviation of weekly demand = 12 units

Cycle-service level = 88 percent

a. What is the EOQ for this item?

b. What is the desired safety stock?

c. What is the reorder point?

d. What are the cost implications if the current policy for this item is Q = 200 and R = 180?

22. Roland provides custom-made coffee mugs, saucers, keychains, magnets, and other souvenirs sought after by tourists visiting the Eiffel Tower. It purchases plain coffee mugs from a wholesaler in Germany and customizes them to suit customer needs. The cost to place orders with the supplier is €45/order; and the inventory holding cost is €2/item/year. Since Roland is located near a tourist hub, demand is fairly consistent throughout the year and it averages 25 mugs per day, with a standard deviation of 2 mugs. The lead time from the supplier is 10 days, with a standard deviation of 3 days. The desired cycle-service level is 97 percent. Roland is open 340 days a year. The owners want to use a continuous review inventory system for mugs.

a. What order quantity should be used?

b. What reorder point should be used?

c. What is the total annual cost for this inventory system?

23. **[D]** Northwoods Living is a country store specializing in knick-knacks suitable for a farmhouse décor. One item experiencing a considerable buying frenzy is a miniature Holstein cow. Average weekly demand is 30 cows, with a standard deviation of 5 cows. The cost to place a replenishment order is \$15 and the holding cost is \$0.75/cow/year. The supplier, however, is in China. The lead time for new orders is 8 weeks, with a standard deviation of 2 weeks. Northwoods Living, which is open only 50 weeks a year, wants to develop a continuous review inventory system for this item with a cycle-service level of 90 percent.

a. Specify the continuous review system for the cows. Explain how it would work in practice.

b. What is the total annual cost for the system you developed?

24. **[D]** Muscle Bound is a chain of fitness stores located in many large shopping centers. Recently, an internal memo from the CEO to all operations personnel complained about the budget overruns at Muscle Bound's central warehouse. In particular, she said that inventories were too high and that the budget will be cut dramatically and proportionately equal for all items in stock. Consequently, warehouse management set up a pilot study to see what effect the budget cuts would have on customer service. They chose 5-pound barbells, which are a high-volume SKU and consume considerable warehouse space. Daily demand for the barbells is 1,000 units, with a standard deviation of 150 units. Ordering costs are \$40 per order. Holding costs are \$2/unit/year. The supplier is located in the Philippines; consequently, the lead time is 35 days with a standard deviation of 5 days. Muscle Bound stores operate 313 days a year (no Sundays).

Suppose that the barbells are allocated a budget of $16,000 for total annual costs. If Muscle Bound uses a continuous review system for the barbells and cannot change the ordering costs and holding costs or the distributions of demand or lead time, what is the best cycle-service level management can expect from this system?

It may be helpful to review online Supplement E, "Simulation," before working Problem 25.

25. The Georgia Lighting Center stocks more than 3,000 lighting fixtures, including chandeliers, swags, wall lamps, and track lights. The store sells at retail, operates 6 days per week, and advertises itself as the "brightest spot in town." One expensive fixture is selling at an average rate of 5 units per day. The reorder policy is $Q = 40$ and $R = 15$. A new order is placed on the day the reorder point is reached. The lead time is 3 business days. For example, an order placed on Monday will be delivered on Thursday. Simulate the performance of this Q system for the next 3 weeks (18 workdays). Any stockouts result in lost sales (rather than backorders). The beginning inventory is 19 units, and no receipts are scheduled. Table 9.2 simulates the first week of operation. Extend Table 9.2 to simulate operations for the next 2 weeks if demand for the next 12 business days is 7, 4, 2, 7, 3, 6, 10, 0, 5, 10, 4, and 7.

- **a.** What is the average daily ending inventory over the 18 days? How many stockouts occurred?
- **b.** Using the same beginning inventory and daily demand data, simulate the inventory performance of the same item, assuming a $Q = 30$, $R = 20$ system is used. Calculate the average inventory level and number of stockouts and compare with part (a).

TABLE 9.2 | FIRST WEEK OF OPERATION

Workday	Beginning Inventory	Orders Received	Daily Demand	Ending Inventory	Inventory Position	Order Quantity
1. Monday	19	—	5	14	14	40
2. Tuesday	14	—	3	11	51	—
3. Wednesday	11	—	4	7	47	—
4. Thursday	7	40	1	46	46	—
5. Friday	46	—	10	36	36	—
6. Saturday	36	—	9	27	27	—

Periodic Review System

26. Nationwide Auto Parts uses a periodic review inventory control system for one of its stock items. The review interval is 6 weeks, and the lead time for receiving the materials ordered from its wholesaler is 3 weeks. Weekly demand is normally distributed, with a mean of 100 units and a standard deviation of 20 units.

- **a.** What is the average and the standard deviation of demand during the protection interval?
- **b.** What should be the target inventory level if the firm desires 97.5 percent stockout protection?
- **c.** If 350 units were in stock at the time of a periodic review, how many units should be ordered?

27. In a P system, the lead time for a box of weed-killer is 2 weeks and the review period is 1 week. Demand during the protection interval averages 218 boxes, with a standard deviation of 40 boxes.

- **a.** What is the cycle-service level when the target inventory is set at 300 boxes?
- **b.** In the fall season, demand for weed-killer decreases but also becomes more highly variable. Assume that during the fall season, demand during the protection interval is expected to decrease to 180 boxes, but with a standard deviation of 50 boxes. What would be the cycle-service level if management keeps the target inventory level set at 300 boxes?

28. Suppose that Sam's Pet Hotel in Problem 13 uses a P system instead of a Q system. The average daily demand is $\bar{d} = \dfrac{90}{6} = 15$ bags and the standard deviation of *daily* demand is $\sigma_d = \dfrac{\sigma_{\text{week}}}{\sqrt{6}} = (15/\sqrt{6}) = 6.124$ bags.

- **a.** What P (in working days) and T should be used to approximate the cost trade-offs of the EOQ?
- **b.** How much more safety stock is needed than with a Q system?
- **c.** It is time for the periodic review. How much kitty litter should be ordered?

29. Your firm uses a periodic review system for all SKUs classified, using ABC analysis, as B or C items. Further, it uses a continuous review system for all SKUs classified as A items. The demand for a specific SKU, currently classified as an A item, has been dropping. You have been asked to evaluate the impact of moving the item from continuous review to periodic review. Assume your firm operates 52 weeks per year; the item's current characteristics are as follows:

Demand (D) = 15,080 units/year
Ordering cost (S) = $125.00/order
Holding cost (H) = $3.00/unit/year
Lead time (L) = 5 weeks
Cycle-service level = 95 percent

Demand is normally distributed, with a standard deviation of weekly demand of 64 units.

a. Calculate the item's EOQ.

b. Use the EOQ to define the parameters of an appropriate continuous review and periodic review system for this item.

c. Which system requires more safety stock and by how much?

30. Using the same information as in Problem 21, develop the best policies for a periodic review system.

a. What value of P gives the same approximate number of orders per year as the EOQ? Round to the nearest week.

b. What safety stock and target inventory level provide an 88 percent cycle-service level?

31. Wood County Hospital consumes 1,000 boxes of bandages per week. The price of bandages is $35 per box, and the hospital operates 52 weeks per year. The cost of processing an order is $15, and the cost of holding one box for a year is 15 percent of the value of the material.

a. The hospital orders bandages in lot sizes of 900 boxes. What *extra* cost does the hospital incur, which it could save by using the EOQ method?

b. Demand is normally distributed, with a standard deviation of weekly demand of 100 boxes. The lead time is 2 weeks. What safety stock is necessary if the hospital uses a continuous review system and a 97 percent cycle-service level is desired? What should be the reorder point?

c. If the hospital uses a periodic review system, with $P = 2$ weeks, what should be the target inventory level, T?

32. A cricket specialty wholesaler operates 50 weeks per year. Management is trying to determine an inventory policy for its bats, which have the following characteristics:

Demand (D) = 350,000 units/year

Standard deviation of *weekly* demand = 65 units

Ordering cost = £35/order

Annual holding cost (H) = £3/unit

Desired cycle-service level = 95 percent

Lead time (L) = 6 weeks

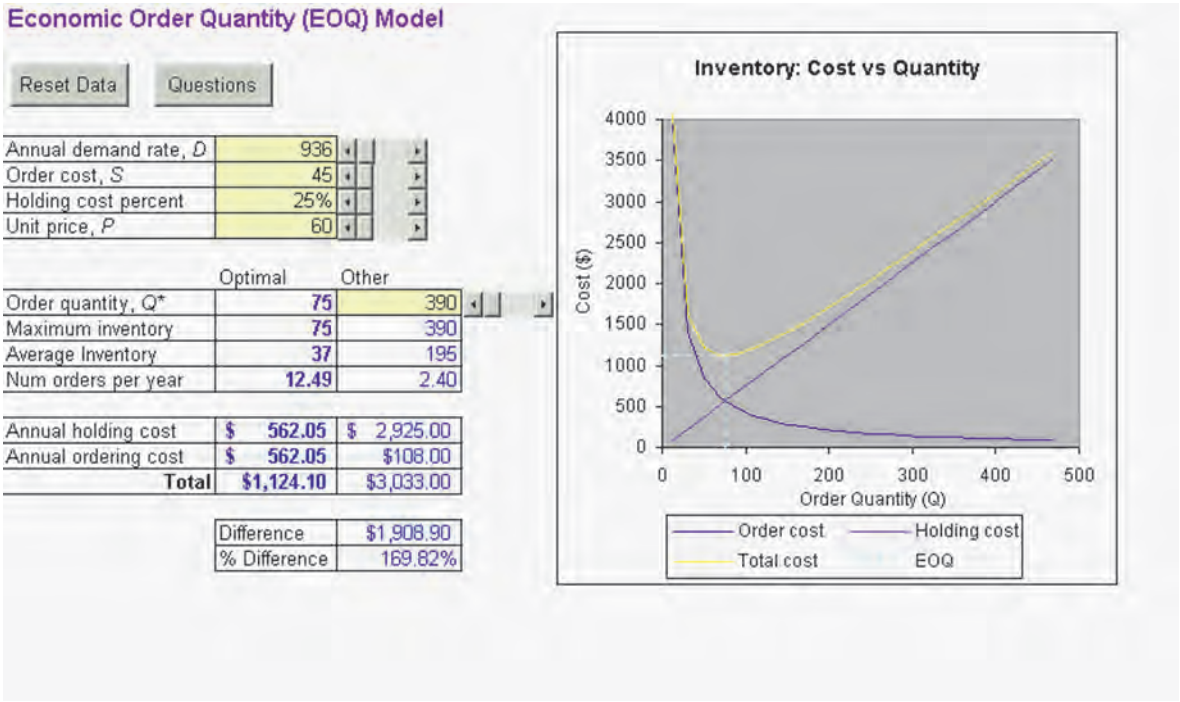
Should the company adopt a periodic review system or a continuous review system, and why?

Active Model Exercise

Active Model 9.1, "Economic Order Quantity," is available online. It allows you to evaluate the sensitivity of the EOQ and associated costs to changes in the demand and cost parameters.

QUESTIONS

1. What is the EOQ and what is the lowest total cost?
2. What is the annual cost of holding inventory at the EOQ and the annual cost of ordering inventory at the EOQ?



3. From the graph, what can you conclude about the relationship between the lowest total cost and the costs of ordering and holding inventory?
4. How much does the total cost increase if the store manager orders twice as many bird feeders as the EOQ? How much does the total cost increase if the store manager orders half as many bird feeders as the EOQ?
5. What happens to the EOQ and the total cost when demand is doubled? What happens to the EOQ and the total cost when unit price is doubled?
6. Scroll through the lower order cost values and describe the changes to the graph. What happens to the EOQ?
7. Comment on the sensitivity of the EOQ model to errors in demand or cost estimates.

EXPERIENTIAL LEARNING 9.1

Swift Electronic Supply, Inc.

It was a typical fall afternoon in Southern California, with thousands of tourists headed to the beaches to have fun. About 40 miles away, however, Steven Holland, the CEO of Swift Electronic Supply, Inc., faced a severe problem with Swift's inventory management.

An Intel veteran, Steven Holland worked in the electronic components distribution industry for more than 20 years. Seven years ago, he founded Swift Electronic Supply, Inc., an electronic distributor. After several successful years, the company is now troubled with eroding profit margins. Recent economic downturns further worsened the situation. Factors such as the growth of B2B e-commerce, the globalization of markets, the increased popularity of value-added services, and ongoing consolidations among electronic distributors affect the future of Swift.

To reverse these influences, Holland talked to a prestigious local university. After consultation, Holland found the most effective way to increase profitability is to cut inventory costs. As a starting point, he studied in detail a representative product, dynamic random-access memory (DRAM), as the basis for his plan.

Industry and Company Preview

Owing to a boom in the telecommunications industry and the information technology revolution, electronics distributors experienced double-digit annual growth over the past decade. To cut the cost of direct purchasing forces, large component manufacturers such as Intel, Cisco, and Texas Instruments decided to outsource their procurement so that they could focus on product development and manufacturing. Therefore, independent electronic distributors like Swift started offering procurement services to these companies.

Swift serves component manufacturers in California and Arizona. Working as the intermediary between its customers and overseas original equipment manufacturers (OEMs), Swift's business model is quite simple. Forecasting customer demand, Swift places orders to a number of OEMs, stocks those products, breaks the quantities down, and delivers the products to its end customers.

Recently, due to more intense competition and declines in demand, Swift offered more flexible delivery schedules and was willing to accommodate small order quantities. However, customers can always shift to Swift's competitors should Swift not fulfill their orders. Steven Holland was in a dilemma: The intangible costs of losing customers can be enormous; however, maintaining high levels of inventory can also be costly.

DRAM

Holland turned his attention to DRAM as a representative product. Previously, the company ordered a large amount every time it felt it was necessary. Holland's assistant developed a table (Table 9.3) that has 2 months of demand history. From Holland's experience, the demand for DRAM is relatively stable in the company's product line and it had no sales seasonality. The sales staff agrees that conditions in the current year will not be different from those of past years, and historical demand will be a good indicator of what to expect in the future.

TABLE 9.3 HISTORICAL DEMAND DATA FOR THE DRAM (UNITS)

Day	Demand	Day	Demand	Day	Demand
1	869	21	663	41	959
2	902	22	1,146	42	703
3	1,109	23	1,016	43	823
4	947	24	1,166	44	862
5	968	25	829	45	966
6	917	26	723	46	1,042
7	1,069	27	749	47	889
8	1,086	28	766	48	1,002
9	1,066	29	996	49	763
10	929	30	1,122	50	932
11	1,022	31	962	51	1,052
12	959	32	829	52	1,062
13	756	33	862	53	989
14	882	34	793	54	1,029
15	829	35	1,039	55	823
16	726	36	1,009	56	942
17	666	37	979	57	986
18	879	38	976	58	736
19	1,086	39	856	59	1,009
20	992	40	1,036	60	852

The primary manufacturers of DRAM are those in Southeast Asia. Currently, Swift can purchase one unit of 128M DRAM for $10. After negotiation with a reputable supplier, Holland managed to sign a long-term agreement, which kept the price at $10 and allowed Swift to place orders at any time. The supplier also supplies other items in Swift's inventory. In addition, it takes the supplier of the DRAM 2 days to deliver the goods to Swift's warehouse using air carriers.

When Swift does not have enough inventory to fill a customer's order, the sales are lost; that is, Swift is not able to backorder the shortage because its customers fill their requirements through competitors. The customers will accept partial shipments, however.

It costs Swift $200 to place an order with the suppliers. This amount covers the corresponding internal ordering costs and the costs of delivering the products to the company. Holland estimates that the cost of lost sales amounts to $2 per unit of DRAM. This rough estimate includes the loss of profits, as well as the intangible damage to customer goodwill.

To simplify its inventory management system, Swift has a policy of maintaining a cycle-service level of 95 percent. The holding cost per day per unit is estimated to be 0.5 percent of the cost of goods, regardless of the product. Inventory holding costs are calculated on the basis of the ending inventory each day. The current balance is 1,700 units of DRAM in stock.

The daily purchasing routine is as follows. Orders are placed at the *beginning* of the day, before Swift is open for customer business. The orders arrive at the beginning of the day, 2 days later, and can be used for sales that day. For example, an order placed at the beginning of day 1 will arrive at Swift before Swift is open for business on day 3. The actual daily demand is always recorded at the *end* of the day, after Swift has closed for customer business. All cost computations are done at the end of the day after the total demand has been recorded.

Simulation

Holland believes that simulation is a useful approach to assess various inventory control alternatives. The historical data from Table 9.3 could be used to develop attractive inventory policies. The table was developed to record various costs and evaluate different alternatives. An example showing some recent DRAM inventory decisions is shown in Table 9.4.

1. Design a new inventory system for Swift Electronic Supply, Inc., using the data provided.
2. Provide the rationale for your system, which should include the decision rules you would follow to determine how much to order and when.
3. Simulate the use of your inventory system and record the costs. Develop a table such as Table 9.4 to record your results. Your instructor will provide actual demands on a day-to-day basis during the simulation.

TABLE 9.4 | EXAMPLE SIMULATION

Day	1	2	3	4	5	6	7	8	9	10
Beginning inventory position	1,700	831	1,500	391	3,000	3,232	2,315			
Number ordered	1,500		3,000	1,200			1,900			
Daily demand	869	902	1,109	947	968	917	1,069			
Day-ending inventory	831	−71	391	−556	2,032	2,315	1,246			
Ordering costs ($200 per order)	200		200	200			200			
Holding costs ($0.05 per piece per day)	41.55	0.00	19.55	0.00	101.60	115.75	62.30			
Shortage costs ($2 per piece)	0	142	0	1,112	0	0	0			
Total cost for day	241.55	142.00	219.55	1,312.00	101.60	115.75	262.30			
Cumulative cost from last day	0.00	241.55	383.55	603.10	1,915.10	2,016.70	2,132.45			
Cumulative costs to date	241.55	383.55	603.10	1,915.10	2,016.70	2,132.45	2,394.75			

CASE Parts Emporium

Parts Emporium, Inc., is a wholesale distributor of automobile parts formed by two disenchanted auto mechanics, Dan Block and Liya Kimathi. Originally located in Block's garage, the firm showed slow but steady growth for 7 years before it relocated to an old, abandoned meat-packing warehouse on Chicago's South Side. With increased space for inventory storage, the company was able to begin offering an expanded line of auto parts. This increased selection, combined with the trend toward longer car ownership, led to an explosive growth of the business. Fifteen years later, Parts Emporium was the largest independent distributor of auto parts in the north central region.

Recently, Parts Emporium relocated to a sparkling new office and warehouse complex off Interstate 55 in suburban Chicago. The warehouse space alone occupied more than 100,000 square feet. Although only a handful of new products have been added since the warehouse was constructed, its utilization increased from 65 percent to more than 90 percent of capacity. During this same

period, however, sales growth stagnated. These conditions motivated Block and Kimathi to hire the first manager from outside the company in the firm's history.

It is June 6, Sue McCaskey's first day in the newly created position of materials manager for Parts Emporium. A recent graduate of a prominent business school, McCaskey is eagerly awaiting her first real-world problem. At approximately 8:30 A.M., it arrives in the form of status reports on inventory and orders shipped. At the top of an extensive computer printout is a handwritten note from Joe Donnell, the purchasing manager: "Attached you will find the inventory and customer service performance data. Rest assured that the individual inventory levels are accurate because we took a complete physical inventory count at the end of last week. Unfortunately, we do not keep compiled records in some of the areas as you requested. However, you are welcome to do so yourself. Welcome aboard!"

A little upset that aggregate information is not available, McCaskey decides to randomly select a small sample of approximately 100 items and compile inventory and customer service characteristics to get a feel for the "total picture." The results of this experiment reveal to her why Parts Emporium decided to create the position she now fills. It seems that the inventory is in all the wrong places. Although an *average* of approximately 60 days of inventory is on hand, the firm's customer service is inadequate. Parts Emporium tries to backorder the customer orders not immediately filled from stock, but some 10 percent of demand is being lost to competing distributorships. Because stockouts are costly, relative to inventory holding costs, McCaskey believes that a cycle-service level of at least 95 percent should be achieved.

McCaskey knows that although her influence to initiate changes will be limited, she must produce positive results immediately. Thus, she decides to concentrate on two products from the extensive product line: the EG151 exhaust gasket and the DB032 drive belt. If she can demonstrate significant gains from proper inventory management for just two products, perhaps Block and Kimathi will give her the backing needed to change the total inventory management system.

The EG151 exhaust gasket is purchased from an overseas supplier, Haipei, Inc. Actual demand for the first 21 weeks of this year is shown in the following table:

Week	Actual Demand	Week	Actual Demand
1	104	12	97
2	103	13	99
3	107	14	102
4	105	15	99
5	102	16	103
6	102	17	101
7	101	18	101
8	104	19	104
9	100	20	108
10	100	21	97
11	103		

A quick review of past orders, shown in another document, indicates that a lot size of 150 units is being used and that the lead time from Haipei is fairly constant at 2 weeks. Currently, at the end of week 21, no inventory is on hand, 11 units are backordered, and the company is awaiting a scheduled receipt of 150 units.

The DB032 drive belt is purchased from the Bendox Corporation of Grand Rapids, Michigan. Actual demand so far this year is shown in the following table:

Week	Actual Demand	Week	Actual Demand
11	18	17	50
12	33	18	53
13	53	19	54
14	54	20	49
15	51	21	52
16	53		

Because this product is new, data are available only since its introduction in week 11. Currently, 324 units are on hand, with no backorders and no scheduled receipts. A lot size of 1,000 units is being used, with the lead time fairly constant at 3 weeks.

The wholesale prices that Parts Emporium charges its customers are $12.99 for the EG151 exhaust gasket and $8.89 for the DB032 drive belt. Because no quantity discounts are offered on these two highly profitable items, gross margins based on current purchasing practices are 32 percent of the wholesale price for the exhaust gasket and 48 percent of the wholesale price for the drive belt.

Parts Emporium estimates its cost to hold inventory at 21 percent of its inventory investment. This percentage recognizes the opportunity cost of tying money up in inventory and the variable costs of taxes, insurance, and shrinkage. The annual report notes other warehousing expenditures for utilities and maintenance and debt service on the 100,000-square-foot warehouse, which was built for $1.5 million. However, McCaskey reasons that these warehousing costs can be ignored because they will not change for the range of inventory policies that she is considering.

Out-of-pocket costs for Parts Emporium to place an order with suppliers are estimated to be $20 per order for exhaust gaskets and $10 per order for drive belts. On the outbound side, the company can charge a delivery fee. Although most customers pick up their parts at Parts Emporium, some orders are delivered to customers. To provide this service, Parts Emporium contracts with a local company for a flat fee of $21.40 per order, which is added to the customer's bill. McCaskey is unsure whether to increase the ordering costs for Parts Emporium to include delivery charges.

QUESTIONS

1. Put yourself in Sue McCaskey's position and prepare a detailed report to Dan Block and Liya Kimathi on managing the inventory of the EG151 exhaust gasket and the DB032 drive belt. Be sure to present a proper inventory system and recognize all relevant costs.
2. By how much do your recommendations for these two items reduce annual cycle inventory, stockout, and ordering costs?

VIDEO CASE Inventory Management at Crayola

Managing inventory at Crayola is a fine balancing act. With the back-to-school period driving 42 percent of company demand for crayons, markers, paints, modeling compounds, and other products, production starts in February so enough finished goods are in the 800,000-square-foot warehouse in time to supply 3,600 Walmarts, 1,400 Targets, and thousands of other retailers in the United States for the fall school-supply rush.



Pearson Education

Crayola must supply customers with nearly 1,500 products, which requires an average inventory investment of $110 million. Finished goods inventory, shown here, must be stored in advance of seasonal demand peaks, such as the back-to-school period, which accounts for 42 percent of annual demand.

This means demand forecasts for raw materials in the master production schedule must be developed months before any of the finished products move to those retail customers. Lead times range from 60 days for domestic raw materials sources to upwards of 90 days for finished goods from suppliers outside the United States. As production ramps up for the back-to-school season well before the first day of classes, Crayola plans inventory levels for the entire year so that production remains reasonably steady. While the back-to-school season represents the lion's share of annual sales, holiday sales account for 35 percent of revenues, and the rest comes from spring sales. Crayola has over 1,500 SKUs, with close to 225 top sellers, so accurate forecasts are essential.

Historical sales patterns as well as orders generated by its U.S. sales divisions located in Easton, Pennsylvania (headquarters), Bentonville, Arkansas (near Walmart's headquarters), and Minneapolis, Minnesota (near Target's headquarters), help managers attain the accuracy needed. Marketing cobranding for the latest movies and comic books plays a role in creating the forecast for new SKUs and bundles, which must be coordinated to hit retailers the same time the movies and comics debut or the company risks missing the market and ending up with inventory that can't easily be sold.

Crayola's inventory holding costs run about 25 percent, and its average inventory value is $110 million. The company must ensure there is warehouse space for finished goods as well as raw materials used in production. Pigments, clays, and packaging materials are moved from the warehouse and positioned close to the production lines, using a Kanban system to pull raw materials inventory as needed. Rail tanker cars from Louisiana and Pennsylvania carrying paraffin wax are delivered twice a week for crayon production. Since the rail cars feed directly into production, any disruption in delivery has the potential for shutting down production. Bad weather is a particular risk in this part of the company's supply chain, since it can prevent the transport of goods during hurricanes or snowstorms.

Crayola attempts to source as many raw materials from domestic sources as possible. Cartons, clay, ink, labels, and corrugated boxes come from the mid-Atlantic region of the United States, while those plastic components Crayola does not manufacture onsite, such as nibs for markers, are sourced from Asia and can take up to 120 days to ship through the Panama Canal to the Port of Newark. Materials used in kits and bundles come from Korea, China, Vietnam, and Brazil, and face similar shipping logistics.

When considering work-in-process inventories at Crayola, paints, markers, modeling clays, and many of the crayons coming off the production line are boxed into trays for use downstream in creating kits and bundles. These items are considered WIP items, even though the individual units are finished goods (i.e., a crayon or marker is completely manufactured once it comes off the line). The same is true for marker barrels, paint pots, and other plastics. Specialized equipment is used to make these items, which feed downstream production.

Recently, Crayola's leadership expected that actual demand for its popular Marker Maker© toy product might come in higher than the original forecast. As a countermeasure, Crayola established duplicate capacities in China and the United States to meet the aggregate potential demand. In China, the company produced the original forecast and delivered to customers as planned. However, when the actual demand was 26 percent over the original forecast, Crayola could meet the surge in demand because it had positioned the long lead time ink bottles in its Pennsylvania plants and was able to mold the plastic parts using marker components from its core marker product. By utilizing existing machine capacity in its plants, reducing the lead time of ink bottles by making them in Pennsylvania, and by duplicating tooling, Crayola was able to ensure that its customers and consumers were satisfied during the holiday season.

QUESTIONS

1. Consider the pressures for small versus large inventories. Which situation does Crayola seem to fit, and why?
2. Explain how both independent and dependent demand items are present at Crayola.
3. The Marker Maker© product recently experienced an unexpected surge in demand and the supply chain's agility was credited with helping to meet the crisis. We have discussed four ways to classify operational inventories by how they are created. Regarding the ways managers can use these inventories to satisfy demand, explain how Crayola can achieve the flexibility to adjust to unexpected demand surges.

SUPPLEMENT

C

SPECIAL INVENTORY MODELS

LEARNING OBJECTIVES *After reading this supplement, you should be able to:*

C.1 Calculate the optimal lot size when replenishment is not instantaneous.

C.2 Determine the optimal order quantity when materials are subject to quantity discounts.

C.3 Calculate the order quantity that maximizes the expected profits for a one-period inventory decision.

Many real-world problems require relaxation of certain assumptions on which the economic order quantity (EOQ) model is based. This supplement addresses three realistic situations that require going beyond the simple EOQ formulation.

1. *Noninstantaneous Replenishment.* Particularly in situations in which manufacturers use a continuous process to make a primary material, such as a liquid, gas, or powder, production is not instantaneous. Thus, inventory is replenished gradually, rather than in lots.
2. *Quantity Discounts.* Three annual costs are (1) the inventory holding cost, (2) the fixed cost for ordering and setup, and (3) the cost of materials. For service providers and for manufacturers alike, the unit cost of purchased materials sometimes depends on the size of the order quantity.
3. *One-Period Decisions.* Retailers and manufacturers of fashion goods often face a situation in which demand is uncertain and occurs during just one period or season.

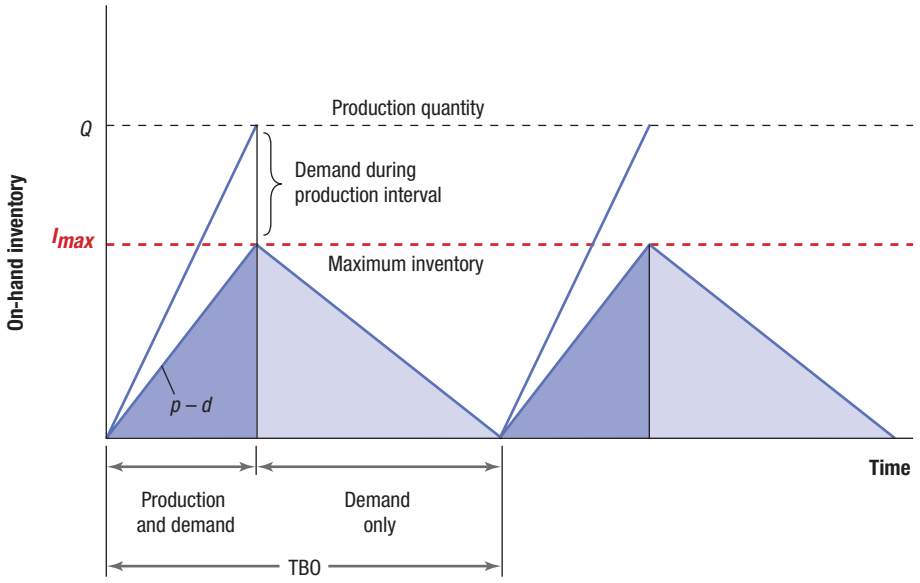
This supplement assumes you have read Chapter 9, "Inventory Management," and Supplement A, "Decision Making."

Noninstantaneous Replenishment

If an item is being produced internally rather than purchased, finished units may be used or sold as soon as they are completed, without waiting until a full lot is completed. For example, a restaurant that bakes its own dinner rolls begins to use some of the rolls from the first pan even before the baker finishes a five-pan batch. The inventory of rolls never reaches the full five-pan level, the way it would if the rolls all arrived at once on a truck sent by a supplier.

Figure C.1 depicts the usual case, in which the production rate, p, *exceeds* the demand rate, d. If demand and production were equal, manufacturing would be continuous with no buildup of cycle inventory. If the production rate is lower than the demand rate, sales opportunities are being missed on an ongoing basis. We assume that $p > d$ in this supplement.

FIGURE C.1 ▶
Lot Sizing with Noninstantaneous Replenishment



Cycle inventory accumulates faster than demand occurs; that is, a buildup of $p - d$ units occurs per time period. For example, if the production rate is 100 units per day and the daily demand is 5 units, the buildup is 95 (or 100 − 5) units each day. This buildup continues until the lot size, Q, has been produced, after which the inventory depletes at a rate of 5 units per day. Just as the inventory reaches 0, the next production interval begins. To be consistent, both p and d must be expressed in units of the same time period, such as units per day or units per week. Here, we assume that they are expressed in units per day.



Tjeerd Kruse/Alamy Stock Photo

This oil refinery stores its product in fixed capacity storage tanks. The next production run of a product is scheduled when the tanks in which it is stored are nearly empty.

The $p - d$ buildup continues for Q/p days, because Q is the lot size and p units are produced each day. In our example, if the lot size is 300 units, the production interval is 3 days (300/100). For the given rate of buildup over the production interval, the maximum cycle inventory, $I_{\max}$, is

$$I_{\max} = \frac{Q}{p}(p - d) = Q\left(\frac{p - d}{p}\right)$$

Cycle inventory is no longer $Q/2$, as it was with the basic EOQ method; instead, it is $I_{\max}/2$. Setting up the total annual cost equation for this production situation, where D is annual demand, and as before d is daily demand, we get

$$\text{Total annual cost} = \text{Annual holding cost} + \text{Annual ordering or setup cost}$$

$$C = \frac{I_{\max}}{2}(H) + \frac{D}{Q}(S) = \frac{Q}{2}\left(\frac{p - d}{p}\right)(H) + \frac{D}{Q}(S)$$

economic production lot size (ELS)
The optimal lot size in a situation in which replenishment is not instantaneous.

Based on this cost function, the optimal lot size, often called the **economic production lot size (ELS)**, is

$$\text{ELS} = \sqrt{\frac{2DS}{H}}\sqrt{\frac{p}{p - d}}$$

Because the second term is a ratio greater than 1, the ELS results in a larger lot size than the EOQ.

EXAMPLE C.1 Finding the Economic Production Lot Size

A plant manager of a chemical plant must determine the lot size for a particular chemical that has a steady demand of 30 barrels per day. The production rate is 190 barrels per day, annual demand is 10,500 barrels, setup cost is $200, annual holding cost is $0.21 per barrel, and the plant operates 350 days per year.

a. Determine the economic production lot size (ELS).

b. Determine the total annual setup and inventory holding cost for this item.

c. Determine the time between orders (TBO), or cycle length, for the ELS.

d. Determine the production time per lot.

What are the advantages of reducing the setup time by 10 percent?

Online Resources

Tutor C.1 in OM Explorer provides a new example to determine the ELS.

Active Model C.1 provides additional insight on the ELS model and its uses.

SOLUTION

a. Solving first for the ELS, we get

$$\text{ELS} = \sqrt{\frac{2DS}{H}}\sqrt{\frac{p}{p-d}} = \sqrt{\frac{2(10{,}500)(\$200)}{\$0.21}}\sqrt{\frac{190}{190-30}}$$
$$= 4{,}873.4 \text{ barrels}$$

b. The total annual cost with the ELS is

$$C = \frac{Q}{2}\left(\frac{p-d}{p}\right)(H) + \frac{D}{Q}(S)$$
$$= \frac{4{,}873.4}{2}\left(\frac{190-30}{190}\right)(\$0.21) + \frac{10{,}500}{4{,}873.4}(\$200)$$
$$= \$430.91 + \$430.91 = \$861.82$$

c. Applying the TBO formula to the ELS, we get

$$\text{TBO}_{\text{ELS}} = \frac{\text{ELS}}{D}(350 \text{ days/year}) = \frac{4{,}873.4}{10{,}500}(350)$$
$$= 162.4, \text{ or } 162 \text{ days}$$

d. The production time during each cycle is the lot size divided by the production rate:

$$\frac{\text{ELS}}{p} = \frac{4{,}873.4}{190} = 25.6, \text{ or } 26 \text{ days}$$

DECISION POINT

As OM Explorer shows in Figure C.2, the net effect of reducing the setup cost by 10 percent is to reduce the lot size, the time between orders, and the production cycle time. Consequently, total annual costs are also reduced. This adds flexibility to the manufacturing process because items can be made more quickly with less expense. Management must decide whether the added cost of improving the setup process is worth the added flexibility and inventory cost reductions.

Period Used in Calculations	Day
Demand per Day	30
Production Rate/Day	190
Annual Demand	10,500
Setup Cost	$180
Annual Holding Cost ($)	$0.21
Operating Days per Year	350
Economic Lot Size (ELS)	4,623
Annual Total Cost	$817.60
Time Between Orders (days)	154.1
Production Time	24.3

(◉) Enter Holding Cost Manually ( ) Holding Cost As % of Value

◀ **FIGURE C.2**
OM Explorer Solver for the Economic Production Lot Size Showing the Effect of a 10 Percent Reduction in Setup Cost



Rafal Rodzoch/caia image/Alamy Stock Photo

Many hospitals join cooperatives (or co-ops) to gain the clout needed to garner price discounts from suppliers. Here a hospital pharmacist checks inventory records of supplies in preparation for placing an order.

Quantity Discounts

Quantity discounts, which are price incentives to purchase large quantities, create pressure to maintain a large inventory. For example, a supplier may offer a price of $4.00 per unit for orders between 1 and 99 units, a price of $3.50 per unit for orders between 100 and 199 units, and a price of $3.00 per unit for orders of 200 or more units. The item's price is no longer fixed, as assumed in the EOQ derivation; instead, if the order quantity is increased enough, the price is discounted. Hence, a new approach is needed to find the best lot size—one that balances the advantages of lower prices for purchased materials and fewer orders (which are benefits of large order quantities) against the disadvantage of the increased cost of holding more inventory.

The total annual cost now includes not only the holding cost, $(Q/2)(H)$, and the ordering cost, $(D/Q)(S)$, but also the cost of purchased materials. For any per-unit price level, P, the total cost is

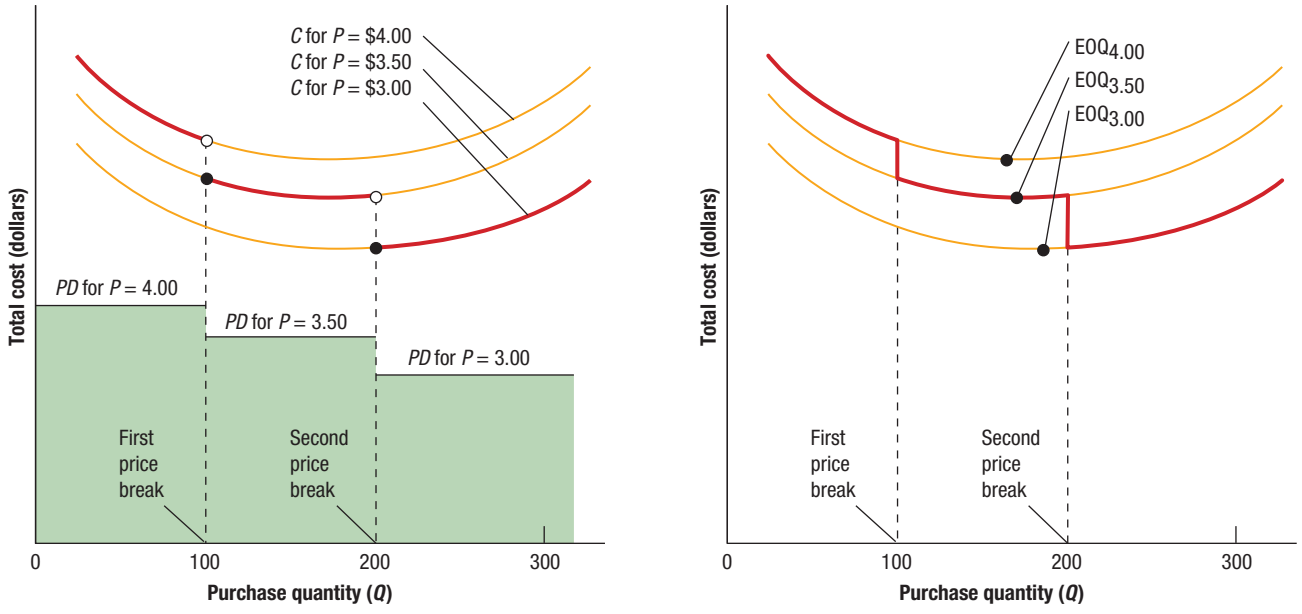
$$\text{Total annual cost} = \text{Annual holding cost} + \text{Annual ordering or setup cost} + \text{Annual cost of materials}$$

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S) + PD$$

The unit holding cost, H, usually is expressed as a percent of the unit price because the more valuable the item held in inventory, the higher is the holding cost. Thus, the lower the unit price, P, the lower is H. Conversely, the higher P is, the higher is H.

The total cost equation yields U-shaped total cost curves. Adding the annual cost of materials to the total cost equation raises each total cost curve by a fixed amount, as shown in Figure C.3(a). The three cost curves illustrate each of the price levels. The top curve applies when no discounts are received; the lower curves reflect the discounted price levels. No single curve is relevant to all purchase quantities. The relevant, or feasible, total cost begins with the top curve, then drops down, curve by curve, at the price breaks. A price break is the minimum quantity needed to get a discount. In Figure C.3(a), two price breaks occur at $Q = 100$ and $Q = 200$. The result is a total cost curve, with steps at the price breaks.

▼ **FIGURE C.3**
Total Cost Curves with Quantity Discounts



(a) Total cost curves with purchased materials added

(b) EOQs and price break quantities

Figure C.3(b) also shows three additional points—the minimum point on each curve—obtained with the EOQ formula at each price level. These EOQs do not necessarily produce the best lot size for two reasons.

1. The EOQ at a particular price level may not be feasible. The lot size may not lie in the range corresponding to its per-unit price. Figure C.3(b) illustrates two instances of an infeasible EOQ. First, the minimum point for the $3.00 curve appears to be fewer than 200 units. However, the supplier's quantity discount schedule does not allow purchases of that small a quantity at the $3.00 unit price. Similarly, the EOQ for the $4.00 price level is greater than the first price break, so the price charged would be only $3.50.
2. The EOQ at a particular price level may be feasible but may not be the best lot size. The feasible EOQ may have a higher cost than is achieved by the EOQ or price break quantity on a lower price curve. In Figure C.3(b), for example, the 200-unit price break quantity for the $3.00 price level has a lower total cost than the feasible EOQ for the $3.50 price level. A feasible EOQ is always better than any feasible point on cost curves with higher price levels, but not necessarily those with lower levels. Thus, the only time we can immediately conclude, without comparing total costs, that a feasible EOQ is the best order quantity is when it is on the curve for the lowest price level. This conclusion is not possible in Figure C.3(b) because the only feasible EOQ is at the middle price level, $P = \$3.50$.

We must, therefore, pay attention only to feasible price–quantity combinations, shown as solid lines in Figure C.3(b), as we search for the best lot size. The following two-step procedure may be used to find the best lot size.

Step 1. Beginning with the lowest price, calculate the EOQ for each price level until a feasible EOQ is found. It is feasible if it lies in the range corresponding to its price. Each subsequent EOQ is smaller than the previous one because P, and thus H, gets larger and because the larger H is in the denominator of the EOQ formula.

Step 2. If the first feasible EOQ found is for the lowest price level, this quantity is the best lot size. Otherwise, calculate the total cost for the first feasible EOQ and for the larger price break quantity at each lower price level. The quantity with the lowest total cost is optimal.

EXAMPLE C.2 Finding Q with Quantity Discounts at St. LeRoy Hospital

A supplier for St. LeRoy Hospital has introduced quantity discounts to encourage larger order quantities of a special catheter. The price schedule is

Order Quantity	Price per Unit
0 to 299	$60.00
300 to 499	$58.80
500 or more	$57.00

The hospital estimates that its annual demand for this item is 936 units, its ordering cost is $45.00 per order, and its annual holding cost is 25 percent of the catheter's unit price. What quantity of this catheter should the hospital order to minimize total costs? Suppose the price for quantities between 300 and 499 is reduced to $58.00. Should the order quantity change?

Online Resources

Tutor C.2 in OM Explorer provides a new example for choosing the best order quantity when discounts are available.

Active Model C.2 provides additional insight on the quantity discount model and its uses.

SOLUTION

Step 1. Find the first feasible EOQ, starting with the lowest price level:

$$EOQ_{57.00} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(936)(\$45.00)}{0.25(\$57.00)}} = 77 \text{ units}$$

A 77-unit order actually costs $60.00 per unit, instead of the $57.00 per unit used in the EOQ calculation, so this EOQ is infeasible. Now, try the $58.80 level:

$$EOQ_{58.80} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(936)(\$45.00)}{0.25(\$58.80)}} = 76 \text{ units}$$

This quantity also is infeasible because a 76-unit order is too small to qualify for the $58.80 price. Try the highest price level:

$$EOQ_{60.00} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(936)(45.00)}{0.25(60.00)}} = 75 \text{ units}$$

This quantity is feasible because it lies in the range corresponding to its price, $P = \$60.00$.

Step 2. The first feasible EOQ of 75 does not correspond to the lowest price level. Hence, we must compare its total cost with the price break quantities (300 and 500 units) at the lower price levels ($58.80 and $57.00):

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S) + \text{PD}$$

$$C_{75} = \frac{75}{2}[(0.25)(\$60.00)] + \frac{936}{75}(\$45.00) + \$60.00\,(936) = \$57{,}284$$

$$C_{300} = \frac{300}{2}[(0.25)(\$58.80)] + \frac{936}{300}(\$45.00) + \$58.80\,(936) = \$57{,}382$$

$$C_{500} = \frac{500}{2}[(0.25)(\$57.00)] + \frac{936}{500}(\$45.00) + \$57.00\,(936) = \$56{,}999$$

The best purchase quantity is 500 units, which qualifies for the deepest discount.

DECISION POINT

If the price per unit for the range of 300 to 499 units is reduced to $58.00, the best decision is to order 300 catheters, as shown by OM Explorer in Figure C.4. This result shows that the decision is sensitive to the price schedule. A reduction of slightly more than 1 percent is enough to make the difference in this example. In general, however, it is not always the case that you should order more than the economic order quantity when given price discounts. When discounts are small, holding cost H is large, and demand D is small, small lot sizes are better even though price discounts are foregone.

FIGURE C.4 ▶
OM Explorer Solver for Quantity Discounts Showing the Best Order Quantity

More | Fewer

Min. Amount Req'd for Price Point	Lot Sizes	Price/Unit
	0–299	$60.00
300	300–499	$58.00
500	500 or more	$57.00

Annual Demand	936
Order Cost	$45
Holding Cost (% or price)	25%
Best Order Quantity	300

	Price Point	EOQ or Req'd Order for Price Point	Inventory Cost	Order Cost	Purchase Cost	Total Cost	
	$60.00	75	$562.50	$561.60	$56,160	$57,284	
>>	$58.00	300	$2,175	$140.40	$54,288	$56,603	<<
	$57.00	500	$3,563	$84.24	$53,352	$56,999	

One-Period Decisions

One of the dilemmas facing many retailers is how to handle seasonal goods, such as winter coats. Often, they cannot be sold at full markup the next year because of changes in styles. Furthermore, the lead time can be longer than the selling season, allowing no second chance to rush through another order to cover unexpectedly high demand. A similar problem exists for manufacturers of other fashion goods.

This type of situation is often called the *newsboy problem*. If the newspaper seller does not buy enough newspapers to resell on the street corner, sales opportunities are lost. If the seller buys too many newspapers, the overage cannot be sold because nobody wants yesterday's newspaper.

The following process is a straightforward way to analyze such problems and decide on the best order quantity.

1. List the different levels of demand that are possible, along with the estimated probability of each.
2. Develop a *payoff* table that shows the profit for each purchase quantity, Q, at each assumed demand level, D. Each row in the table represents a different order quantity, and each column represents a different demand level. The payoff for a given quantity–demand combination depends on whether all units are sold at the regular profit margin during the regular season, which results in two possible cases.
   - **a.** If demand is high enough ($Q \leq D$), then all units are sold at the full profit margin, p, during the regular season,
   $$\text{Payoff} = (\text{Profit per unit})(\text{Purchase quantity}) = pQ$$
   - **b.** If the purchase quantity exceeds the eventual demand ($Q > D$), only D units are sold at the full profit margin, and the remaining units purchased must be disposed of at a loss, ℓ, after the season. In this case,
   $$\text{Payoff} = \begin{pmatrix}\text{Profit per unit sold}\\ \text{during season}\end{pmatrix}(\text{Demand}) - \begin{pmatrix}\text{Loss per}\\ \text{unit}\end{pmatrix}\begin{pmatrix}\text{Amount disposed of}\\ \text{after season}\end{pmatrix}$$
   $$= pD - \ell(Q - D)$$
3. Calculate the expected payoff for each Q (or row in the payoff table) by using the *expected value* decision rule. For a specific Q, first multiply each payoff in the row by the demand probability associated with the payoff, and then add these products.
4. Choose the order quantity Q with the highest expected payoff.

Using this decision process for all such items over many selling seasons will maximize profits. However, it is not foolproof, and it can result in an occasional bad outcome.

EXAMPLE C.3 Finding Q for One-Period Inventory Decisions

One of many items sold at a museum of natural history is a Christmas ornament carved from wood. The gift shop makes a $10 profit per unit sold during the season, but it takes a $5 loss per unit after the season is over. The following discrete probability distribution for the season's demand has been identified:

Demand	10	20	30	40	50
Demand Probability	0.2	0.3	0.3	0.1	0.1

How many ornaments should the museum's buyer order?

Online Resources

Tutor C.3 in OM Explorer provides a new example to practice the one-period inventory decision.

Active Model C.3 provides additional insight on the one-period inventory decision model and its uses.

SOLUTION

Each demand level is a candidate for best order quantity, so the payoff table should have five rows. For the first row, where $Q = 10$, demand is at least as great as the purchase quantity. Thus, all five payoffs in this row are

$$\text{Payoff} = pQ = (\$10)(10) = \$100$$

This formula can be used in other rows but only for those quantity–demand combinations where all units are sold during the season. These combinations lie in the upper-right portion of the payoff table, where $Q \leq D$. For example, the payoff when $Q = 40$ and $D = 50$ is

$$\text{Payoff} = pQ = (\$10)(40) = \$400$$

The payoffs in the lower-left portion of the table represent quantity–demand combinations where some units must be disposed of after the season ($Q > D$). For this case, the payoff must be calculated with the second formula. For example, when $Q = 40$ and $D = 30$,

$$\text{Payoff} = pD - \ell(Q - D) = (\$10)(30) - (\$5)(40 - 30) = \$250$$

OM Explorer or POM for Windows can be used to analyze this problem. Using OM Explorer, we obtain the payoff table in Figure C.5.

FIGURE C.5 ▶
OM Explorer Solver for One-Period Inventory Decisions Showing the Payoff Table

Profit	$10.00	(if sold during preferred period)
Loss	$5.00	(if sold after preferred period)

Enter the possible demands along with the probability of each occurring. Use the buttons to increase or decrease the number of allowable demand forecasts. NOTE: Be sure to enter demand forecasts and probabilities in all tinted cells, and be sure probabilities add up to 1.

< >

Demand	10	20	30	40	50
Profitability	0.2	0.3	0.3	0.1	0.1

Payoff Table

		Demand				
		10	20	30	40	50
Quantity	10	100	100	100	100	100
	20	50	200	200	200	200
	30	0	150	300	300	300
	40	–50	100	250	400	400
	50	–100	50	200	350	500

Now we calculate the expected payoff for each Q by multiplying the payoff for each demand quantity by the probability of that demand and then adding the results. For example, for $Q = 30$,

$$\text{Payoff} = 0.2(\$0) + 0.3(\$150) + 0.3(\$300) + 0.1(\$300) + 0.1(\$300) = \$195$$

Using OM Explorer, Figure C.6 shows the expected payoffs.

DECISION POINT

Because $Q = 30$ has the highest payoff at $195, it is the best order quantity. Management can use OM Explorer or POM for Windows to do sensitivity analysis on the demands and their probabilities to see how confident they are with that decision.

FIGURE C.6 ▶
OM Explorer Solver Showing the Expected Payoffs for One-Period Inventory Decisions

Weighted Payoffs

Order Quantity	Expected Payoff
10	100
20	170
30	195
40	175
50	140

Greatest Expected Payoff	195
Associated with Order Quantity	30

The need for one-time inventory decisions also can arise in manufacturing plants when (1) customized items are made (or purchased) to a single order and (2) scrap quantities are high. A customized item produced for a single order is never intentionally held in stock because the demand for it is too unpredictable. In fact, it may never be ordered again, so the manufacturer would like to make just the amount requested by the customer—no more, no less. The manufacturer also would like to satisfy an order in just one run to avoid an extra setup and a delay in delivering goods ordered. These two goals may conflict if the likelihood of some units being scrapped is high. Suppose that a customer places an order for 20 units. If the manager orders 20 units from the shop or from the supplier, one or two units may have to be scrapped. This shortage will force the manager to place a second (or even third) order to replace the defective units. Replacement can be costly if setup time is high and can also delay shipment to the customer. To avoid such problems, the manager could order more than 20 units the first time. If some units are left over, the customer might be willing to buy the extras or the manager might find an internal use for them. For example, some manufacturing companies set up a special account for obsolete materials. These materials can be "bought" by departments within the company at less than their normal cost, as an incentive to use them.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines	Online Resources
C.1 Calculate the optimal lot size when replenishment is not instantaneous.	See the section "Noninstantaneous Replenishment." Study Example C.1 and Solved Problem 1 for help on determining the ELS.	**Active Model:** C.1: Economic Production Lot Size **OM Explorer Solver:** Economic Production Lot Size **OM Explorer Tutor:** C.1: Economic Production Lot Size **POM for Windows:** Economic Production Lot Size
C.2 Determine the optimal order quantity when materials are subject to quantity discounts.	See the section "Quantity Discounts." Study Example C.2 and Solved Problem 2 for a step-by-step approach to determine the best order quantity.	**Active Model:** C.2: Quantity Discounts **OM Explorer Solver:** Quantity Discounts **OM Explorer Tutor:** C.2: Finding Q with Quantity Discounts **POM for Windows:** Quantity Discount Model
C.3 Calculate the order quantity that maximizes the expected profits for a one-period inventory decision.	See the section "One-Period Decisions." Be sure to understand Example C.3 and Solved Problem 3.	**Active Model:** C.3: One-Time Inventory Decisions **OM Explorer Solver:** One-Period Inventory Decisions **OM Explorer Tutor:** C.3: One-Period Inventory Decisions **POM for Windows:** Decision Tables

Key Equations

Noninstantaneous Replenishment

1. Maximum cycle inventory: $I_{\max} = Q\left(\frac{p-d}{p}\right)$
2. Total annual cost = Annual holding cost + Annual ordering or setup cost

$$C = \frac{Q}{2}\left(\frac{p-d}{p}\right)(H) + \frac{D}{Q}(S)$$

3. Economic production lot size: $\text{ELS} = \sqrt{\frac{2DS}{H}}\sqrt{\frac{p}{p-d}}$
4. Time between orders, expressed in years: $\text{TBO}_{\text{ELS}} = \frac{\text{ELS}}{D}$

Quantity Discounts

5. Total annual cost = Annual holding cost + Annual ordering or setup cost + Annual cost of material

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S) + PD$$

One-Period Decisions

6. Payoff matrix: $\text{Payoff} = \begin{cases} pQ & \text{if } Q \le D \\ pD - \ell(Q-D) & \text{if } Q > D \end{cases}$

Key Term

economic production lot size (ELS) 402

Solved Problem 1

Peachy Keen, Inc., makes mohair sweaters, blouses with Peter Pan collars, pedal pushers, poodle skirts, and other popular clothing styles of the 1950s. The average demand for mohair sweaters is 100 per week. Peachy's production facility has the capacity to sew 400 sweaters per week. Setup cost is $351. The value of finished goods inventory is $40 per sweater. The annual per-unit inventory holding cost is 20 percent of the item's value.

a. What is the economic production lot size (ELS)?
b. What is the average time between orders (TBO)?
c. What is the total of the annual holding cost and setup cost?

SOLUTION

a. The production lot size that minimizes total cost is

$$\text{ELS} = \sqrt{\frac{2DS}{H}}\sqrt{\frac{p}{p-d}} = \sqrt{\frac{2(100 \times 52)(\$351)}{0.20(\$40)}}\sqrt{\frac{400}{(400-100)}}$$

$$= \sqrt{456{,}300}\sqrt{\frac{4}{3}} = 780 \text{ sweaters}$$

b. The average time between orders is

$$\text{TBO}_{\text{ELS}} = \frac{\text{ELS}}{D} = \frac{780}{5{,}200} = 0.15 \text{ year}$$

Converting to weeks, we get

$$\text{TBO}_{\text{ELS}} = (0.15 \text{ year})(52 \text{ weeks/year}) = 7.8 \text{ weeks}$$

c. The minimum total of setup and holding costs is

$$C = \frac{Q}{2}\left(\frac{p-d}{p}\right)(H) + \frac{D}{Q}(S) = \frac{780}{2}\left(\frac{400-100}{400}\right)(0.20 \times \$40) + \frac{5{,}200}{780}(\$351)$$

$$= \$2{,}340/\text{year} + \$2{,}340/\text{year} = \$4{,}680/\text{year}$$

Solved Problem 2

A hospital buys disposable surgical packages from Pfisher, Inc. Pfisher's price schedule is $50.25 per package on orders of 1 to 199 packages and $49.00 per package on orders of 200 or more packages. Ordering cost is $64 per order, and annual holding cost is 20 percent of the per-unit purchase price. Annual demand is 490 packages. What is the best purchase quantity?

SOLUTION

We first calculate the EOQ at the *lowest* price:

$$EOQ_{49.00} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(490)(\$64.00)}{0.20(\$49.00)}} = \sqrt{6{,}400} = 80 \text{ packages}$$

This solution is infeasible because, according to the price schedule, we cannot purchase 80 packages at a price of $49.00 each. Therefore, we calculate the EOQ at the next lowest price ($50.25):

$$EOQ_{50.25} = \sqrt{\frac{2DS}{H}} = \sqrt{\frac{2(490)(\$64.00)}{0.20(\$50.25)}} = \sqrt{6{,}241} = 79 \text{ packages}$$

This EOQ is feasible, but $50.25 per package is not the lowest price. Hence, we have to determine whether total costs can be reduced by purchasing 200 units and thereby obtaining a quantity discount.

$$C = \frac{Q}{2}(H) + \frac{D}{Q}(S) + PD$$

$$C_{79} = \frac{79}{2}(0.20 \times \$50.25) + \frac{490}{79}(\$64.00) + \$50.25(490)$$

$$= \$396.98/\text{year} + \$396.68/\text{year} + \$24{,}622.50/\text{year} = 25{,}416.44/\text{year}$$

$$C_{200} = \frac{200}{2}(0.20 \times \$49.00) + \frac{490}{200}(\$64.00) + \$49.00(490)$$

$$= \$980.00/\text{year} + \$156.80/\text{year} + \$24{,}010.00/\text{year} = \$25{,}146.80/\text{year}$$

Purchasing 200 units per order will save \$269.64/year, compared to buying 79 units at a time.

Solved Problem 3

Swell Productions is sponsoring an outdoor conclave for owners of collectible and classic Fords. The concession stand in the T-Bird area will sell clothing such as T-shirts and official Thunderbird racing jerseys. Jerseys are purchased from Columbia Products for \$40 each and are sold during the event for \$75 each. If any jerseys are left over, they can be returned to Columbia for a refund of \$30 each. Jersey sales depend on the weather, attendance, and other variables. The following table shows the probability of various sales quantities. How many jerseys should Swell Productions order from Columbia for this one-time event?

Sales Quantity	Probability	Quantity Sales	Probability
100	0.05	400	0.34
200	0.11	500	0.11
300	0.34	600	0.05

SOLUTION

Table C.1 is the payoff table that describes this one-period inventory decision. The upper-right portion of the table shows the payoffs when the demand, D, is greater than or equal to the order quantity, Q. The payoff is equal to the per-unit profit (the difference between price and cost) multiplied by the order quantity—for example, when the order quantity is 100 and the demand is 200.

$$\text{Payoff} = (p - c)Q = (\$75 - \$40)100 = \$3{,}500$$

The lower-left portion of Table C.1 shows the payoffs when the order quantity exceeds the demand. Here the payoff is the profit from sales, pD, minus the loss associated with returning overstock, $\ell(Q - D)$, where ℓ is the difference between the cost and the amount refunded for each jersey returned and $Q - D$ is the number of jerseys returned. For example, when the order quantity is 500 and the demand is 200,

$$\text{Payoff} = pD - \ell(Q - D) = (\$75 - \$40)200 - (\$40 - \$30)(500 - 200) = \$4{,}000$$

The highest expected payoff occurs when 400 jerseys are ordered:

$$\begin{aligned}\text{Expected payoff}_{400} &= (\$500 \times 0.05) + (\$5{,}000 \times 0.11) + (\$9{,}500 \times 0.34) \\ &\quad + (\$14{,}000 \times 0.34) + (\$14{,}000 \times 0.11) + (\$14{,}000 \times 0.05) \\ &= \$10{,}805\end{aligned}$$

TABLE C.1 | PAYOFFS

	DEMAND, *D*						
Q	100	200	300	400	500	600	Expected Payoff
100	\$3,500	\$3,500	\$3,500	\$3,500	\$3,500	\$ 3,500	\$ 3,500
200	\$2,500	\$7,000	\$7,000	\$7,000	\$7,000	\$ 7,000	\$ 6,775
300	\$1,500	\$6,000	\$10,500	\$10,500	\$10,500	\$10,500	\$ 9,555
400	\$ 500	\$5,000	\$ 9,500	\$14,000	\$14,000	\$14,000	\$10,805
500	(\$ 500)	\$4,000	\$ 8,500	\$13,000	\$17,500	\$17,500	\$10,525
600	(\$1,500)	\$3,000	\$ 7,500	\$12,000	\$16,500	\$21,000	\$ 9,750

Problems

The OM Explorer, POM for Windows, and Active Models software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download the software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations. The software also can be a valuable resource well after your course is completed.

Noninstantaneous Replenishment

1. Bold Vision, Inc., makes laser printer and photocopier toner cartridges. The demand rate is 625 EP cartridges per week. The production rate is 1,736 EP cartridges per week, and the setup cost is $100. The value of inventory is $130 per unit, and the holding cost is 20 percent of the inventory value. Bold Vision operates 52 weeks a year. What is the economic production lot size?
2. Sharpe Cutter is a small company that produces specialty knives for paper cutting machinery. The annual demand for a particular type of knife is 100,000 units. The demand is uniform over the 250 working days in a year. Sharpe Cutter produces this type of knife in lots and, on average, can produce 450 knives a day. The cost to set up a production lot is $300, and the annual holding cost is $1.20 per knife.
   a. Determine the economic production lot size (ELS).
   b. Determine the total annual setup and inventory holding cost for this item.
   c. Determine the TBO, or cycle length, for the ELS.
   d. Determine the production time per lot.
3. Suds's Bottling Company does bottling, labeling, and distribution work for several local microbreweries. The demand rate for Wortman's beer is 600 cases (24 bottles each) per week. Suds's bottling production rate is 2,400 cases per week, and the setup cost is $800. The value of inventory is $12.50 per case, and the annual holding cost is 30 percent of the inventory value. Suds's facilities operate 52 weeks each year. What is the economic production lot size?
4. One-Eyed Toad Pottery makes custom planters for upscale clients. The average demand for planters is 20 per week. One-Eyed Toad's production facility has the capacity to make 25 planters per week. Setup cost is $1,500. The value of finished goods inventory is $250 per planter. The annual per-unit inventory holding cost is 35 percent of the item's value.
   a. What is the economic production lot size (ELS)?
   b. What is the average time between orders (TBO)?
   c. What is the total of the annual holding cost and setup cost?

Quantity Discounts

5. The Bucks Grande exhibition baseball team plays 50 weeks each year and uses an average of 350 baseballs per week. The team orders baseballs from Coopers-Town, Inc., a ball manufacturer noted for Six Sigma–level consistency and high product quality. The cost to order baseballs is $100 per order and the annual holding cost per ball is 38 percent of the purchase price. Coopers-Town's price structure is:

Order Quantity	Price per Unit
1–999	$7.50
1,000–4,999	$7.25
5,000 or more	$6.50

   a. How many baseballs should the team buy per order?
   b. What is the total annual cost associated with the best order quantity?
   c. Coopers-Town, Inc. discovers that, owing to special manufacturing processes required for the Buck's baseballs, it has underestimated the setup time required on a capacity-constrained piece of machinery. Coopers-Town adds another category to the price structure to provide an incentive for larger orders and thereby hopes to reduce the number of setups required. If the Bucks buy 15,000 baseballs or more, the price will drop to $6.25 each. Should the Bucks revise their order quantity?
6. To boost sales, Pfisher (refer to Solved Problem 2) announces a new price structure for disposable surgical packages. Although the price break no longer is available at 200 units, Pfisher now offers an even greater discount if larger quantities are purchased. On orders of 1 to 499 packages, the price is $50.25 per package. For orders of 500 or more, the price per unit is $47.80. Ordering costs, annual holding costs, and annual demand remain at $64 per order, 20 percent of the per-unit cost, and 490 packages per year, respectively. What is the new lot size?
7. The University Bookstore at a prestigious private university buys mechanical pencils from a wholesaler. The wholesaler offers discounts for large orders according to the following price schedule:

Order Quantity	Price per Unit
0 to 200	$4.00
201 to 2,000	$3.50
2,001 or more	$3.25

The bookstore expects an annual demand of 2,500 units. It costs $10 to place an order, and the annual cost of holding a unit in stock is 30 percent of the unit's price. Determine the best order quantity.

8. Mac-in-the-Box, Inc., sells computer equipment by mail and telephone order. Mac sells 1,200 flat-bed scanners per year. Ordering cost is $300, and annual holding cost is 16 percent of the item's price. The scanner manufacturer offers the following price structure to Mac-in-the-Box:

Order Quantity	Price per Unit
0 to 11	$520
12 to 143	$500
144 or more	$400

What order quantity minimizes total annual costs?

9. As inventory manager, you must decide on the order quantity for an item that has an annual demand of 2,000 units. Placing an order costs you $20 each time. Your annual holding cost, expressed as a percentage of average inventory value, is 20 percent. Your supplier has provided the following price schedule.

Minimum Order Quantity	Price per Unit
1	$2.50
200	$2.40
300	$2.25
1,000	$2.00

What ordering policy do you recommend?

10. Bold Vision, Inc. (from Problem 1), must purchase toner from a local supplier. The company does not wish to carry raw material inventory and therefore purchases only enough toner to satisfy the demand of each individual batch of cartridges. Each toner cartridge requires one pound of toner. The raw material supplier offers Bold Vision a purchase discount of $2.00 per pound if the company orders at least 2,000 pounds at a time. Should Bold Vision accept this offer and alter its toner purchase quantity?

One-Period Decisions

11. Downtown Health Clinic needs to order influenza vaccines for the next flu season. The clinic charges its patients $15.00 per vaccination and each dose of vaccine costs the clinic $4.00 to purchase. The Centers for Disease Control has a long-standing policy of buying back unused vaccines for $1.00 per dose. The clinic estimates the following probability distribution for the season's demand.

Demand	Probability
2,000	0.05
3,000	0.20
4,000	0.25
5,000	0.40
6,000	0.10

a. How many vaccines should the clinic order to maximize its expected profit?

b. The clinic is trying to determine if it should participate in a new federal program in which the cost of each dose is reduced to $2.00. However, to participate in the program, the clinic can charge no more than $10.00 per vaccine. On strictly a profit-maximizing basis, should the clinic agree to participate?

12. Dorothy's pastries are freshly baked and sold at several specialty shops throughout Perth. When they are a day old, they must be sold at reduced prices. Daily demand is distributed as follows:

Demand	Probability
50	0.25
150	0.50
200	0.25

Each pastry sells for $1.00 and costs $0.60 to make. Each one not sold at the end of the day can be sold the next day for $0.30 as day-old merchandise. How many pastries should be baked each day?

13. The Aggies will host Tech in this year's homecoming football game. Based on advance ticket sales, the athletic department has forecast hot dog sales as shown in the following table. The school buys premium hot dogs for $1.50 and sells them during the game at $3.00 each. Hot dogs left over after the game will be sold for $0.50 each to the Aggie student cafeteria, where they will be used in making hotdog casserole.

Sales Quantity	Probability
2,000	0.10
3,000	0.30
4,000	0.30
5,000	0.20
6,000	0.10

Use a payoff matrix to determine the number of hot dogs to buy for the game.

14. The Lake Sharkey BBQ Pit serves slow cooked beef brisket by the pound. Based on historical sales during the Labor Day weekend, management has forecasted brisket sales in pounds as shown in the following table. Lake Sharkey spends $14 to produce each pound of brisket for which it charges $23 per pound. Any unsold brisket at the end of the weekend is ground into chili, which sells for $12 per pound. How many pounds of brisket should the Lake Sharkey BBQ Pit prepare for sale this Labor Day?

Demand in Pounds	Probability
500	0.10
1000	0.40
1500	0.30
2000	0.15
2500	0.05

10

OPERATIONS PLANNING AND SCHEDULING

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

10.1 Explain the rationale behind the levels in the operations planning and scheduling process.

10.2 Describe the supply options used in sales and operations planning.

10.3 Compare the chase planning strategy to the level planning strategy for developing sales and operations plans.

10.4 Use spreadsheets for sales and operations planning.

10.5 Develop workforce and workstation schedules.

Cooper Tire and Rubber Company



Mark Bullimore Photography/Alamy Stock Photo

In 1997 Cooper Tires purchased Avon Rubber PLC of Melksham, Wiltshire, in the United Kingdom. The Cooper facility in Melksham is a major employer in the region. Avon, heavily involved with Formula One racing since 1982, had been the sole supplier of tires for the British Formula Three Championship and, from 2009, its tires were rebranded "Cooper" as Cooper became the championship's sole sponsor. For its own part, Cooper became the official tire of the A1 Grand Prix for the initial season and was under contract to produce slick and treaded rain tires until 2008. It also became the official tire for two other championships: Champ Car Atlantic Championship and USF2000 National Championship. Cooper Tires remains a major source of racing tires worldwide.

The Cooper Tire and Rubber Company is a $2.9 billion company with 9,000 employees worldwide. The company is the fourth-largest tire manufacturer in North America and the eleventh largest globally. Rather than participating in both the original equipment and replacement tire markets as do its major competitors, Bridgestone, Goodyear Tire and Rubber, and Michelin, it focuses on producing and selling replacement tires for the passenger car, light truck, motorcycle, race car, commercial, and off-road vehicle markets worldwide. It has nine manufacturing facilities located in North America, Europe, and China and 60 manufacturing, sales, distribution, technical, and design facilities worldwide. Tires are distributed through independent dealers, regional retailers and wholesalers, and national retailers.

Cooper has three key strategic imperatives to guide operations: (1) Develop a competitive cost structure and improve profitability, (2) drive top-line profitable growth, and (3) build organizational capabilities. Indeed, while everything we have to offer in this text comes to bear in supporting these imperatives, let us see what Cooper has done regarding operations planning and scheduling, the topic of this chapter. We examine several press releases to gain insight into the nature of operations planning and scheduling at a large manufacturer.

March 7, 2013. Cooper Tire and Rubber Company temporarily idled production at its Findlay, Ohio, plant due to high tire inventories and Cooper's implementation of a new software system. Cooper built the extra tires in 2012's fourth-quarter to offset any lost production in 2013. However, company officials said the expiration of tariffs on imported Chinese-made tires in the fall of 2012 resulted in higher-than-normal tire inventories, resulting in fewer orders. In its annual report, Cooper said that the tariff expiration was expected to affect sales and production in the first and possibly second quarter of 2013.

September 16, 2013. JDA Software Group and Cooper Tire and Rubber Company announced the implementation of JDA Production Scheduling—Discrete at its manufacturing facilities. With the size proliferation in original equipment tires, including the phasing out of 12-, 13-, and 14-inch tires and the increase in bigger tires and better designs, Cooper realized that the changes in designs and sizes would make it increasingly more difficult to meet the needs of its customers. Before the software change, the company operated with a manual, weekly planning cycle. The schedulers reviewed the demand data SKU by SKU to create a curing schedule for each plant. The curing process is a capacity-limited resource that controls the flow of tires in a plant. The scheduling process was time consuming and the data were not up to date by the time the schedule was completed. With the new software, the scheduling lead time was reduced by 9 days; all of the plant constraints were automatically recognized, and inventory management was improved.

January 27, 2017. Companies must include contingency plans in their operations planning and scheduling. The Cooper Tire and Rubber Company announced that a tire warehouse and distribution facility in Albany, Georgia, sustained damage from a tornado and was not operational. Such a loss immediately puts pressure on other facilities in the supply chain. Cooper activated its logistics contingency plans and rerouted customer orders to other

facilities in its network. These other facilities experienced an unexpected increase in demand and had to adjust schedules and production plans to maintain customer service.

January 18, 2019. Cooper Tire and Rubber Company Europe Ltd announced the layoff of 300 workers at its Melksham, England, facility due to the cessation of light vehicle tire production at the facility. Deliberation with employee representatives concluded with the result that production will be phased out over a 10-month period and Europe will receive light vehicle tires from other facilities in Cooper's supply chain. Approximately 400 employees will remain in Melksham to produce motorsports and motorcycle tires and staff sales, marketing, and technical support positions.

November 26, 2019. Cooper Tire and Rubber and Sailun Vietnam Co., Ltd., celebrated the first tire produced at their new joint venture facility located near Ho Chi Minh City, Vietnam. The new facility adds about 2 million tires per year to the production capacity of truck and bus radial tires for the global markets.

Cooper Tire's example shows us how temporary use of undertime by idling a plant, facility scheduling, multi-facility contingency planning for disasters, layoffs, and additional capacity can be used to achieve its strategic initiatives.[1]

Managing supply chains effectively requires more than just good demand forecasts or knowing how much to order and when. Demand is the first half of the equation, and the other half is supply. As Cooper Tires in the chapter opener has shown, the firm must develop plans to supply the resources needed to meet the forecasted demand. These resources include the workforce, materials, inventories, dollars, and equipment capacity.

operations planning and scheduling

The process of balancing supply with demand, from the aggregate level down to the short-term scheduling level.

Operations planning and scheduling is the process of making sure that demand and supply plans are in balance, from the aggregate level down to the short-term scheduling level. Operations planning and scheduling lies at the core of supply chain integration, around which plans are made up and down the supply chain, from supplier deliveries to customer due dates and services. Why is it so important? First, it requires managerial inputs from all of the firm's functions. Marketing provides inputs on demand and accounting provides important cost data and a firm's financial condition. Second, each function is affected by the plan. A plan that calls for expanding the workforce has a direct impact on the hiring and training requirements for the human resources function. As the plan is implemented, it creates revenue and cost streams that finance must deal with as it manages the firm's cash flows. Third, each department and group in a firm has its own workforce. Managers of these departments must make choices on hiring, overtime, and vacations. Finally, whether the business is an airline, hotel, computer manufacturer, or university, schedules are a part of everyday life. Schedules involve an enormous amount of detail and affect every process in a firm. For example, service, product, and employee schedules determine specific cash flow requirements, trigger the firm's billing process, and initiate requirements for the employee training process. Firms use the scheduling process to lower their costs and improve their responsiveness, affecting operations up and down the supply chain worldwide. Table 10.1 defines several types of plans related to operations planning and scheduling.

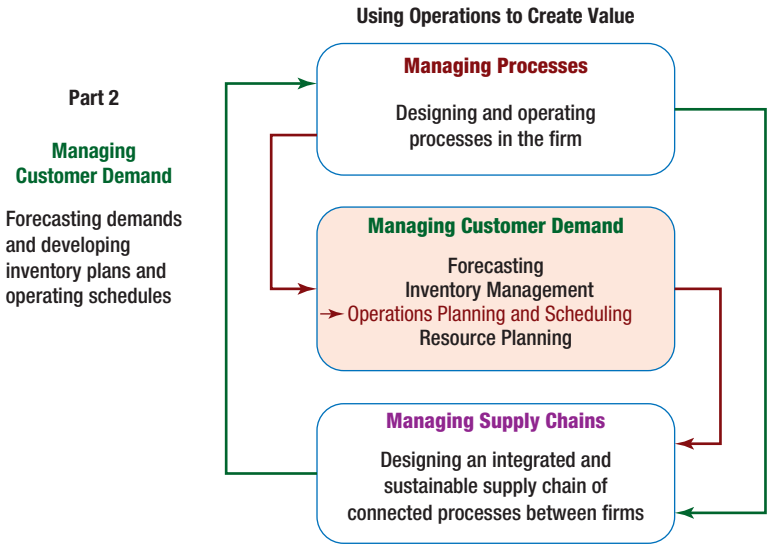
In this chapter, we begin by discussing the three levels of operations planning and scheduling: (1) sales and operations planning (S&OP), (2) resource planning, and (3) scheduling. We explain the purpose of aggregation in sales and operations planning and the various information inputs required for its development. We examine how S&OP relates with other plans and functional areas within the firm and describe the supply options and planning strategies for effective S&OP. We show how spreadsheets can help find good solutions. Leaving a detailed discussion of resource

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[1] *Sources:* http://coopertire.com/about/history; http://www.answers.com/topic/cooper-tire-rubber-company (2014); JDA Software Group, "Case Study: Optimizing the Planning Schedule" (September 16, 2013); http://coopertire.com/news.aspx (January 27, 2017); http://coopertire.com/news.aspx (January 18, 2019); http://coopertire.com/news.aspx (November 26, 2019).

TABLE 10.1 | TYPES OF PLANS WITH OPERATIONS PLANNING AND SCHEDULING

Key Term	Definition
Sales and operations plan (S&OP)	A plan of future aggregate resource levels so that supply is in balance with demand. It states a company's or department's production rates, workforce levels, and inventory holdings that are consistent with demand forecasts and capacity constraints. The S&OP is a time-phased plan, meaning that it is projected for several time periods (such as months or quarters) into the future.
Aggregate plan	Another term for the sales and operations plan.
Production plan	A sales and operations plan for a *manufacturing firm* that centers on production rates and inventory holdings.
Staffing plan	A sales and operations plan for a *service firm*, which centers on staffing and on other human resource–related factors.
Resource plan	An intermediate step in the planning process that lies between S&OP and scheduling. It determines requirements for materials and other resources on a more detailed level than the S&OP. It is covered in the next chapter.
Schedule	A detailed plan that allocates resources over shorter time horizons to accomplish specific tasks.



planning to Chapter 11, "Resource Planning," we conclude with the topic of scheduling, including performance measures and some basic techniques for creating schedules. Online Supplement J, "Operations Scheduling," provides additional help with scheduling problems.

Levels in Operations Planning and Scheduling

Managers develop plans for their operations covering varying time spans, from the long term to the short term. These plans form a hierarchy: The long-term plans form an umbrella under which short-term plans exist. Sales and operations plans exist at Level 1 and represent the long-term operations plans. These plans form the basis for major outlays for materials and resources and consequently cannot be very specific regarding products or services. Resource plans exist at Level 2 and are more detailed than the sales and operations plans and cover a shorter term. The most detailed plans are the schedules in Level 3, which cover very short time horizons and relate to specific products and resources. Level 2 plans must be consistent with Level 1 plans, and Level 3 plans must be consistent with Level 2 plans.

Level 1: Sales and Operations Planning

In this section, we explain why companies begin with plans that take a macro, or big-picture, view of their business. We also describe how these plans relate to their other plans and how the long-term plans ultimately are translated into detailed schedules ready for immediate action.

Aggregation The sales and operations plan is useful because it focuses on a general course of action, consistent with the company's strategic goals and objectives, without getting bogged down in details. We must first aggregate, and then use the targets and resources from the plan to create effective, coordinated schedules. A company's managers must determine whether they can satisfy budgetary goals without having to schedule each of the company's thousands of products and employees individually. While schedules with such detail are the goal, the operations planning and scheduling process begins at the aggregate level.

In general, companies perform aggregation along three dimensions: (1) services or products, (2) workforce, and (3) time.

product family
A group of services or products that have similar demand requirements and common process, labor, and materials requirements.

1. **Services or products** A group of customers, services, or products that have similar demand requirements and common process, workforce, and materials requirements is called a **product family**. Sometimes, product families relate to market groupings or to specific processes. A firm can aggregate its services or products into a set of relatively broad families, avoiding too much detail at this stage of the planning process. For instance, a manufacturer of bicycles that produces 12 different models of bikes might divide them into two groups,

mountain bikes and road bikes, for the purpose of preparing the sales and operations plan. Common and relevant measurements should be used.

2. **Workforce** A company can aggregate its workforce in various ways as well, depending on its flexibility. For example, if workers at the bicycle manufacturer are trained to work on either mountain bikes or road bikes, for planning purposes management can consider its workforce to be a single aggregate group, even though the skills of individual workers may differ.
3. **Time** The planning horizon covered by a sales and operations plan typically is 1 year, although it can differ in various situations. To avoid the expense and disruptive effect of frequent changes in output rates and the workforce, adjustments usually are made monthly or quarterly. In other words, the company looks at time in the aggregate—months, quarters, or seasons—rather than in weeks, days, or hours.

Information Inputs Just as it is needed to manage the demand side, consensus is needed among the firm's departments when decisions for the supply side are made. Information inputs are sought to create a sales and operations plan that works for all. Figure 10.1 lists inputs from each functional area. They must be accounted for to make sure that the plan is a good one and also doable. Such coordination helps synchronize the flow of services, materials, and information through the supply chain to best balance supply with customer demand.



PIROSCHKA VAN DE WOUW/EPA-EFE/Shutterstock

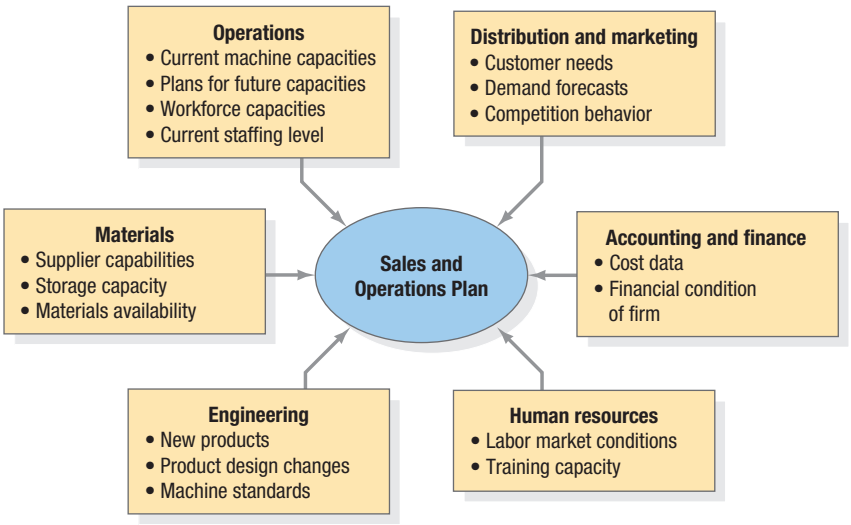
This plant is manufacturing electric bikes for Gazelle, the largest bicycle manufacturer in the Netherlands. The company, founded in 1892, aggregates its products into three groups: city, trekking, and rugged lifestyle bikes. Customers can choose from 7 models.

Related Plans A financial assessment of the organization's near future—that is, for 1 or 2 years ahead—is called either a business plan (in for-profit firms) or an annual plan (in nonprofit service organizations). A **business plan** is a projected statement of income, costs, and profits. It usually is accompanied by budgets, a projected (pro forma) balance sheet, and a projected cash flow statement showing sources and allocations of funds. The business plan unifies the plans and expectations of a firm's operations, finance, sales, and marketing managers. In particular, it reflects plans for market penetration, new product introduction, and capital investment. Manufacturing firms and for-profit service organizations, such as a retail store, a firm of attorneys, or a hospital, prepare such plans. A nonprofit service organization, such as the United Way or a municipal government, prepares a different type of plan for financial assessment, called an **annual plan or financial plan**.

business plan
A projected statement of income, costs, and profits.

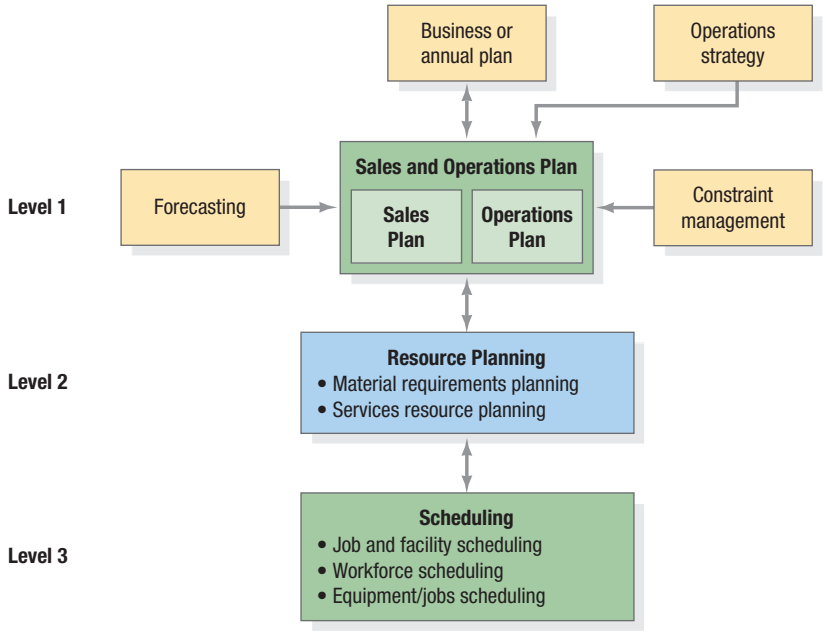
annual plan (or financial plan)
A plan for financial assessment used by a nonprofit service organization.

Figure 10.2 illustrates the relationships among the business or annual plan, constraint management, forecasting, operations strategy, sales and operations plan, and the detailed plans and schedules derived from it. For *service providers* in the supply chain, top management sets the organization's direction and objectives in the business plan (in a for-profit organization) or annual plan (in a nonprofit organization). This plan then provides the framework for developing the sales and operations plan, which typically focuses on staffing and other human resource–related factors at a more aggregate level. It presents the number and types of employees needed to meet



◀ **FIGURE 10.1**
Managerial Inputs from Functional Areas to Sales and Operations Plans

FIGURE 10.2 ▶
The Relationship of Sales and Operations Plans and Schedules to Other Plans



the objectives of the business or annual plan. For *manufacturing firms* in the supply chain, top management sets the company's strategic objectives for at least the next year in the business plan. It provides the overall framework, along with inputs coming from operations strategy, forecasting, and capacity constraint management. The sales and operations plan specifies product family production rates, inventory levels, and workforce levels. Regardless of whether the firm is a service provider or a manufacturer, the sales and operations plan sets the stage for the two levels to follow.

Level 2: Resource Planning

The next planning level is *resource planning*, which is a process that takes sales and operations plans; processes time standards, routings, and other information on how services or products are produced; and then plans the timing of capacity and material requirements. It decomposes the aggregate quantities of product families, workforce, and time to arrive at the material and resource requirements implied in the sales and operations plan over a shorter time horizon. For a manufacturing firm, the resource plan gets specific as to individual products within each product family, purchased materials, and resources on a detailed level. A major input is the *master production schedule*, which specifies the timing and size of production quantities for each product in the product families. The *material requirements planning* process then derives plans for components, purchased materials, and workstations. For a service firm, the resource plan may specify the daily or weekly facility capacity requirements for service facilities or labor over the next several months. In essence, the resource planning activity provides due dates for the supply of materials, components, products, and other resources such as labor, space, vehicles, and dollars. This activity sets up Level 3, scheduling. Because of its importance, we devote Chapter 11, "Resource Planning," to this topic.

Level 3: Scheduling

Scheduling takes the resource plan and translates it into specific operational tasks on a detailed basis. Facility schedules can be developed by assigning activities to facilities so as to utilize them efficiently. For example, surgeries for specific patients can be assigned to operating rooms so as to meet the needs of the patients while adhering to the capacity constraints of the operating rooms. Another important schedule is the *workforce schedule*, which details the specific work schedule for each category of employee. For example, a sales and operations plan might allocate 10 firefighters for the day shift in a particular district; the resource plan may determine the fire protection requirements for a typical week, and the workforce schedule might assign five of them to work Monday through Friday and the other five to work Wednesday through Sunday to meet the varying daily needs for fire protection in that district. Finally, given the material requirements plan for a group of jobs in a manufacturing plant, the specific sequence of those jobs can be scheduled on a bottleneck machine. We will address scheduling problems later in this chapter. Thus, the sales and operations plan plays a key role in translating the strategies of the business plan into an operational plan for the manufacturing process.

As the arrows in Figure 10.2 indicate, information flows in two directions: from the top down (broad to detailed) and from the bottom up (detailed to broad). If a sales and operations plan cannot be developed to satisfy the objectives of the business or annual plan with the existing

resources, the business or annual plan might need some adjustment. Similarly, if a feasible capacity requirements or material requirements plan cannot be developed, the sales and operations plan might need some adjustment. The planning process is dynamic, with periodic plan revisions or adjustments based on two-way information flows, typically on a monthly basis.

S&OP Supply Options

Developing sales and operations plans means making decisions. In this section, we concentrate on the supply options that ultimately are combined to develop a sales and operations plan. Given demand forecasts, operations managers must develop a plan to meet the demand. There are six options that can be used singly or in combination to arrive at a plan.

1. **Anticipation Inventory** *Anticipation inventory* can be used to absorb uneven rates of demand or supply. For example, a plant facing seasonal demand can stock anticipation inventory during light demand periods and use it during heavy demand periods. Manufacturers of air conditioners, such as Whirlpool, can experience 90 percent of their annual demand during just 3 months of a year. Extra, or anticipation inventory, also can help when supply, rather than demand, is uneven. For example, a company can stock up on a certain purchased item if the company's suppliers expect severe capacity limitations. Despite its advantages, anticipation inventory can be costly to hold, particularly if stocked in its finished state. Moreover, when services or products are customized, anticipation inventory is not usually an option. Service providers in the supply chain generally cannot use anticipation inventory because services cannot be stocked.



Buddhika Weerasinghe/Bloomberg/Getty Images

Workers assemble indoor units of Daiken Industries Ltd. split type air conditioners at the company's Shinga plant in Kusatsu, Shinga, Japan. The demand for air conditioners is highly seasonal. Manufacturers typically begin production of room air conditioners in the fall and hold them in inventory until they are shipped in spring. Building anticipation inventory in the slack season allows the company to even out production rates over much of the year.

2. **Workforce Adjustment** Management can adjust workforce levels by hiring or laying off employees. The use of this alternative can be attractive if the workforce is largely unskilled or semiskilled and the labor pool is large. These conditions are more likely found in some countries than in others. However, for a particular company, the size of the qualified labor pool may limit the number of new employees that can be hired at any one time. Also, new employees must be trained, and the capacity of the training facilities themselves might limit the number of new hires at any one time. In some industries, laying off employees is difficult or unusual for contractual reasons (unions); in other industries, such as tourism and agriculture, seasonal layoffs and hirings are the norm.

3. **Workforce Utilization** An alternative to a workforce adjustment is a change in workforce utilization involving overtime and undertime. **Overtime** means that employees work longer than the regular workday or workweek and receive additional pay for the extra hours. It can be used to satisfy output requirements that cannot be completed on regular time. Overtime is expensive (typically 150 percent of the regular-time pay rate), and workers often do not want to work overtime for an extended period of time. Excessive overtime also can result in declining quality and productivity. However, it helps avoid the costly fringe benefits (such as health insurance, dental care, Social Security, retirement funds, paid vacations, and holidays) that come with hiring a new full-time employee. **Undertime** means that employees do not have enough work for the regular-time workday or workweek. For example, they cannot be fully utilized for 8 hours per day or for 5 days per week. Undertime occurs when labor capacity exceeds demand requirements (net of anticipation inventory), and this excess capacity cannot or should not be used productively to build up inventory or to satisfy customer orders earlier than the delivery dates already promised.

   Undertime can either be paid or unpaid. An example of *paid undertime* is when employees are kept on the payroll rather than being laid off. In this scenario, employees work a full day and receive their full salary but are not as busy because of the light workload. Some companies use paid undertime (though they do not call it that) during slack periods, particularly with highly skilled, hard-to-replace employees or when there are obstacles to laying off workers. The disadvantages of paid undertime include the cost of paying for work not performed and lowered productivity.

overtime

The time that employees work that is longer than the regular workday or workweek for which they receive additional pay.

undertime

The situation that occurs when employees do not have enough work for the regular-time workday or workweek.

4. **Part-Time Workers** Another option apart from undertime is to hire part-time workers, who are paid only for the hours and days worked. Perhaps they work only during the peak times of the day or peak days of the week. Sometimes, part-time arrangements provide predictable work schedules, but in other cases workers are not called in if the workload

is light. Such arrangements are more common in low-skill positions or when the supply of workers seeking such an arrangement is sufficient. Part-time workers typically do not receive fringe benefits.

5. **Subcontractors** Subcontractors can be used to overcome short-term capacity shortages, such as during peaks of the season or business cycle. Subcontractors can supply services, make components and subassemblies, or even assemble an entire product.
6. **Vacation Schedules** A manufacturer can shut down during an annual lull in sales, leaving a skeleton crew to cover operations and perform maintenance. Hospital employees might be encouraged to take all or part of their allowed vacation time during slack periods. The use of this alternative depends on whether the employer can mandate the vacation schedules of its employees. In any case, employees may be strongly discouraged from taking vacations during peak periods or encouraged to take vacations during slack periods.

Developing a sales and operations plan can be a formidable task, especially when sales are seasonal, as the following Managerial Challenge demonstrates.

MANAGERIAL CHALLENGE Human Resources

The Redwood Hotel is a large five-star hotel and convention complex located in rural Colorado. The hotel, one of six hotels owned by King Enterprises, headquartered in Denver, is a mecca for patrons interested in outdoor activities and businesses looking for a relaxing environment in which to hold meetings and conventions. Recently, Ryan Blake was hired as director of human resources for the hotel because staffing has been a problem. Headquarters has been receiving complaints from clients that "nobody was around when you needed them," or "staff members were rude or didn't have a clue as to how to resolve my problem." There were even comments that the staff was just standing around with nothing to do.

Ryan started by learning how the planning process was done at Redwood. Headquarters provides a business plan that stipulates the monthly forecasted demands for hotel and convention services. These forecasts are a basis for the revenue target that Redwood is expected to meet. Ryan realized that his job, to achieve those targets with appropriate staff levels, was critical because roughly 40 percent of the annual budget is payroll. Further, he had to plan staff levels in several categories, including food and beverage, housekeeping, guest services, and accounting.

A complicating factor is the seasonality of the business, with peaks being experienced from July to September, and then again from December to February. Recognizing that each employee category would need its own plan, Ryan wondered if he should adjust the workforce according to the seasons, using hires and layoffs, or utilize a level plan? Should he use overtime or undertime? How viable are temporary workers, and how will he factor in the vacation schedules of the staff? The comments about "rudeness" and "clueless" were troublesome and indicated that training was needed for the current staff members (which would take them out of service for a while) and new hires had to be trained before they were put into service. He had to make sure that he had enough resources to cover demand while training was taking place. How can he put together a plan that will meet the expectations at headquarters? The remainder of this chapter provides some guidance for Ryan.

S&OP Strategies

Here we focus on supply options that define output rates and workforce levels. Two basic strategies are useful starting points in searching for the best plan.

chase strategy
A strategy that involves hiring and laying off employees to match the demand forecast.

level strategy
A strategy that keeps the workforce constant, but varies its utilization via overtime, undertime, and vacation planning to match the demand forecast.

Chase Strategy

The **chase strategy** involves hiring and laying off employees to match the demand forecast over the planning horizon. Varying the workforce's regular-time capacity to equate supply to demand requires no inventory investment, overtime, or undertime. The drawbacks are the expense of continually adjusting workforce levels, the potential alienation of the workforce, and the loss of productivity and quality because of constant changes in the workforce.

Level Strategy

The **level strategy** involves keeping the workforce constant (except possibly at the beginning of the planning horizon). It can vary its utilization to match the demand forecast via overtime, undertime

(paid or unpaid), and vacation planning (i.e., paid vacations when demand is low). A constant workforce can be sized at many levels: Managers can choose to maintain a large workforce so as to minimize the planned use of overtime during peak periods (which, unfortunately, also maximizes the need for undertime during slack periods). Alternatively, they can choose to maintain a smaller workforce and rely heavily on overtime during the peak periods (which places a strain on the workforce and endangers quality).

These two "pure" strategies used alone usually do not produce the best sales and operations plan. It might not be best to keep the workforce exactly level or to vary it to exactly match forecasted demand on a period-by-period basis. The best strategy, therefore, usually is a **mixed strategy** that considers the full range of supply options. The chase strategy is limited to just hiring and laying off employees. The level strategy is limited to overtime, undertime, and vacation schedules. The mixed strategy opens things up to all options, including anticipation inventory, part-time workers, subcontractors, backorders, and stockouts.

mixed strategy
A strategy that considers the full range of supply options.

Constraints and Costs

An acceptable sales and operations plan must recognize relevant constraints or costs. Constraints can be either physical limitations or related to managerial policies. Examples of physical constraints might be machine capacities that limit maximum output or inadequate inventory storage space. Policy constraints might include limitations on the number of backorders or the use of subcontractors or overtime, as well as the minimum inventory levels needed to achieve desired safety stocks. Ethical issues may also be involved, such as excessive layoffs or required overtime.

Typically, many plans can contain a number of constraints. Table 10.2 lists the costs that the planner considers when preparing sales and operations plans.



Stephen Chernin/Getty Images

The greeting card business is highly seasonal, which poses problems for the producers of those cards. Hallmark strives to keep a level strategy to maintain some security for their workforce. Here a shopper is selecting a Valentine's day card at a Hallmark store on the Upper West Side, New York City.

Sales and Operations Planning as a Process

Sales and operations planning is a decision-making process involving both planners and management. It is dynamic and continuing, as aspects of the plan are updated periodically when new information becomes available and new opportunities emerge. It is a cross-functional process that seeks a set of plans that all of a firm's functions can support. For each product family, decisions are made based on cost trade-offs, recent history, recommendations by planners and middle management, and the executive team's judgment.

Figure 10.3 shows a typical plan for a manufacturer. The plan is for one of the manufacturer's make-to-stock product families expressed in aggregate units. This simple format shows the interplay between demand and supply. The history on the left for January through March shows how forecasts are tracking actual sales and how well actual production conforms to the plan. The inventory projections are of particular interest to finance because they significantly affect the

TABLE 10.2 | TYPES OF COSTS WITH SALES AND OPERATIONS PLANNING

Cost	Definition
Regular time	Regular-time wages paid to employees plus contributions to benefits, such as health insurance, dental care, Social Security, retirement funds, and pay for vacations, holidays, and certain other types of absences.
Overtime	Wages paid for work beyond the normal workweek, typically 150 percent of regular-time wages (sometimes up to 200 percent for Sundays and holidays), exclusive of fringe benefits. Overtime can help avoid the extra cost of fringe benefits that come with hiring another full-time employee.
Hiring and layoff	Costs of advertising jobs, interviews, training programs for new employees, scrap caused by the inexperience of new employees, loss of productivity, and initial paperwork. Layoff costs include the costs of exit interviews, severance pay, retaining and retraining remaining workers and managers, and lost productivity.
Inventory holding	Costs that vary with the level of inventory investment: the costs of capital tied up in inventory, variable storage and warehousing costs, pilferage and obsolescence costs, insurance costs, and taxes.
Backorder and stockout	Additional costs to expedite past-due orders, the costs of lost sales, and the potential cost of losing a customer to a competitor (sometimes called loss of goodwill).

FIGURE 10.3 ▶
Sales and Operations Plan for Make-to-Stock Product Family

Artic Air Company—April Sales and Operations Plan

Family: Medium window units (make-to-stock) *Unit of measure:* 100 units

	HISTORY													
SALES	J	F	M	A*	M	J	J	A	S	3rd 3 Mos**	4th 3 Mos	Mos 13–18	Fiscal Year Projection ($000)	Business Plan ($000)
New forecast	45	55	60	70	85	95	130	110	70	150	176	275	$8,700	$8,560
Actual sales	52	40	63											
Diff for month	7	–15	3											
Cum		–8	–5											
OPERATIONS														
New Plan	75	75	75	75	75	85	85	85	75	177	225			
Actual	75	78	76											
Diff for month	0	3	1											
Cum		3	4											
INVENTORY														
Plan	85	105	120	125	115	105	60	35	40	198	321			
Actual	92	130	143											

DEMAND ISSUES AND ASSUMPTIONS
1. New product design to be launched in January of next year.

SUPPLY ISSUES
1. Vacations primarily in November and December.
2. Overtime in June–August.

* April is the first month of the planning horizon for this current plan. When next month's plan is developed, its first month in the planning horizon will be May, and the most recent month of the history will be April (with January no longer shown in the history).

** This column provides the sales, operations, and inventory totals for October through December. For example, the forecast of 150 units translates into an average of 50 units per month (or 150/3 = 50).

manufacturer's cash requirements. The last two columns on the top right show how current fiscal year sales projections match up with the current business plan.

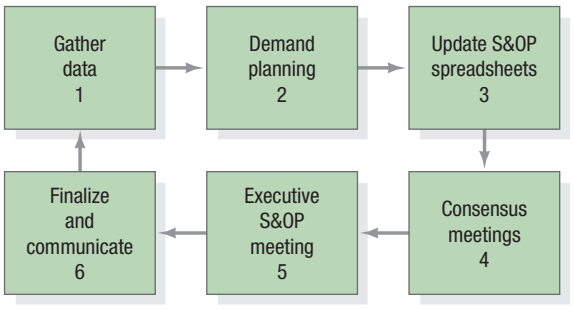
This plan is projected out for 18 months, beginning with April. The forecast, operations, and inventory sections for the first 6 months are shown on a month-by-month basis. They then are shown on a quarterly basis for the second 6 months. Finally, the totals for the last 6 months in the time horizon are given in just one column. This display gives more precision to the short term and yet gives coverage well into the future—all with a limited number of columns.

The medium-window product family is a make-to-stock product that experiences highly seasonal demand. The operations plan is to build up anticipation inventory in the slack season of January through April; schedule vacations as much as possible in November and December; and use overtime in the peak season of June, July, and August. For example, the Operations plan increases monthly production from 75 to 85 for June through August, returns to 75 for September, and then drops to an average of only 59 (or 177/3) for October through December. Sales and operations plans use different formats depending on the production and inventory strategy. For an assemble-to-order strategy, the inventory does not consist of finished goods. Instead, it is inventory of standardized components and subassemblies built for the finishing and assembly operations. For a make-to-order strategy, the inventory section in the plan of Figure 10.3 is replaced by a section showing the planned and actual order backlog quantities.

Sales and operations plans for service providers are quite different. For one thing, their plan does not contain an inventory section, but focuses instead on the demand and supply of human resources. Forecasts are typically expressed in terms of employees required, with separate rows for regular time, overtime, vacations, part-time workers, and so on. Different departments or worker classifications replace product families.

The S&OP process itself, typically done on a monthly basis, consists of six basic steps. They are much like the forecasting process steps we discussed in Chapter 8, "Forecasting."

Step 1. Begin to "roll forward" the plan for the new planning horizon. Start preliminary work right after the month's end. Update files with actual sales, production, inventory, costs, and constraints.

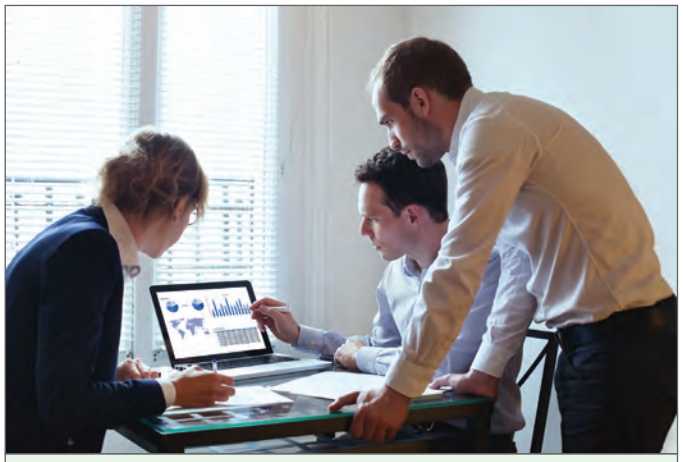


Step 2. Participate in the forecasting and demand planning process to create the authorized demand forecasts. For service providers, the forecasts are staff requirements for each workforce group. For example, a director of nursing in a hospital can develop a workload index for a nursing staff and translate a projection of the month-to-month patient load into an equivalent total amount of nursing care time—and thus the number of nurses—required for each month of the year.

Step 3. Update the sales and operations plans for each family, recognizing relevant constraints and costs, including availability of materials from suppliers, training facilities capable of handling only so many

new hires at a time, machine capacities, or limited storage space. Policy constraints might include limitations on the number of backorders, or the use of subcontractors or overtime, as well as the minimum inventory levels needed to achieve desired safety stocks. Typically, many plans can satisfy a specific set of constraints. The planner searches for a plan that best balances costs, customer service, and workforce stability, which may necessitate revising the plan several times.

Step 4. Have one or more consensus meetings with the stakeholders on how best to balance supply with demand. Participants could include the supply chain manager, plant manager, director of human resources, controller, purchasing manager, production control manager, or logistics manager. The goal is one set of recommendations to present at the firm's executive sales and operations planning (S&OP) meeting. Where agreement cannot be reached, prepare scenarios of alternative plans. Also prepare an updated financial view of the total business by rolling up the plans for all product families into a spreadsheet expressed in total dollars.



Anna Berkut/Alamy Stock Photo

Forecasting and demand planning is a critical aspect of the sales and operations planning process. Here a team examines international sales patterns to prepare sales projections.

Step 5. Present recommendations by product family at the executive S&OP meeting, which typically includes the firm's president and the vice presidents of functional areas. The plan is reviewed relative to the business plan, new product issues, special projects, and other relevant factors. The executives may ask for final changes to the plan, such as to balance conflicting objectives better. Acceptance of this authorized plan does not necessarily mean that everyone is in total agreement, but it does imply that everyone will work to achieve the plan.

Step 6. Update the plans to reflect the outcome of the executive S&OP meeting, and communicate them to the important stakeholders for implementation. Important recipients include those who do resource planning, covered in the next chapter.

Spreadsheets for Sales and Operations Planning

The sales and operations plan in Figure 10.3 does not show much on the supply options used in the operations plan or their cost implications. Here we discuss using spreadsheets that do just that. Supplement D, "Linear Programming," describes using the transportation method for production planning. Both spreadsheets and linear programming could be used in a supportive role as a planner develops prospective plans in step 3 of the S&OP process.

Various spreadsheets can be used, including ones that you develop on your own. Here we work with the *Sales and Operations Planning with Spreadsheets* Solver in OM Explorer.

Spreadsheets for a Manufacturer

Figure 10.4 shows a plan for a manufacturer, which uses all supply options except overtime. The top part of the spreadsheet shows the *input values* that consist of the forecasted demand requirements and the supply option choices period by period. In this example, we convert the forecast into employee-period equivalents, or the number of employees needed to produce the forecasted number of units in a period. Vary these "levers" as you search for better plans.

The next part of the spreadsheet shows the *derived values* that follow from the input values. The first row of derived values is called *utilized time*, which is that portion of the workforce's regular time that is paid for and productively used. In any period, the utilized time equals the workforce level minus undertime and vacation time. For example, in period 1 the utilized time is 94 (or 120−6−20). Given the utilized time of the workforce, the *inventory* can be calculated by subtracting the forecast from the utilized time, adding last period's ending inventory, and adding subcontracting time and backorders. In period 1, assuming last period's ending inventory is zero, the inventory is 70 (or 94−24+0+0+0). The *hires* and *layoffs* rows can be derived from the workforce levels. In this example, the workforce is increased for period 2 from its initial size of 120 employees to 158, which means that 38 employees are hired. Because the workforce size remains constant at 158 throughout the rest of the planning horizon, no other hirings or layoffs happen. When additional alternatives, such as vacations, inventory, and backorders are all possible, the overtime and undertime cannot be derived just from information on

forecasted demand and workforce levels. Thus, undertime and overtime are shown as input values (rather than derived values) in the spreadsheet, and the user must be careful to specify consistent input values.

The final part of the spreadsheet, the *calculated values* of the plan, shows the plan's cost consequences. Along with qualitative considerations, the cost of each plan determines whether the plan is satisfactory or whether a revised plan should be considered. When seeking clues about how to improve a plan already evaluated, we identify its highest cost elements. Revisions that would reduce these specific costs might produce a new plan with lower overall costs. Spreadsheet programs make analyzing these plans easy, and they present a whole new set of possibilities for developing sound sales and operations plans.

The plan in Figure 10.4 definitely is for a manufacturer because it uses inventory to advantage, particularly in the first two periods. It is a mixed strategy, and not just because it uses anticipation inventory, backorders, and subcontracting. The workforce level changes in period 2, but it does not exactly match the forecasted demand as with a chase strategy. It has some elements of the level strategy, because undertime and vacation time are part of the plan, but it does not rely exclusively on these supply options.

FIGURE 10.4 ▶
Manufacturer's Plan Using a Spreadsheet and Mixed Strategy

	1	2	3	4	5	6	Total
Inputs							
Forecasted demand	24	142	220	180	136	168	870
Workforce level	120	158	158	158	158	158	910
Undertime	6	0	0	0	0	0	6
Overtime	0	0	0	0	0	0	0
Vacation time	20	6	0	0	4	10	40
Subcontracting time	0	0	0	0	0	6	6
Backorders	0	0	0	4	0	0	4
Derived							
Utilized time	94	152	158	158	154	148	864
Inventory	70	80	18	0	14	0	182
Hires	0	38	0	0	0	0	38
Layoffs	0	0	0	0	0	0	0
Calculated							
Utilized time cost	$376,000	$608,000	$632,000	$632,000	$616,000	$592,000	$3,456,000
Undertime cost	$24,000	$0	$0	$0	$0	$0	$24,000
Overtime cost	$0	$0	$0	$0	$0	$0	$0
Vacation time cost	$80,000	$24,000	$0	$0	$16,000	$40,000	$160,000
Inventory cost	$2,800	$3,200	$720	$0	$560	$0	$7,280
Backorders cost	$0	$0	$0	$4,000	$0	$0	$4,000
Hiring cost	$0	$91,200	$0	$0	$0	$0	$91,200
Layoff cost	$0	$0	$0	$0	$0	$0	$0
Subcontracting cost	$0	$0	$0	$0	$0	$43,200	$43,200
Total cost	$482,800	726,400	632,720	636,000	632,560	675,200	$3,785,680

Care must be taken to recognize differences in how inputs are measured. The workforce level might be expressed as the number of employees, but the forecasted demand and inventory expressed as units of the product. The OM Explorer spreadsheets require a common unit of measure, so we must translate some of the data prior to entering the input values. Perhaps the easiest approach is to express the forecasted demand and supply options as *employee-period equivalents* as in Figure 10.4. If demand forecasts are given as units of product, we can convert them to employee-period equivalents by dividing them by the productivity of a worker. For example, if the demand is for 1,500 units of product and the average employee produces 100 units in one period, the demand requirement is 15 employee-period equivalents.

Spreadsheets for a Service Provider

The same spreadsheets can be used by service providers, except anticipation inventory is not an option. You can unprotect the sheet and then hide the rows that are not relevant. It is useful not to hide the inventory row until the end, however, because positive or negative values signal an inconsistency in your plan. Whereas Figure 10.4 shows a good plan found after several revisions for a manufacturer, here we illustrate with Example 10.1 how to find a good plan for a service provider beginning with the chase and level (ignoring vacations) strategies. These plans can provide insights that lead to even better mixed strategy plans.

EXAMPLE 10.1 Using the Chase and Level Strategies as Starting Points

The manager of a large distribution center must determine how many part-time stockpickers to maintain on the payroll. She wants to develop a staffing plan that minimizes total costs, and wants to begin with the chase strategy and level strategy. For the level strategy, she wants to first try the workforce level that meets demand with the minimum use of undertime and not consider vacation scheduling.

First, the manager divides the next year into six time periods, each one 2 months long. Each part-time employee can work a maximum of 20 hours per week on regular time, but the actual number can be less. Instead of paying undertime, each worker's day is shortened during slack periods. Once on the payroll, each worker is used each day, but he or she may work only a few hours. Overtime can be used during peak periods.

The distribution center's forecasted demand is shown as the number of part-time employees required for each time period at the maximum regular time of 20 hours per week. For example, in period 3, an estimated 18 part-time employees working 20 hours per week on regular time will be needed.

	1	2	3	4	5	6	Total
Forecasted demand*	6	12	18	15	13	14	78

*Number of part-time employees

Currently, 10 part-time clerks are employed. They have not been subtracted from the forecasted demand shown. Constraints and cost information are as follows:

a. The size of training facilities limits the number of new hires in any period to no more than 10.

b. No backorders are permitted; demand must be met each period.

c. Overtime cannot exceed 20 percent of the regular-time capacity (that is, 4 hours) in any period. Therefore, the most that any part-time employee can work is 1.20 (20) = 24 hours per week.

d. The following costs can be assigned:

Regular-time wage rate	$2,000 per time period at 20 hours per week
Overtime wages	150 percent of the regular-time rate
Hires	$1,000 per person
Layoffs	$500 per person



Matthew Horwood/Alamy Stock Photo

Stock pickers in the Amazon Fulfillment Centre warehouse in Swansea, Wales. Extra staff are hired on Cyber Monday & Black Friday.

SOLUTION

a. Chase Strategy

Online Resource
Tutor 10.1 in OM Explorer provides a new example for planning using the chase strategy with hiring and layoffs.

This strategy simply involves adjusting the workforce as needed to meet demand, as shown in Figure 10.5. Rows in the spreadsheet that do not apply (such as inventory and vacations) are hidden. The workforce level row is identical to the forecasted demand row. A large number of hirings and layoffs begin with laying off four part-time employees immediately because the current staff is 10 and the staff level required in period 1 is only six. However, many employees, such as college students, prefer part-time work. The total cost is $173,500, and most of the cost increase comes from frequent hiring and layoffs, which add $17,500 to the cost of utilized regular-time costs.

FIGURE 10.5 ▶
Spreadsheet for Chase Strategy

	1	2	3	4	5	6	Total
Inputs							
Forecasted demand	6	12	18	15	13	14	78
Workforce level	6	12	18	15	13	14	78
Undertime	0	0	0	0	0	0	0
Overtime	0	0	0	0	0	0	0
Derived							
Utilized time	6	12	18	15	13	14	78
Hires	0	6	6	0	0	1	13
Layoffs	4	0	0	3	2	0	9
Calculated							
Utilized time cost	$12,000	$24,000	$36,000	$30,000	$26,000	$28,000	$156,000
Undertime cost	$0	$0	$0	$0	$0	$0	$0
Hiring cost	$0	$6,000	$6,000	$0	$0	$1,000	$13,000
Layoff cost	$2,000	$0	$0	$1,500	$1,000	$0	$4,500
Total cost	$14,000	30,000	42,000	31,500	27,000	29,000	$173,500

b. Level Strategy

Online Resource
Tutor 10.2 in OM Explorer provides a new example for planning using the level strategy with overtime and undertime.

To minimize undertime, the maximum use of overtime possible must occur in the peak period. For this particular level strategy (other workforce options are possible), the most overtime that the manager can use is 20 percent of the regular-time capacity, w, so

$$1.20\,w = 18 \text{ employees required in peak period (period 3)}$$

$$w = \frac{18}{1.20} = 15 \text{ employees}$$

Online Resource
Active Model 10.1 shows the impact of changing the workforce level, the cost structure, and overtime capacity.

A 15-employee staff size minimizes the amount of undertime for this level strategy. Because the staff already includes 10 part-time employees, the manager should immediately hire five more. The complete plan is shown in Figure 10.6. The total cost is $164,000, which seems reasonable because the minimum conceivable cost is only $156,000 (78 employee-periods × $2,000/employee-period). This cost could be achieved only if the manager found a way to cover the forecasted demand for all 78 employee-periods with regular time. The plan seems reasonable primarily because it involves the use of large amounts of undertime (15 employee-periods), which in this example are unpaid.

FIGURE 10.6 ▶
Spreadsheet for Level Strategy

	1	2	3	4	5	6	Total
Inputs							
Forecasted demand	6	12	18	15	13	14	78
Workforce level	15	15	15	15	15	15	90
Undertime	9	3	0	0	2	1	15
Overtime	0	0	3	0	0	0	3
Derived							
Utilized time	6	12	15	15	13	14	75
Hires	5	0	0	0	0	0	5
Layoffs	0	0	0	0	0	0	0
Calculated							
Utilized time cost	$12,000	$24,000	$30,000	$30,000	$26,000	$28,000	$150,000
Undertime cost	$0	$0	$0	$0	$0	$0	$0
Overtime cost	$0	$0	$9,000	$0	$0	$0	$9,000
Hiring cost	$5,000	$0	$0	$0	$0	$0	$5,000
Layoff cost	$0	$0	$0	$0	$0	$0	$0
Total cost	$17,000	24,000	39,000	30,000	26,000	28,000	$164,000

DECISION POINT

The manager, now having a point of reference with which to compare other plans, decided to evaluate some other plans before making a final choice, beginning with the chase strategy. The only way to reduce costs is somehow to reduce the premium in period 3 for three overtime employee periods (3 employee-periods × $3,000/employee-period) or to reduce the hiring cost of five employees (5 hires × $1,000/person). Nonetheless, better solutions may be possible. For example, undertime can be reduced by delaying the hiring until period 2 because the current workforce is sufficient until then. This delay would decrease the amount of unpaid undertime, which is a qualitative improvement. See Active Model 10.1 for additional insights.

Workforce and Workstation Scheduling

Scheduling is the last step in Figure 10.2. It takes the operations and scheduling process from planning to execution, and is where the "rubber meets the road." This important aspect of supply chain management is itself a process. It requires gathering data from sources such as demand forecasts or specific customer orders, resource availability from the sales and operations plan, due dates for resource or material requirements from resource planning activities, and specific constraints to be reckoned with from employees and customers. It then involves generating a schedule for the supply of resources or materials to meet the needs determined in resource planning. Here we cover workforce scheduling, job and facility scheduling, job sequencing at a workstation, and software support.

Workforce Scheduling

workforce scheduling
A type of scheduling that determines when employees work.

Another way to manage capacity is **workforce scheduling**, which is a type of scheduling that determines when employees work. Of particular interest are situations when not all employees work the same 5 days a week, and the same 8 hours per day. The schedule specifies the on-duty and off-duty periods for each employee over a certain time period, as in assigning postal clerks, nurses, pilots, attendants, or police officers to specific workdays and shifts. This approach is used when customers demand quick response, and total demand can be forecasted with reasonable accuracy. In these instances, capacity is adjusted to meet the expected loads on the service system. Sometimes the demand is known with certainty, such as a schedule of baseball games or football games at the start of the season. For the 2018 NFL season, 59,031 schedules were generated and the 58,911th was chosen. Factors such as the quality of the matchups and equity considerations such as rest disparity (teams playing teams coming off bye weeks), three-game road trips, and being home after Monday night road games were considered in the final schedule. Managerial Practice 10.1 shows that even with demand certainty, the problem of scheduling a workforce of Major League Baseball umpires is very complex.

As the MLB umpire scheduling example shows, workforce schedules translate the staffing plan (the number of MLB umpire crews), and the specific, time-based staff requirements (the schedule of MLB games), into schedules of work for each employee (umpire crew assignments to series). Determining the workdays for each employee in itself does not make the staffing plan operational. Daily workforce requirements, stated in aggregate terms in the staffing plan and decomposed in the resource requirements plan, must be satisfied. The workforce capacity available each day must meet or exceed daily workforce requirements. If it does not, the scheduler must try to rearrange days off until the requirements are met. If no such schedule can be found, management might have to change the staffing plan and hire more employees, authorize overtime hours, or allow for larger backlogs.

Constraints The technical constraints imposed on the workforce schedule are the resources provided by the staffing plan and the requirements placed on the operating system. However, other constraints, including legal and behavioral considerations, also can be imposed. For example, MLB umpires must not travel more than 300 miles preceding a series whose first game is a day game. Similarly, a minimum number of fire and safety personnel must be on duty at a fire station at all times. Such constraints limit management's flexibility in developing workforce schedules.

The constraints imposed by the psychological needs of workers complicate scheduling even more. Some of these constraints are written into labor agreements. For example, an employer might agree to give employees a certain number of consecutive days off per week or to limit employees' consecutive workdays to a certain maximum. Other provisions might govern the allocation of vacations, days off for holidays, or rotating shift assignments. In addition, the preferences of the employees themselves need to be considered.

rotating schedule
A schedule that rotates employees through a series of workdays or hours.

One way that managers deal with certain undesirable aspects of scheduling is to use a **rotating schedule**, which rotates employees through a series of workdays or hours. Thus, over

MANAGERIAL PRACTICE 10.1 Scheduling Major League Baseball Umpires

It's 7:07 p.m. on October 30, 2019, at Minute Maid Park in Houston, Texas. The Houston Astros and the Washington Nationals are playing game 7 of the World Series, the deciding game. The stadium is rocking with 43,326 fans, and 40 million more are watching the event on television in the United States alone. Astros pitcher, Zack Greinke, prepares to fire the first pitch to Nationals shortstop Trea Turner, and home-plate umpire Sam Holbrook leans down to call the balls and strikes. The Nationals won 6–2 and won the World Series 4 games to 3. There was a lot of press about the performances of the players; however, the umpires largely went unnoticed. Yet, the game could not have been played without them.

Each year, 30 teams in Major League Baseball (MLB) play 2,430 games in 780 series during a 6-month season. Each series, defined as a sequence of two to four games played consecutively between two opponents, requires a crew of four umpires. Each crew stays together for the entire season and gets scheduled as a unit. An umpire's job is full time, working about 142 games a year and spending most of his time traveling. Unlike a baseball player, whose team has a home city and plays half of its games there, an umpire who lives near a team's home city will not be able to work half of his games there. The reason is that MLB does not want an umpire working the games of any one team too frequently in one season. Consequently, umpires must travel after the completion of a series. A typical umpire crew may travel up to 35,000 miles during the season.

Before you submit your resume for the position of umpire scheduler, let's take a look at the complexity of the problem. There are 17 umpire crews in the staffing plan. Because of union vacation requirements, each week 15 crews are available to schedule a series. The schedule of games has already been developed, so the problem is to assign crews to series so as to minimize the number of miles traveled by each crew. Now comes the hard part. There are many constraints that any solution must recognize. Here are several examples:

- Crews traveling from the West Coast to the East Coast must have an intermediate day off.
- Working consecutive series more than 1,700 miles apart must have an intermediate day off.



Tim Warner/Getty Images

Anthony Rendon (6) of the Washington Nationals hits a two-run home run against the Houston Astros during the seventh inning of Game 6 of the 2019 World Series at Minute Maid Park on October 29, 2019 in Houston, Texas. The Nationals went on to win the World Series in Game 7.

- Crews should not work more than 21 days without a day off (21-day rule).
- Umpiring more than one series played by any team within an 18-day period should be avoided (18-day rule).
- Working more than four series played by any one team during the entire season should be avoided (four-series rule).

Beyond these constraints, the crews should travel to every MLB city, work each team at home and on the road, and have roughly equivalent schedules regarding travel and vacations. Creating these schedules manually would be mindboggling. Fortunately, Raquel Wagner, MLB Manager of Umpire Operations, has access to powerful mathematical models to help. Resumes, anyone?[2]

fixed schedule

A schedule that calls for each employee to work the same days and hours each week.

a period of time, each person has the same opportunity to have weekends and holidays off and to work days, as well as evenings and nights. A rotating schedule gives each employee the next employee's schedule the following week. In contrast, a **fixed schedule** calls for each employee to work the same days and hours each week.

Developing a Workforce Schedule Suppose that we are interested in developing a workforce schedule for a company that operates 7 days a week and provides each employee with 2 consecutive days off. In this section, we demonstrate a method that recognizes this constraint. The objective is to identify the 2 consecutive days off for each employee that will minimize the amount of total slack capacity, thereby maximizing the utilization of the workforce. The work schedule for each employee, then, is the 5 days that remain after the 2 days off have been determined. The procedure involves the following steps.

Step 1. From the schedule of net requirements for the week, derived from the resource plan in Level 2, find all the pairs of consecutive days, excluding the day (or days) with the maximum daily requirement. Select the unique pair that has the lowest total requirements for the 2 days. In some unusual situations, all pairs may contain a day with the maximum requirements.

[2] *Sources:* Michael A. Trick, Hakan Yildiz, and Tallys Yunes, "Scheduling Major League Baseball Umpires and the Travelling Umpire Problem," *Interfaces* vol. 42, no. 3 (May-June 2012), pp. 232–244; Ted Berg, "Umpiring a World Series Game is Extremely Hard and MLB Umps Are Great at It," http://ftw.usatoday.com (November 1, 2016); https:/en.wikipedia.org/wiki/2019_World_Series.

If so, select the pair with the lowest total requirements. Suppose that the numbers of employees required are

Monday: 8	Thursday: 12	Saturday: 4
Tuesday: 9	Friday: 7	Sunday: 2
Wednesday: 2		

The maximum daily requirement is 12 employees, on Thursday. The consecutive pair with the lowest total requirements is Saturday and Sunday, with $4+2 = 6$.

Step 2. If a tie occurs, choose one of the tied pairs, consistent with the provisions written into the labor agreement, if any. Alternatively, the tie could be broken by asking the employee being scheduled to make the choice. As a last resort, the tie could be broken arbitrarily. For example, preference could be given to Saturday–Sunday pairs as requested by the employee.

Step 3. Assign the employee the selected pair of days off. Subtract the requirements satisfied by the employee from the net requirements for each day the employee is to work. In this example, the employee is assigned Saturday and Sunday off. After requirements are subtracted, Monday's requirement is 7, Tuesday's is 8, Wednesday's is 1, Thursday's is 11, and Friday's is 6. Saturday's and Sunday's requirements do not change because no employee is yet scheduled to work those days.

Step 4. Repeat steps 1 through 3 until all the requirements have been satisfied or a certain number of employees have been scheduled.

This method reduces the amount of slack capacity assigned to days with low requirements and forces the days with high requirements to be scheduled first. It also recognizes some of the behavioral and contractual aspects of workforce scheduling in the tie-breaking rules. Example 10.2 demonstrates the use of the four-step procedure for a parcel service.

EXAMPLE 10.2 Developing a Workforce Schedule

The Amalgamated Parcel Service is open 7 days a week. The schedule of requirements is

Day	M	T	W	Th	F	S	Su
Required number of employees	6	4	8	9	10	3	2

Online Resource
Tutor 10.3 in OM Explorer provides a new example to practice workforce scheduling.

The manager needs a workforce schedule that provides 2 consecutive days off and minimizes the amount of total slack capacity. To break ties in the selection of off-days, the scheduler gives preference to Saturday and Sunday if it is one of the tied pairs. If not, she selects one of the tied pairs arbitrarily.

SOLUTION

Friday contains the maximum requirements, and the pair S–Su has the lowest total requirements. Therefore, Employee 1 is scheduled to work Monday through Friday.

Note that Friday still has the maximum requirements and that the requirements for the S–Su pair are carried forward because these are Employee 1's days off. These updated requirements are the ones the scheduler uses for the next employee.

The day-off assignments for the employees are shown in the following table.

SCHEDULING DAYS OFF

M	T	W	Th	F	S	Su	Employee	Comments
6	4	8	9	10	3	2	**1**	The S–Su pair has the lowest total requirements. Assign Employee **1** to a Monday through Friday schedule and update the requirements.
5	3	7	8	9	3	2	**2**	The S–Su pair has the lowest total requirements. Assign Employee **2** to a Monday through Friday schedule and update the requirements.
4	2	6	7	8	3	2	**3**	The S–Su pair has the lowest total requirements. Assign Employee **3** to a Monday through Friday schedule and update the requirements.
3	1	5	6	7	3	2	**4**	The M–T pair has the lowest total requirements. Assign Employee **4** to a Wednesday through Sunday schedule and update the requirements.

SCHEDULING DAYS OFF

M	T	W	Th	F	S	Su	Employee	Comments
3	1	4	5	6	2	1	**5**	The S–Su pair has the lowest total requirements. Assign Employee **5** to a Monday through Friday schedule and update the requirements.
2	0	3	4	5	2	1	**6**	The M–T pair has the lowest total requirements. Assign Employee **6** to a Wednesday through Sunday schedule and update the requirements.
2	0	2	3	4	1	0	**7**	The S–Su pair has the lowest total requirements. Assign Employee **7** to a Monday through Friday schedule and update the requirements.
1	0	1	2	3	1	0	**8**	Four pairs have the minimum requirement and the lowest total: S–Su, Su–M, M–T, and T–W. Choose the S–Su pair according to the tie-breaking rule. Assign Employee **8** to a Monday through Friday schedule and update the requirements.
0	0	0	1	2	1	0	**9**	Arbitrarily choose the Su–M pair to break ties because the S–Su pair does not have the lowest total requirements. Assign Employee **9** to a Tuesday through Saturday schedule and update the requirements.
0	0	0	0	1	0	0	**10**	Choose the S–Su pair according to the tie-breaking rule. Assign Employee **10** to a Monday through Friday schedule.

In this example, Friday always has the maximum requirements and should be avoided as a day off. The final schedule for the employees is shown in the following table.

FINAL SCHEDULE

Employee	M	T	W	Th	F	S	Su	Total
1	X	X	X	X	X	off	off	
2	X	X	X	X	X	off	off	
3	X	X	X	X	X	off	off	
4	off	off	X	X	X	X	X	
5	X	X	X	X	X	off	off	
6	off	off	X	X	X	X	X	
7	X	X	X	X	X	off	off	
8	X	X	X	X	X	off	off	
9	off	X	X	X	X	X	off	
10	X	X	X	X	X	off	off	
Capacity, C	7	8	10	10	10	3	2	50
Requirements, R	6	4	8	9	10	3	2	42
Slack, C – R	1	4	2	1	0	0	0	8

DECISION POINT

With its substantial amount of slack capacity, the schedule is not unique. Employee 9, for example, could have Sunday and Monday, Monday and Tuesday, or Tuesday and Wednesday off without causing a capacity shortage. Indeed, the company might be able to get by with one fewer employee because of the total of 8 slack days of capacity. However, all 10 employees are needed on Fridays. If the manager were willing to get by with only 9 employees on Fridays or if someone could work 1 day of overtime on a rotating basis, she would not need Employee 10. As indicated in the table, the net requirement left for Employee 10 to satisfy amounts to only 1 day, Friday. Thus, Employee 10 can be used to fill in for vacationing or sick employees.

Job and Facility Scheduling

Schedules can be displayed in various ways. For different jobs or activities, schedules can simply list the job due dates, show in a table their start and finish times, or show in a graph their start and finish times. The *Gantt chart* uses the third approach. Refer to Figure 7.4, which demonstrates how a "picture can be worth a thousand words" in managing projects. Associates not familiar with scheduling techniques can still grasp the essence of the plan by just looking at such a chart. This tool can be used to monitor the progress of work and to view the load on workstations or other facilities. The chart takes two basic forms: (1) the job or activity progress chart, which can be used to monitor and revise schedules, and (2) the workstation chart, which can be used to schedule the capacity of facilities.

Gantt Progress Chart The *Gantt progress chart* graphically displays the current status of each job or activity relative to its scheduled completion date. For example, suppose that an automobile parts manufacturer has three jobs under way, one each for Ford, Nissan, and Buick. The actual status of these orders is shown by the solid bars in Figure 10.7; the brackets indicate the desired schedule for the start and finish of each job. For the current date, April 21, this Gantt chart shows that the Ford order is behind schedule because operations has completed only the work scheduled through April 18. The Nissan order is exactly on schedule, and the Buick order is ahead of schedule.

Gantt Workstation Chart Figure 10.8 shows a *Gantt workstation chart* of the operating rooms at a hospital for a particular day. Using the same notation as in Figure 10.7, the chart shows the load on the operating rooms and the nonproductive time. The time slots assigned to each doctor include the time needed to clean the room prior to the next surgery. The chart can be used to identify time slots for unscheduled emergency surgeries. It can also be used to accommodate requests to change the time of surgeries. For example, Dr. Flowers may be able to change the start of her surgery to 2 P.M. by swapping time slots with Dr. Gillespie in operating room C or by asking Dr. Brothers to start her surgery 1 hour earlier in operating room A and asking Dr. Bright to schedule her surgery for the morning in operating room C. In any event, the hospital administrator would have to get involved in rescheduling the surgeries.



Poznyakov/Shutterstock

An operating room represents a fixed capacity that must be scheduled carefully to avoid unused capacity. Any time not used by surgeons is time lost forever.

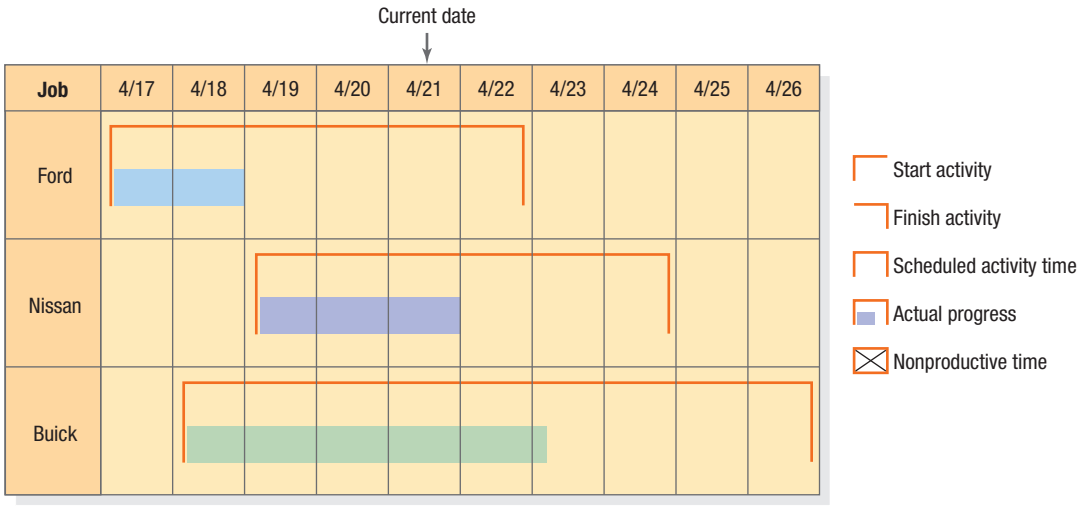
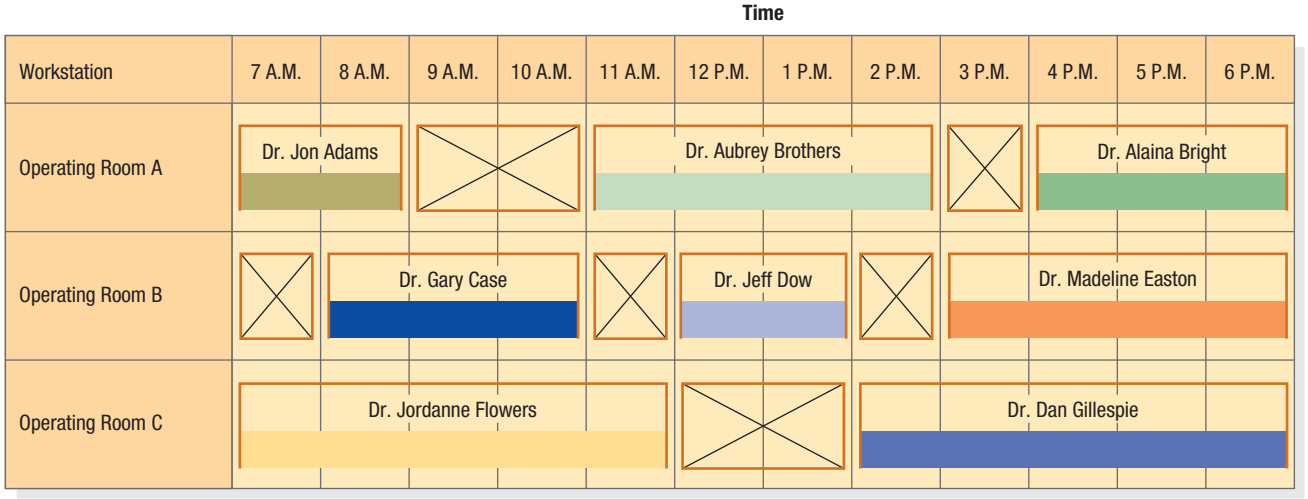


FIGURE 10.7
Gantt Progress Chart for an Auto Parts Company



▲ **FIGURE 10.8**
Gantt Workstation Chart for Operating Rooms at a Hospital

Sequencing Jobs at a Workstation

Another aspect of scheduling is sequencing work at workstations. **Sequencing** determines the order in which jobs are processed in the waiting line at a workstation. In this regard, the term "job" refers to either production orders or human customers. When combined with the expected processing times, the sequence allows you to estimate the start and finish times of each job and use a workstation Gantt chart to display the schedule.

sequencing
Determining the order in which jobs or customers are processed in the waiting line at a workstation.

priority sequencing rule
A rule that specifies the job or customer processing sequence when several jobs are waiting in line at a workstation.

first-come, first-served (FCFS)
A priority sequencing rule that specifies that the job or customer arriving at the workstation first has the highest priority.

earliest due date (EDD)
A priority sequencing rule that specifies that the job or customer with the earliest due date is the next job to be processed.

expediting
The process of completing a job or finishing with a customer sooner than would otherwise be done.

flow time
The amount of time a job spends in the service or manufacturing system.

Priority Sequencing Rules One way to determine what job to process next is with the help of a **priority sequencing rule**. The following two priority sequencing rules are commonly used in practice.

- *First-Come, First-Served.* The job arriving at the workstation first has the highest priority under a **first-come, first-served (FCFS)** rule. This rule is "fair" in that each job is treated equally, with no one stepping ahead of others already in line. It is commonly used at service facilities and is the rule that was assumed in Supplement B, "Waiting Lines."
- *Earliest Due Date.* The job with the **earliest due date (EDD)** is the next one to be processed. The *due date* specifies when work on a job should be finished. Due dates are commonly used by manufacturers and suppliers in the supply chain. For example, a product cannot be assembled until all of its purchased and produced components are available. If these components were not already in inventory, they must be ordered prior to when the product assembly can begin. Their due date is the start date for assembling the product to be assembled. This simple relationship is fundamental to coordinating with suppliers and with the manufacturer's own shops in the supply chain. It is also the key to **expediting**, which is the process of completing a job sooner than would otherwise be done. Expediting can be done by revising the due date, moving the job to the front of the waiting line, making a special appeal to the supplier, adding extra capacity, or even putting a red tag on the job that says the job is urgent.

Neither rule guarantees finding an optimal solution. Different sequences found by trial and error can produce better schedules. See online Supplement J, "Operations Scheduling," for additional priority sequencing rules. There are multiple performance measures for judging a schedule. A schedule that does well on one measure may do poorly on another.

Performance Measures The quality of a schedule can be judged in various ways. Two commonly used performance measures are flow time and past due.

- *Flow Time.* The amount of time a job spends in the service or manufacturing system is called **flow time**. It is the sum of the waiting time for servers or machines; the process time, including setups; the time spent moving between operations; and delays resulting from machine breakdowns, unavailability of facilitating goods or components, and the like. Flow time is sometimes referred to as *throughput time* or *time spent in the system, including service*. For a set of jobs to be processed at a single workstation, a job's flow time is

$$\text{Flow time} = \text{Finish time} + \text{Time since job arrived at the workstation}$$

- When using this equation, we assume for convenience that the first job scheduled starts at time zero (0). At time 0, all the jobs were available for processing at the workstation.
- *Past Due.* The measure **past due** can be expressed as the amount of time by which a job missed its due date (also referred to as **tardiness**) or as the percentage of total jobs processed over some period of time that missed their due dates. Minimizing these past due measures supports the competitive priorities of cost (penalties for missing due dates), quality (perceptions of poor service), and time (on-time delivery).

past due
The amount of time by which a job missed its due date.

tardiness
See past due.

Example 10.3 demonstrates the use of priority rules to schedule jobs at a consulting service.

EXAMPLE 10.3 Using Priority Sequencing Rules

Currently a consulting company has five jobs in its backlog. The time since the order was placed, processing time, and promised due dates are given in the following table. Determine the schedule by using the FCFS rule, and calculate the average days past due and flow time. How can the schedule be improved, if average flow time is the most critical?

Customer	Time Since Order Arrived (days ago)	Processing Time (days)	Due Date (days from now)
A	15	25	29
B	12	16	27
C	5	14	68
D	10	10	48
E	0	12	80

SOLUTION

a. The FCFS rule states that Customer A should be the first one in the sequence, because that order arrived earliest—15 days ago. Customer E's order arrived today, so it is processed last. The sequence is shown in the following table, along with the days past due and flow times.

Customer Sequence	Start Time (days)		Processing Time (days)		Finish Time (days)	Due Date	Days Past Due	Days Ago Since Order Arrived	Flow Time (days)
A	0	+	25	=	25	29	**0**	15	**40**
B	25	+	16	=	41	27	**14**	12	**53**
D	41	+	10	=	51	48	**3**	10	**61**
C	51	+	14	=	65	68	**0**	5	**70**
E	65	+	12	=	77	80	**0**	0	**77**

The *finish time* for a job is its start time plus the processing time. Its finish time becomes the start time for the next job in the sequence, assuming that the next job is available for immediate processing. The days past due for a job is zero (0) if its due date is equal to or exceeds the finish time. Otherwise it equals the shortfall. The flow time for each job equals its finish time plus the number of days ago since the order first arrived at the workstation. For example, Customer C's flow time is its scheduled finish time of 65 days plus the 5 days since the order arrived, or 70 days. The days past due and average flow time performance measures for the FCFS schedule are

$$\text{Average days past due} = \frac{0 + 14 + 3 + 0 + 0}{5} = 3.4 \text{ days}$$

$$\text{Average flow time} = \frac{40 + 53 + 61 + 70 + 77}{5} = 60.2 \text{ days}$$

b. The average flow time can be reduced. One possibility is the sequence shown in the following table, which uses the Shortest Processing Time (SPT) rule, which is one of several rules developed more fully in Supplement J, "Operations Scheduling." (For still another possibility, see Solved Problem 3, which applies the EDD rule.)

Customer Sequence	Start Time (days)		Processing Time (days)		Finish Time (days)	Due Date	Days Past Due	Days Ago Since Order Arrived	Flow Time (days)
D	0	+	10	=	10	48	**0**	10	**20**
E	10	+	12	=	22	80	**0**	0	**22**
C	22	+	14	=	36	68	**0**	5	**41**
B	36	+	16	=	52	27	**25**	12	**64**
A	52	+	25	=	77	29	**48**	15	**92**

$$\text{Average days past due} = \frac{0 + 0 + 0 + 25 + 48}{5} = 14.6 \text{ days}$$

$$\text{Average flow time} = \frac{20 + 22 + 41 + 64 + 92}{5} = 47.8 \text{ days}$$

This schedule reduces the average flow time from 60.2 to 47.8 days—a 21 percent improvement. However, the past due times for jobs A and B have increased.

DECISION POINT

Management decided to use a modified version of the second schedule, adding overtime when Customer B is processed. Further, Customer A agreed to extend its due date to 77 days, because in this case the advanced warning allowed it to reschedule its own operations with little problem.



Alex Kraus/Bloomberg/Getty Images

Scheduling an automobile assembly line is a challenging task and requires the help of sophisticated software. Even with robots doing much of the work, parts, components, and workers must be scheduled to to come together when the frame is available for assembly. Here an employee uses a robotic arm to fit a dashboard into an Audi A5 automobile in Audi's factory in Ingolstadt, Germany.

Software Support

Computerized scheduling systems are available to cope with the complexity of workforce scheduling, such as the myriad constraints and concerns scheduling Major League Baseball umpires. In some types of firms, such as telephone companies, mail-order catalog houses, or emergency hotline agencies, employees must be on duty 24 hours a day, 7 days a week.

Sometimes a portion of the staff is part time, which allows management a great deal of flexibility but adds considerable complexity to the scheduling requirements. The flexibility comes from the opportunity to match anticipated loads closely through the use of overlapping shifts or odd shift lengths; the complexity comes from the need to evaluate the numerous possible alternatives. Management also must consider the timing of lunch breaks and rest periods, the number and starting times of shift schedules, and the days off for each employee. The programs select the schedule that minimizes the sum of expected costs of over- and understaffing.

Software packages are also available for sequencing jobs at workstations. They help firms design and manage the linkages between customers and suppliers in the supply chain. True integration requires the manipulation of large amounts of complex data in real time because the customer order work flow must be synchronized with the required material, manufacturing, and distribution activity. Coupled with the Internet and improved data storage and manipulation methods, such computer software has given rise to **advanced planning and scheduling (APS) systems**, which seek to optimize resources across the supply chain and align daily operations with strategic goals. A firm's ability to change its schedules quickly and still keep the goods and services flowing smoothly through the supply chain provides a competitive edge.

advanced planning and scheduling (APS) systems

Computer software systems that seek to optimize resources across the supply chain and align daily operations with strategic goals.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
10.1 Explain the rationale behind the levels in the operations planning and scheduling process.	The section "Levels in Operations Planning and Scheduling" shows the various levels in a hierarchy of plans and how they relate to each other. There are two key figures in this section: Figure 10.1 shows the information inputs to the sales and operations plan, which is at the top of the hierarchy, and Figure 10.2 shows the levels of plans.	
10.2 Describe the supply options used in sales and operations planning.	See the section "S&OP Supply Options" for the six ways managers can satisfy demands with the sales and operations plan.	
10.3 Compare the chase planning strategy to the level planning strategy for developing sales and operations plans.	"S&OP Strategies" explains the chase and level strategies, the related constraints and costs, and the process managers use to develop a sales and operations plan. Figure 10.3 shows what a sales and operations plan looks like.	**Active Model Exercise:** 10.1: Level Strategy **OM Explorer Tutors:** 10.1: Chase Strategy; 10.2: Level Strategy **Tutor Exercise:** 10.1: Results of Different Scenarios with a Level Strategy
10.4 Use spreadsheets for sales and operations planning.	See "Spreadsheets for Sales and Operations Planning" for a detailed discussion of how to use spreadsheets in S&OP. Example 10.1 demonstrates the procedure for doing S&OP for a service facility. See also Solved Problem 1.	**OM Explorer Solver:** Sales and Operations Planning with Spreadsheets **OM Explorer Tutor:** 10.4: Staffing Strategies with Spreadsheets
10.5 Develop workforce and workstation schedules.	The section "Workforce and Workstation Scheduling" shows how to create workforce schedules, use Gantt charts, and sequence jobs at a workstation. Additional help can be found in Example 10.2 and Solved Problem 2 for workforce schedules and in Example 10.3 and Solved Problem 3 for sequencing jobs.	**OM Explorer Solvers:** Workforce Scheduler; Single-Workstation Scheduler **OM Explorer Tutor:** 10.3: Developing a Workforce Schedule **Tutor Exercise:** 10.2: Staffing for the Newest MBA Class **POM for Windows:** Scheduling **Case:** Food King

Key Terms

advanced planning and scheduling (APS) systems 436
aggregate plan 418
annual plan (or financial plan) 419
backorder and stockout cost 423
business plan 419
chase strategy 422
earliest due date (EDD) 434
expediting 434
first-come, first-served (FCFS) 434
fixed schedule 430
flow time 434
hiring and layoff cost 423
inventory holding cost 423
level strategy 422
mixed strategy 423
operations planning and scheduling 417
overtime 421
overtime cost 423
past due 435
priority sequencing rule 434
product family 418
production plan 418
regular time cost 423
resource plan 418
rotating schedule 429
sales and operations plan (S&OP) 418
schedule 418
sequencing 434
staffing plan 418
tardiness 435
undertime 421
workforce scheduling 429

Solved Problem 1

Online Resource

Tutor 10.4 in OM Explorer provides another example for practicing sales and operations planning using a variety of strategies.

The Cranston Telephone Company employs workers who lay telephone cables and perform various other construction tasks. The company prides itself on good service and strives to complete all service orders within the planning period in which they are received.

Each worker puts in 600 hours of regular time per planning period and can work as many as an additional 100 hours of overtime. The operations department has estimated the following staff requirements for such services over the next four planning periods:

Planning Period	1	2	3	4
Demand (hours)	21,000	18,000	30,000	12,000

Cranston pays regular-time wages of $6,000 per employee per period for any time worked up to 600 hours (including undertime). The overtime pay rate is $15 per hour over 600 hours. Hiring, training, and outfitting a new employee costs $8,000. Layoff costs are $2,000 per employee. Currently, 40 employees work for Cranston in this capacity. No delays in service, or backorders, are allowed. Use the spreadsheet approach to answer the following questions:

a. Prepare a chase strategy using only hiring and layoffs. What are the total numbers of employees hired and laid off?

b. Develop a staffing plan that uses the level strategy, relying only on overtime and undertime. Maximize the use of overtime during the peak period so as to minimize the workforce level and amount of undertime.

c. Propose an effective mixed-strategy plan.

d. Compare the total costs of the three plans.

SOLUTION

a. The chase strategy workforce level is calculated by dividing the demand for each period by 600 hours, or the amount or regular-time work for one employee during one period. This strategy calls for a total of 20 workers to be hired and 40 to be laid off during the four-period plan. Figure 10.9 shows the "chase strategy" solution that OM Explorer's *Sales and Operations Planning with Spreadsheets* Solver produces. We simply hide any unneeded columns and rows in this general-purpose solver.

FIGURE 10.9 ▶
Spreadsheet for Chase Strategy

	1	2	3	4	Total
Inputs					
Forecasted demand	35	30	50	20	135
Workforce level	35	30	50	20	135
Undertime	0	0	0	0	0
Overtime	0	0	0	0	0
Derived					
Utilized time	35	30	50	20	135
Hires	0	0	20	0	20
Layoffs	5	5	0	30	40
Calculated					
Utilized time cost	$210,000	$180,000	$300,000	$120,000	$810,000
Undertime cost	$0	$0	$0	$0	$0
Overtime cost	$0	$0	$0	$0	$0
Hiring cost	$0	$0	$160,000	$0	$160,000
Layoff cost	$10,000	$10,000	$0	$60,000	$80,000
Total cost	$220,000	190,000	460,000	180,000	$1,050,000

b. The peak demand is 30,000 hours in period 3. As each employee can work 700 hours per period (600 on regular time and 100 on overtime), the workforce level of the level strategy that minimizes undertime is 30,000/700 = 42.86, or 43 employees. This strategy calls for three employees to be hired in the first quarter and for none to be laid off. To convert the demand requirements into employee-period equivalents, divide the demand in hours by 600. For example, the demand of 21,000 hours in period 1 translates into 35 employee-period equivalents (21,000/600) and demand in period 3 translates into 50 employee-period equivalents (30,000/600). Figure 10.10 shows OM Explorer's spreadsheet for this level strategy that minimizes undertime.

	1	2	3	4	Total
Inputs					
Forecasted demand	35	30	50	20	135
Workforce level	43	43	43	43	172
Undertime	8	13	0	23	44
Overtime	0	0	7	0	7
Derived					
Utilized time	35	30	43	20	128
Hires	3	0	0	0	3
Layoffs	0	0	0	0	0
Calculated					
Utilized time cost	$210,000	$180,000	$258,000	$120,000	$768,000
Undertime cost	$48,000	$78,000	$0	$138,000	$264,000
Overtime cost	$0	$0	$63,000	$0	$63,000
Hiring cost	$24,000	$0	$0	$0	$24,000
Layoff cost	$0	$0	$0	$0	$0
Total cost	$282,000	258,000	321,000	258,000	$1,119,000

◀ **FIGURE 10.10**
Spreadsheet for Level Strategy

c. The mixed-strategy plan that we propose uses a combination of hires, layoffs, and overtime to reduce total costs. The workforce is reduced by 5 at the beginning of the first period, increased by 8 in the third period, and reduced by 13 in the fourth period. Figure 10.11 shows the results.

	1	2	3	4	Total
Inputs					
Forecasted demand	35	30	50	20	135
Workforce level	35	35	43	30	143
Undertime	0	5	0	10	15
Overtime	0	0	7	0	7
Derived					
Utilized time	35	30	43	20	128
Hires	0	0	8	0	8
Layoffs	5	0	0	13	18
Calculated					
Utilized time cost	$210,000	$180,000	$258,000	$120,000	$768,000
Undertime cost	$0	$30,000	$0	$60,000	$90,000
Overtime cost	$0	$0	$63,000	$0	$63,000
Hiring cost	$0	$0	$64,000	$0	$64,000
Layoff cost	$10,000	$0	$0	$26,000	$36,000
Total cost	$220.000	210,000	385,000	206,000	$1,021,000

◀ **FIGURE 10.11**
Spreadsheet for Mixed Strategy

d. The total cost of the chase strategy is $1,050,000. The level strategy results in a total cost of $1,119,000. The mixed-strategy plan was developed by trial and error and results in a total cost of $1,021,000. Further improvements are possible.

Solved Problem 2

The Food Bin grocery store operates 24 hours per day, 7 days per week. Fred Bulger, the store manager, has been analyzing the efficiency and productivity of store operations recently. Bulger decided to observe the need for checkout clerks on the first shift for a 1-month period. At the end of the month, he calculated the average number of checkout registers that should be open during the first shift each day. His results showed peak needs on Saturdays and Sundays.

Day	M	T	W	Th	F	S	Su
Number of Clerks Required	3	4	5	5	4	7	8

Bulger now has to come up with a workforce schedule that guarantees each checkout clerk 2 consecutive days off, but still covers all requirements.

a. Develop a workforce schedule that covers all requirements while giving 2 consecutive days off to each clerk. How many clerks are needed? Assume that the clerks have no preference regarding which days they have off.

b. Plans can be made to use the clerks for other duties if slack or idle time resulting from this schedule can be determined. How much idle time will result from this schedule, and on what days?

SOLUTION

a. We use the method demonstrated in Example 10.2 to determine the number of clerks needed. The minimum number of clerks is eight.

	DAY						
	M	**T**	**W**	**Th**	**F**	**S**	**Su**
Requirements	3	4	5	5	4	7	8*
Clerk 1	off	off	X	X	X	X	X
Requirements	3	4	4	4	3	6	7*
Clerk 2	off	off	X	X	X	X	X
Requirements	3	4	3	3	2	5	6*
Clerk 3	X	X	X	off	off	X	X
Requirements	2	3	2	3	2	4	5*
Clerk 4	X	X	X	off	off	X	X
Requirements	1	2	1	3	2	3	4*
Clerk 5	X	off	off	X	X	X	X
Requirements	0	2	1	2	1	2	3*
Clerk 6	off	off	X	X	X	X	X
Requirements	0	2*	0	1	0	1	2*
Clerk 7	X	X	off	off	X	X	X
Requirements	0	1*	0	1*	0	0	1*
Clerk 8	X	X	X	X	off	off	X
Requirements	0	0	0	0	0	0	0

* Maximum requirements

b. Based on the results in part (a), the number of clerks on duty minus the requirements is the number of idle clerks available for other duties:

	M	**T**	**W**	**Th**	**F**	**S**	**Su**
Number on duty	5	4	6	5	5	7	8
Requirements	3	4	5	5	4	7	8
Idle clerks	2	0	1	0	1	0	0

The slack in this schedule would indicate to Bulger the number of employees he might ask to work part time (fewer than 5 days per week). For example, Clerk 7 might work Tuesday, Saturday, and Sunday, and Clerk 8 might work Tuesday, Thursday, and Sunday. That would eliminate slack from the schedule.

Solved Problem 3

Revisit Example 10.3, in which the consulting company has five jobs in its backlog. Create a schedule using the EDD rule, calculating the average days past due and flow time. In this case, does EDD outperform the FCFS rule?

SOLUTION

Customer Sequence	Start Time (days)		Processing Time (days)		Finish Time (days)	Due Date	Days Past Due	Days Ago Since Order Arrived	Flow Time (days)
B	0	+	16	=	16	27	**0**	12	**28**
A	16	+	25	=	41	29	**12**	15	**56**
D	41	+	10	=	51	48	**3**	10	**61**
C	51	+	14	=	65	68	**0**	5	**70**
E	65	+	12	=	77	80	**0**	0	**77**

The days past due and average flow time performance measures for the EDD schedule are

$$\text{Average days past due} = \frac{0 + 12 + 3 + 0 + 0}{5} = 3.0 \text{ days}$$

$$\text{Average flow time} = \frac{28 + 56 + 61 + 70 + 77}{5} = 58.4 \text{ days}$$

By both measures, EDD outperforms the FCFS (3.0 versus 3.4 days past due and 58.4 versus 60.2 days of flow time). However, the solution found in part (b) of Example 10.3 still has the best average flow time of only 47.8 days.

Discussion Questions

1. List the types of costs incurred when employees are laid off. What costs are difficult to estimate in monetary terms? Suppose that a firm is facing a downturn in business, each employee has skills valued at $40,000 per year, and it costs $100,000 to lay off an employee. If business is expected to improve in 1 year, are layoffs financially justified? What is the "payback" period for the layoff decision?
2. When Netflix releases a new season for a popular series, the number of its viewers is likely to increase substantially. Do you think the concepts of operations planning can be used for satisfying the demand for data?
3. Consider Managerial Practice 10.1 and the scheduling of Major League Baseball umpires. Relate the three levels in Figure 10.2 to the seasonal production of baseball games.
4. Explain why management should be concerned about priority systems in service and manufacturing organizations.

Problems

The OM Explorer, POM for Windows, and Active Models software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download the software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decision, the software entirely replaces the manual calculations.

S&OP Strategies

1. The Barberton Municipal Division of Road Maintenance is charged with road repair in the city of Barberton and the surrounding area. Vijay Gupta, road maintenance director, must submit a staffing plan for the next year based on a set schedule for repairs and on the city budget. Gupta estimates that the labor hours required for the next four quarters are 6,000, 12,000, 19,000, and 9,000, respectively. Each of the 11 workers on the workforce can contribute 500 hours per quarter. Payroll costs are $6,000 in wages per worker for regular time worked up to 500 hours, with an overtime pay rate of $18 for each overtime hour. Overtime is limited to 20 percent of the regular-time capacity in any quarter. Although unused overtime capacity has no cost, unused regular time is paid at $12 per hour. The cost of hiring a worker is $3,000, and the cost of laying off a worker is $2,000. Subcontracting is not permitted.

   a. Find a level staffing plan that relies just on overtime and the minimum amount of undertime possible. Overtime can be used to its limits in any quarter. What is the total cost of the plan and how many undertime hours does it call for?

b. Use a chase strategy that varies the workforce level without using overtime or undertime. What is the total cost of this plan?

c. Propose a plan of your own. Compare your plan with those in parts (a) and (b), and discuss its comparative merits.

2. Bob Carlton's golf camp estimates the following staff requirements for its services over the next 2 years.

Quarter	1	2	3	4
Demand (hours)	4,200	6,400	3,000	4,800
Quarter	5	6	7	8
Demand (hours)	4,400	6,240	3,600	4,800

Each certified instructor puts in 480 hours per quarter regular time and can work an additional 120 hours overtime. Regular-time wages and benefits cost Carlton $7,200 per employee per quarter for regular time worked up to 480 hours, with an overtime cost of $20 per hour. Unused regular time for certified instructors is paid at $15 per hour. There is no cost for unused overtime capacity. The cost of hiring, training, and certifying a new employee is $10,000. Layoff costs are $4,000 per employee. Currently, eight employees work in this capacity.

a. Find a staffing plan using the level strategy that allows for no delay in service. It should rely only on overtime and the minimum amount of undertime necessary. What is the total cost of this plan?

b. Use a chase strategy that varies the workforce level without using overtime or undertime. What is the total cost of this plan?

c. Propose a better plan and calculate its total cost.

3. Continuing Problem 2, now assume that Carlton is permitted to employ some uncertified, part-time instructors, provided they represent no more than 15 percent of the total workforce hours (regular, overtime, and part time) in any quarter. Each part-time instructor can work up to 240 hours per quarter, with no overtime or undertime cost. Labor costs for part-time instructors are $12 per hour. Hiring and training costs are $2,000 per uncertified instructor, and there are no layoff costs.

a. Propose a low-cost, mixed-strategy plan and calculate its total cost.

b. What are the primary advantages and disadvantages of having a workforce consisting of both regular and temporary employees?

4. The Donald Fertilizer Company produces industrial chemical fertilizers. The projected manufacturing requirements (in thousands of gallons) for the next four quarters are 80, 50, 80, and 130, respectively. A level workforce is desired, relying only on anticipation inventory as a supply option. Stockouts and backorders are to be avoided, as are overtime and undertime.

a. Determine the quarterly production rate required to meet total demand for the year, and minimize the anticipation inventory that would be left over at the end of the year. Beginning inventory is zero.

b. Specify the anticipation inventory that will be produced.

c. Suppose that the requirements for the next four quarters are revised to 80, 130, 50, and 80, respectively. If total demand is the same, what level of production rate is needed now, using the same strategy as part (a)?

5. Management at the Kerby Corporation has determined the following aggregated demand schedule (in units):

Month	1	2	3	4
Demand	500	800	1,000	1,400
Month	5	6	7	8
Demand	2,000	3,000	2,700	1,500
Month	9	10	11	12
Demand	1,400	1,500	2,000	1,200

An employee can produce an average of 10 units per month. Each worker on the payroll costs $2,000 in regular-time wages per month. Undertime is paid at the same rate as regular time. In accordance with the labor contract in force, Kerby Corporation does not work overtime or use subcontracting. Kerby can hire and train a new employee for $2,000 and lay off one for $500. Inventory costs $32 per unit on hand at the end of each month. At present, 140 employees are on the payroll and anticipation inventory is zero.

a. Prepare a production plan that only uses a level workforce and anticipation inventory as its supply options. Minimize the inventory left over at the end of the year. Layoffs, undertime, vacations, subcontracting, backorders, and stockouts are not options. The plan may call for a one-time adjustment of the workforce before month 1 begins.

b. Prepare a production plan using a chase strategy, relying only on hiring and layoffs.

c. Prepare a mixed-strategy production plan that uses only a level workforce and anticipation inventory through month 7 (an adjustment of the workforce may be made before month 1 begins) then switches to a chase strategy for months 8 through 12.

d. Contrast these three plans on the basis of annual costs.

6. Gretchen's Kitchen is a fast-food restaurant located in an ideal spot near the local high school. Gretchen Lowe must prepare an annual staffing plan. The only menu items are hamburgers, chili, soft drinks, shakes, and French fries. A sample of 1,000 customers taken at random revealed that they purchased 2,100 hamburgers, 200 pints of chili, 1,000 soft drinks and shakes, and 1,000 bags of French fries. Thus, for purposes of estimating staffing requirements, Lowe assumes that each customer purchases 2.1 hamburgers, 0.2 pint of chili, 1 soft drink or shake, and 1 bag of French fries. Each hamburger requires 4 minutes of labor, a pint of chili requires 3 minutes, and a soft drink or shake and a bag of fries each take 2 minutes of labor.

The restaurant currently has 10 part-time employees who work 80 hours a month on staggered shifts. Wages are $400 per month for regular time and $7.50 per hour for overtime. Hiring and training costs are $250 per new employee, and layoff costs are $50 per employee.

Lowe realizes that building up seasonal inventories of hamburgers (or any of the products) would not be wise because of shelf-life considerations. Also, any demand not satisfied is a lost sale and must be avoided. Three strategies come to mind.

- Use a level strategy relying on overtime and undertime, with up to 20 percent of regular-time capacity on overtime.
- Maintain a base of 10 employees, hiring and laying off as needed to avoid any overtime.
- Utilize a chase strategy, hiring and laying off employees as demand changes to avoid overtime.

When performing her calculations, Lowe always rounds to the next highest integer for the number of employees. She also follows a policy of not using an employee more than 80 hours per month, except when overtime is needed. The projected demand by month (number of customers) for next year is as follows:

Jan.	3,200	July	4,800
Feb.	2,600	Aug.	4,200
Mar.	3,300	Sept.	3,800
Apr.	3,900	Oct.	3,600
May	3,600	Nov.	3,500
June	4,200	Dec.	3,000

a. Develop the schedule of service requirements (hours per month) for the next year.

b. Which strategy is most effective?

c. Suppose that an arrangement with the high school enables the manager to identify good prospective employees without having to advertise in the local newspaper. This source reduces the hiring cost to $50, which is mainly the cost of charred hamburgers during training. If cost is her only concern, will this method of hiring change Gretchen Lowe's strategy? Considering other objectives that may be appropriate, do you think she should change strategies?

7. A manager faces peak (weekly) demand for one of her operations, but is not sure how long the peak will last. She can either use overtime from the current workforce or hire/lay off and just pay regular-time wages. Regular-time pay is $500 per week, overtime is $750 per week, the hiring cost is $2,000, and the layoff cost is $3,000. Assuming that people are available seeking such a short-term arrangement, how many weeks must the surge in demand last to justify a temporary hire? *Hint:* Use break-even analysis (see Supplement A, "Decision Making"). Let w be the number of weeks of the high demand (rather than using Q for the break-even quantity). What is the fixed cost for the regular-time option? Overtime option?

Spreadsheets for Sales and Operations Planning

8. Tax Prep Advisers, Inc., has forecasted the following staffing requirements for tax preparation associates over the next 12 months. Management would like three alternative staffing plans to be developed.

Month	**1**	**2**	**3**	**4**
Demand	5	8	10	13
Month	**5**	**6**	**7**	**8**
Demand	18	20	20	14
Month	**9**	**10**	**11**	**12**
Demand	12	8	2	1

The company currently has 10 associates. No more than 10 new hires can be accommodated in any month because of limited training facilities. No backorders are allowed, and overtime cannot exceed 25 percent of regular-time capacity on any month. There is no cost for unused overtime capacity. Regular-time wages are $1,500 per month, and overtime wages are 150 percent of regular-time wages. Undertime is paid at the same rate as regular time. The hiring cost is $2,500 per person, and the layoff cost is $2,000 per person.

a. Prepare a staffing plan utilizing a level workforce strategy, minimizing undertime. The plan may call for a one-time adjustment of the workforce before month 1.

b. Using a chase strategy, prepare a plan that is consistent with the constraint on hiring and minimizes use of overtime.

c. Prepare a mixed strategy in which the workforce level is slowly increased by two employees per month through month 5 and is then decreased by two employees per month starting in month 6 and continuing through month 12. Does this plan violate the hiring or overtime constraints set by the company?

d. Contrast these three plans on the basis of annual costs.

9. Climate Control, Inc., makes expedition-quality rain gear for outdoor enthusiasts. Management prepared a forecast of sales (in suits) for next year and now must prepare a production plan. The company has traditionally maintained a level workforce strategy. All nine workers are treated like family and have been employed by the company for a number of years. Each employee can produce 2,000 suits per month. At present, finished goods inventory holds 24,000 suits. The demand forecast follows:

Month	**1**	**2**	**3**	**4**
Demand	25,000	16,000	15,000	19,000
Month	**5**	**6**	**7**	**8**
Demand	32,000	29,000	27,000	22,000
Month	**9**	**10**	**11**	**12**
Demand	14,000	15,000	20,000	6,000

Use the *Sales and Operations Planning with Spreadsheets* Solver in OM Explorer or develop your own spreadsheet models to address the following questions.

a. Management is willing to authorize overtime in periods for which regular production and current levels of anticipation inventory do not satisfy

demand. However, overtime must be strictly limited to no more than 20 percent of regular-time capacity. Management wants to avoid stockouts and backorders and is not willing to accept a plan that calls for shortages. Is it feasible to hold the workforce constant, assuming that overtime is only used in periods for which shortages would occur?

b. Assume that management is not willing to authorize any overtime. Instead, management is willing to negotiate with customers so that backorders may be used as a supply option. However, management is not willing to carry more than 5,000 suits from one month to the next in backorder. Is it feasible to hold the workforce constant, assuming that a maximum backorder of 5,000 suits may be maintained from month to month?

c. Assume management is willing to authorize the use of overtime over the next 4 months to build additional anticipation inventory. However, overtime must be strictly limited to no more than 20 percent of regular-time capacity. Management wants to avoid stockouts and backorders and is not willing to accept a plan that calls for shortages. Is it feasible to hold the workforce constant, assuming that overtime is only used in months 1 through 4? If not, in which months would additional overtime be required?

10. The Kool King Company has followed a policy of no layoffs for most of the manufacturer's life, even though the demand for its air conditioners is highly seasonal. Management wants to evaluate the cost effectiveness of this policy. Competitive pressures are increasing, and ways need to be found to reduce costs. The following demand (expressed in employee-month equivalents) has been forecast for next year:

Jan.	70	May	130	Sept.	110
Feb.	90	June	170	Oct.	60
Mar.	100	July	170	Nov.	20
Apr.	100	Aug.	150	Dec.	40

Additional planning data follow, with costs, inventory, and backorders expressed in employee-month equivalents:

Regular-time production cost	$1,500	Hire cost	$500/ person
Overtime production cost	150% of regular-time production cost	Layoff cost	$2,000/ person
Subcontracting cost	$2,500	Current back-orders	10
Inventory holding cost	$100	Current inventory	0
Backorder cost	$1,000	Desired ending inventory	0
Maximum overtime	20% of regular-time capacity	Current employment	130 employees

Hiring costs are lower than layoff costs because the facility is located near a technical training school. Undertime is paid at the rate equivalent to regular-time production. Each employee who has been with the company at least 1 year also received 0.5 month of paid vacation. All 130 employees currently employed qualify for vacations next year, assuming that they remain on the workforce. Answer the following questions using *Sales and Operations Planning with Spreadsheets* Solver in OM Explorer, or an Excel spreadsheet that you developed on your own.

a. Develop an S&OP with the level strategy, using overtime, undertime, and vacations as the only supply options. Use the maximum amount of overtime so as to minimize undertime. What is the total cost of this plan, and what are its advantages and disadvantages?

b. Develop an S&OP with the chase strategy. Part of your decision will be when and how many vacation periods to grant. What is the total cost of this plan, and what are its advantages and disadvantages?

c. Develop an S&OP with a lower cost than found with either the level or chase strategy, being open to the full range of supply options (including anticipation inventory). Subcontractors can supply up to 50 employee-month equivalents. What is the total cost of this plan, and what are its advantages and disadvantages?

11. Jane Dapna, the operations manager of Classico Inc., is using the *Sales and Operations Planning with Spreadsheets* Solver in OM Explorer to develop a 5-month production plan. Her initial plan is to maintain a level workforce and use overtime and backorders as shown in the table. Use the provided inputs to calculate the derived inputs: Utilized time, Inventory, Hires and Layoffs, and the associated costs. (*Hint*: Don't forget to express the forecasted demand and reactive alternatives as employee-period equivalents.)

Inputs			
Starting Workforce	20	Cost to Hire One Worker	$ 10,000.00
Wages per Worker per Period	$ 4,000.00	Cost to Lay Off One Worker	$ 20,000.00
Overtime Pay Percentage	150%	Initial Inventory Level	10
Subcontracting Cost per Period	0	Initial Backorders	0
		Inventory Cost	$ 100.00
		Backorder Cost	$ 250.00

Period	January	February	March	April	May		Total
Inputs							
Forecasted demand	20	30	40	30	20		140
Workforce level	20	20	20	20	20		100
Undertime	0	0	0	0	0		0
Overtime	0	0	10	20	0		30
Vacation time	0	0	0	0	0		0
Subcontracting time	0	0	0	0	0		0
Backorders	0	0	10	0	0		10
Derived							
Utilized time							100
Inventory							10
Hires							0
Layoffs							0
Calculated							
Utilized time cost							$ 400,000.00
Undertime cost							$ –
Overtime cost							$ 180,000.00
Vacation time cost							$ –
Inventory cost							$ 1,000.00
Backorders cost							$ 2,500.00
Hiring cost							$ –
Layoff cost							$ –
Subcontracting cost							$ –
Total cost							$ 583,500.00
Reminder: Express the forecasted demand and reactive alternatives as employee-period equivalents.							

12. Gemini Inc. is using the *Sales and Operations Planning with Spreadsheets* Solver in OM Explorer to develop a 5-month production plan. Use the provided derived outputs and calculated costs to specify the model's inputs. (*Hint*: Don't forget that the forecasted demand and reactive alternatives are expressed as employee-period equivalents.)

Inputs			
Starting Workforce	20	Cost to Hire One Worker	$ 20,000.00
Wages per Worker per Period	$ 2,500.00	Cost to Lay Off One Worker	$ 5,000.00
Overtime Pay Percentage	150%	Initial Inventory Level	0
Subcontracting Cost per Period	0	Initial Backorders	10
		Inventory Cost	$ 100.00
		Backorder Cost	$ 250.00

Period	January	February	March	April	May		Total
Inputs							
Forecasted demand							165
Workforce level							130
Undertime							0
Overtime							35
Vacation time							0
Subcontracting time							0
Backorders							10
Derived							
Utilized time	20	20	30	30	30		130
Inventory	0	10	15	15	0		40
Hires	0	0	10	0	0		10
Layoffs	0	0	0	0	0		0
Calculated							
Utilized time cost	$ 50,000.00	$ 50,000.00	$ 75,000.00	$ 75,000.00	$ 75,000.00		$ 325,000.00
Undertime cost	$ –	$ –	$ –	$ –	$ –		$ –
Overtime cost	$ –	$ –	$ 56,250.00	$ 37,500.00	$ 37,500.00		$ 131,250.00
Vacation time cost	$ –	$ –	$ –	$ –	$ –		$ –
Inventory cost	$ –	$ 1,000.00	$ 1,500.00	$ 1,500.00	$ –		$ 4,000.00
Backorders cost	$ –	$ –	$ –	$ –	$ 2,500.00		$ 2,500.00
Hiring cost	$ –	$ –	$ 20,000.00	$ –	$ –		$ 20,000.00
Layoff cost	$ –	$ –	$ –	$ –	$ –		$ –
Subcontracting cost	$ –	$ –	$ –	$ –	$ –		$ –
Total cost	$ 50,000.00	$ 51,000.00	$ 152,750.00	$ 114,000.00	$ 115,000.00		$ 482,750.00
Reminder: Express the forecasted demand and reactive alternatives as employee-period equivalents.							

Workforce and Workstation Scheduling

13. Gerald Glynn manages the Michaels Distribution Center. After careful examination of his database information, he has determined the daily requirements for part-time loading dock personnel. The distribution center operates 7 days a week, and the daily part-time staffing requirements are

Day	M	T	W	Th	F	S	Su
Requirements	6	3	5	3	7	2	3

Find the minimum number of workers Glynn must hire. Prepare a workforce schedule for these individuals so that each will have 2 consecutive days off per week and all staffing requirements will be satisfied. Give preference to the S–Su pair in case of a tie.

14. Cara Ryder manages a ski school in a large resort and is trying to develop a schedule for instructors. The instructors receive little salary and work just enough to earn room and board. They receive free skiing and spend most of their free time tackling the resort's notorious double black-diamond slopes. Hence, the instructors work only 4 days a week. One of the lesson packages offered at the resort is a 4-day beginner package. Ryder likes to keep the same instructor with a group over the 4-day period, so she schedules the instructors for 4 consecutive days and then 3 days off. Ryder uses years of experience with demand forecasts provided by management to formulate her instructor requirements for the upcoming month.

Day	M	T	W	Th	F	S	Su
Requirements	7	5	4	5	6	9	8

a. Determine how many instructors Ryder needs to employ. Give preference to Saturday and Sunday off. (*Hint:* Look for the group of 3 days with the lowest requirements.)

b. Specify the work schedule for each employee. How much slack does your schedule generate for each day?

15. The mayor of Cambridge, Colorado, wanting to be environmentally progressive, decides to implement a recycling plan. All residents of the city will receive a special three-part bin to separate their glass, plastic, and aluminum, and the city will be responsible for picking up the materials. A young city and regional planning graduate, Michael Duffy, has been hired to manage the recycling program. After carefully studying the city's

population density, Duffy decides that the following numbers of recycling collectors will be needed:

Day	M	T	W	Th	F	S	Su
Requirements	12	7	9	9	5	3	6

The requirements are based on the populations of the various housing developments and subdivisions in the city and surrounding communities. To motivate residents of some areas to have their pickups scheduled on weekends, a special tax break will be given.

a. Find the minimum number of recycling collectors required if each employee works 5 days a week and has 2 consecutive days off. Give preference to the S–Su pair when that pair is involved in a tie.

b. Specify the work schedule for each employee. How much slack does your schedule generate for each day?

c. Suppose that Duffy can smooth the requirements further through greater tax incentives. The requirements then will be eight collectors on Monday and seven on the other days of the week. How many collectors will be needed now? Does smoothing of requirements have capital investment implications? If so, what are they?

16. Little 6, Inc., an accounting firm, forecasts the following weekly workload during the tax season:

	DAY						
	M	T	W	Th	F	S	Su
Personal Tax Returns	24	14	18	18	10	28	16
Corporate Tax Returns	16	10	12	15	24	12	4

Corporate tax returns each require 4 hours of an accountant's time, and personal returns each require 90 minutes. During tax season, each accountant can work up to 10 hours per day. However, error rates increase to unacceptable levels when accountants work more than 5 consecutive days per week.

Hint: Read Supplement D, "Linear Programming", before doing this problem. Let x_i = number for each working schedule, e.g., x_1 = number for Tuesday through Saturday.

a. Create an effective and efficient work schedule by formulating the problem as a linear program and solve using POM for Windows.

b. Assume that management has decided to offer a pay differential to those accountants who are scheduled to work on a weekend day. Normally, accountants earn $1,200 per week, but management will pay a bonus of $100 for Saturday work and $150 for Sunday work. What schedule will cover all demand as well as minimize payroll cost?

c. Assume that Little 6 has three part-time employees available to work Friday, Saturday, and Sunday at a rate of $800. Could these employees be cost effectively utilized?

17. Return to Problem 13 and the workforce schedule for part-time loading dock workers. Suppose that each part-time worker can work only 3 days, but the days must be consecutive. Formulate and solve this workforce scheduling problem as a linear program and solve it using POM for Windows. Your objective is to minimize total slack capacity. What is the minimum number of loaders needed now, and what are their schedules?

Hint: Read Supplement D, "Linear Programming", before doing this problem. Let x_i = number of workers for each 3-day schedule, for instance, x_1 = number of workers for Tuesday through Thursday.

18. A shipyard services ships and makes it seaworthy as per the regulations. Management schedules overtime during periods of high demand to reduce backlog. The following ships need to be scheduled for servicing:

Ship	Time Since Ship Arrived (days)	Estimated Service Time (days)	Due Date (days from now)
1	6	11	13
2	5	4	9
3	3	17	20
4	2	11	22
5	1	9	24

The due dates reflect the need for the ship to be ready for its next operation at sea.

a. Develop separate schedules by using the FCFS and EDD rules. Compare the schedules on the basis of average flow time and average past due hours.

b. Comment on the performance of the two rules relative to these measures.

19. Currently a company that designs online instructional courses has five customers in its backlog. The day when the order arrived, processing time, and promised due dates are given in the following table. The customers are listed in the order of when they arrived. They are ready to be scheduled today, which is the start of day 95.

Customer	Time Since Order Arrived (days ago)	Processing Time (days)	Due Date (days from now)
1	12	25	30
2	10	17	54
3	8	33	70
4	5	29	63
5	4	37	110

a. Develop separate schedules by using the FCFS and EDD rules. Compare the schedules on the basis of average flow time and average days past due.

b. Comment on the performance of the two rules relative to these measures. Which one gives the best schedule? Why?

20. Zenith Printers specializes in printing wedding cards, business cards, corporate brochures, and marketing leaflets. The company serves a wide range of commercial and noncommercial clients. Due to the closure of its competitor's store, Zenith is flooded with new orders. The shop still has five jobs to be processed as of 7 P.M. today (day 17). The day when the order arrived, processing time, and promised due dates are given in the following table. The jobs are listed in the order of arrival.

Order	Time Since Order Arrived (days ago)	Processing Time (days)	Due Date (days from now)
1	12	12	24
2	9	9	15
3	7	6	21
4	4	3	17
5	1	4	32

a. Develop separate schedules by using the FCFS and EDD rules. Compare the schedules on the basis of average flow time and average days past due.

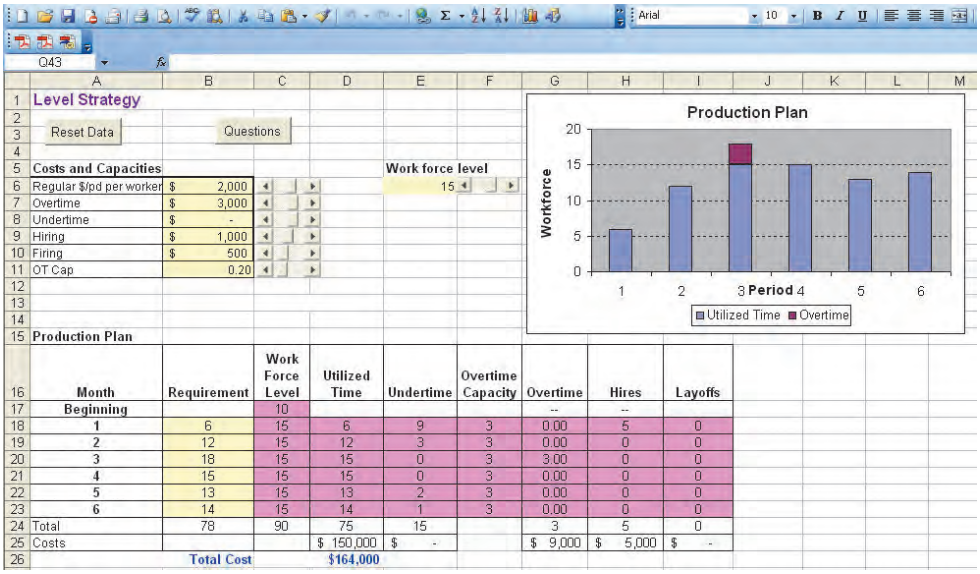
b. Which rule gives the best schedule, in your judgment? Why?

Active Model Exercise

Active Model 10.1, "Level Strategy," is available online. It allows you to evaluate the effects of modifying the size of a constant workforce.

QUESTIONS

1. If we use the same number of workers in each period, what happens as the number of workers increases from 15?
2. If we use the same number of workers in each period, what happens as the number of workers decreases from 15?
3. Suppose the hiring cost is $1,100. What happens as the number of workers increases?
4. Suppose the overtime cost is $3,300. What happens as the number of workers increases?
5. Suppose the undertime cost is the same as the regular-time cost (i.e., paid undertime). What is the best number of workers to have in each month and still meet the demand?
6. If the overtime capacity increases to 30 percent, what is the minimum number of workers that meets the demand in every month?



CASE Memorial Hospital

Memorial Hospital is a 265-bed regional health care facility located in the mountains of western North Carolina. The mission of the hospital is to provide quality health care to the people of Ashe County and the six surrounding counties. To accomplish this mission, Memorial Hospital's CEO has outlined three objectives: (1) maximize customer service to increase customer satisfaction, (2) minimize costs to remain competitive, and (3) minimize fluctuations in workforce levels to help stabilize area employment.

The hospital's operations are segmented into eight major wards for the purposes of planning and scheduling the nursing staff. These wards are listed in Table 10.3, along with the number of beds, targeted patient-to-nurse ratios, and average patient census for each ward. The overall demand for hospital services remained relatively constant over the past few years even though the population of the seven counties served increased. This stable demand can be attributed to increased competition from other hospitals in the area and the rise in alternative health care delivery systems, such as health maintenance organizations (HMOs). However, demand for Memorial Hospital's services does vary considerably by type of ward and time of year. Table 10.4 provides a historical monthly breakdown of the average daily patient census per ward.

TABLE 10.3 | WARD CAPACITY DATA

Ward	Number of Beds	Patients per Nurse	Patient Census*
Intensive Care	20	2	10
Cardiac	25	4	15
Maternity	30	4	10
Pediatric	40	4	22
Surgery	5	†	†
Post-Op	15	5	8 (T–F daily equivalent)‡
Emergency	10	3	5 (daily equivalent)‡
General	120	8	98

* Yearly average per day

† The hospital employs 20 surgical nurses. Routine surgery is scheduled on Tuesdays and Fridays; five surgeries can be scheduled per day per operating room (bed) on these days. Emergency surgery is scheduled as needed.

‡ Daily equivalents are used to schedule nurses because patients flow through these wards in relatively short periods of time. A daily equivalent of 5 indicates that throughout a typical day, an average of five patients are treated in the ward.

TABLE 10.4 | AVERAGE DAILY PATIENT CENSUS PER MONTH

	MONTH											
Ward	J	F	M	A	M	J	J	A	S	O	N	D
Intensive Care	13	10	8	7	7	6	11	13	9	10	12	14
Cardiac	18	16	15	13	14	12	13	12	13	15	18	20
Maternity	8	8	12	13	10	8	13	13	14	10	8	7
Pediatric	22	23	24	24	25	21	22	20	18	20	21	19
Surgery*	20	18	18	17	16	16	22	21	17	18	20	22
Post-Op†	10	8	7	7	6	6	10	10	7	8	9	10
Emergency†	6	4	4	7	8	5	5	4	4	3	4	6
General	110	108	100	98	95	90	88	92	98	102	107	94

* Average surgeries per day on Tuesday and Thursday.

† Daily equivalents

The director of nursing for Memorial Hospital is Darlene Fry. Each fall she confronts one of the most challenging aspects of her job: planning the nurse-staffing levels for the next calendar year. Although the average demand for nurses has remained relatively stable over the past couple of years, the staffing plan usually changes because of changing work policies, changing pay structures, and temporary nurse availability and cost. With fall quickly approaching, Fry is collecting information to plan next year's staffing levels.

The nurses at Memorial Hospital work a regular schedule of four 10-hour days per week. The average regular-time pay across all nursing grades is $12.00 per hour. Overtime may be scheduled when necessary. However, because of the intensity of the demands placed on nurses, only a limited amount of overtime is permitted per week. Nurses may be scheduled for as many as 12 hours per day, for a maximum of 5 days per week. Overtime is compensated at a rate of $18.00 per hour. In periods of extremely high demand, temporary part-time nurses may be hired for a limited period of time. Temporary nurses are paid $15.00 per hour. Memorial Hospital's policy limits the proportion of temporary nurses to 15 percent of the total nursing staff.

Finding, hiring, and retaining qualified nurses is an ongoing problem for hospitals. One reason is that various forms of private practice lure many nurses away from hospitals with higher pay and greater flexibility. This situation has caused Memorial to guarantee its full-time staff nurses pay for a minimum of 30 hours per week, regardless of the demand placed on nursing services. In addition, each nurse receives 4 weeks of paid vacation each year. However, vacation scheduling may be somewhat restricted by the projected demand for nurses during particular times of the year.

At present, the hospital employs 130 nurses, including 20 surgical nurses. The other 110 nurses are assigned to the remaining seven major areas of the hospital. The personnel department informed Fry that the average cost to the hospital for hiring a new full-time nurse is $400 and for laying off or firing a nurse is $150. Although layoffs are an option, Fry is aware of the hospital's objective of maintaining a level workforce.

After looking over the information that she collected, Darlene Fry wants to consider staffing changes in all areas except the surgery ward, which is already correctly staffed.[3]

QUESTIONS

1. Explain the alternatives available to Darlene Fry as she develops a nurse-staffing plan for Memorial Hospital. How does each alternative plan meet the objective stated by the CEO?
2. On the basis of the data presented, develop a nurse-staffing plan for Memorial Hospital. Explain your rationale for this plan.

[3] *Source:* This case was prepared by Dr. Brooke Saladin, Wake Forest University, North Carolina, as a basis for classroom discussion. Copyright © Brooke Saladin. Reprinted with permission.

VIDEO CASE Sales and Operations Planning at Starwood

Business travel often means staying overnight in a hotel. Upon arrival, you may be greeted by a doorman or valet to assist you with your luggage. Front desk staff awaits your check-in. Behind the scenes, housekeeping, maintenance, and culinary staff prepare for your stay. Making a reservation gives the hotel notice of your plan to stay, but even before your trip is ever conceived, the hotel is staffed and ready. How? Through a process called *sales and operations planning*.

Sales and operations planning is a process every organization performs to some degree. Called a staffing plan (or service resource plan if more detailed) in service organizations, the plan must strike the right level of customer service while maintaining workforce stability and cost control so as to achieve the organization's profit expectations. So where do companies begin? Let us take a look at Starwood Hotels and Resorts to see how it is done.

Starwood operates in more than 750 locations around the globe. At the highest levels, Starwood engages in sales and operations planning on an annual basis, with adjustments made as needed each month by region and by property. Budgeted revenues and other projections come from headquarters; the regions and individual properties then break down the forecasts to meet their expected occupancies. Typically, the director of human resources determines the staffing mix needed across divisions such as food and beverage service, rooms (including housekeeping, spa, and guest services), engineering, Six Sigma (see Chapter 3, "Quality and Performance"), revenue management, and accounting.

At the property level, general managers and their staff must provide input into next year's plan while implementing and monitoring activity in the current year. For most properties, payroll is close to 40 percent of budgeted revenues and represents the largest single expense the hotel incurs. It is also the most controllable expense. Many of Starwood's hotels and most resorts experience patterns of seasonality that affect demand for rooms and services. This seasonality, in turn, significantly affects the organization's staffing plan.

To determine the staffing levels, the company uses a proprietary software program that models occupancy demand based on historical data. The key drivers of staffing are occupied rooms and restaurant meals, called "covers." Starwood knows on a *per room* and *per cover* basis how many staff are required to function properly. When occupancy and covers are entered into the software program, the output provides a recommended staffing level for each division. This recommendation is then reviewed by division managers and adjusted as needed to be sure staffing is in line with budgeted financial plans. Job fairs to recruit nonmanagement staff are held several times a year so a qualified candidate pool of both part-time and full-time staff is ready when needed. Most hotels maintain a pool of part-time workers who can contract or expand the hours worked if required by property guest levels. Vacations for management are scheduled for the low season. Overtime will be worked as needed, but is less desirable than scheduling the appropriate level of staff in each division.

The program also takes into account both the complexity and positioning of the property within Starwood. For example, a 400-room city hotel that is essentially a high-rise building is not as complex as a 400-room sprawling resort with golf, spa, convention, and other services not offered by the city hotel. Positioning also is important. A five-star resort hotel's customer service expectations are much greater than a three-star airport hotel location and requires much higher ratios of staff to guests. Finally, if the hotel is a new property, historical data from similar properties are used to model staffing for the first year or two of operation.



Pearson Education

A software program that forecasts occupancy based on historical data helps Starwood maintain proper staffing levels at its hotels. Managers know on a per-room, and "per-cover," basis how many hotel employees should be scheduled so that customers get good service.

Starwood attempts to modify demand and smooth out the peaks and valleys of its demand patterns. Many of the company's hotels experience three seasons: high, mid (called "shoulder"), and low season. Starwood, like its competitors, offers special rates, family packages, and weekend specials to attract different segments of the market during slower business periods. Staff is cross-trained to work in multiple areas, such as front reception and the concierge desk, so additional staff does not have to be added across seasons. Employees may also be temporarily redeployed among Starwood's properties to help out during peak periods. For example, when occupancy is forecast to be high in one region of the country, staff from areas entering their low season will be assigned to cover the demand.

QUESTIONS

1. At what points in the planning process would you expect accounting/finance, marketing, information systems, and operations to play a role? What inputs should these areas provide, and why?
2. Does Starwood employ a chase, level, or mixed strategy? Why is this approach the best choice for the company?
3. How would staffing for the opening of a new hotel or resort differ from that of an existing property? What data might Starwood rely upon to make sure the new property is not over- or understaffed in its first year of operation?

SUPPLEMENT

D

LINEAR PROGRAMMING

LEARNING OBJECTIVES *After reading this supplement, you should be able to:*

- **D.1** Define the seven characteristics of all linear programming models.
- **D.2** Formulate a linear programming model.
- **D.3** Perform a graphic analysis and derive a solution for a two-variable linear programming model.
- **D.4** Use a computer routine to solve a linear programming problem.
- **D.5** Apply the transportation method to sales and operations planning (S&OP) problems.

In many business situations, resources are limited and demand for them is great. For example, a limited number of vehicles may have to be scheduled to make multiple trips to customers, or a staffing plan may have to be developed to cover expected variable demand with the fewest employees. In this supplement, we describe a technique called **linear programming**, which is useful for allocating scarce resources among competing demands. The resources may be time, money, or materials, and the limitations are known as constraints. Linear programming can help managers find the best allocation solution and provide information about the value of additional resources.

linear programming
A technique that is useful for allocating scarce resources among competing demands.

Characteristics of Linear Programming Models

Before we can demonstrate how to solve problems in operations and supply chain management with linear programming, we must first explain seven characteristics of all linear programming models: (1) objective function, (2) decision variables, (3) constraints, (4) feasible region, (5) parameters, (6) linearity, and (7) nonnegativity.

Objective Function Linear programming is an *optimization* process. A single **objective function** states mathematically what is being maximized (e.g., profit or present value) or minimized (e.g., cost or scrap). The objective function provides the scorecard on which the attractiveness of different solutions is judged.

objective function
An expression in linear programming models that states mathematically what is being maximized or minimized.

Decision Variables Solving a linear programming model yields the optimal values for **decision variables**, which represent choices that the decision maker can control. For example, a decision variable could be the number of units of a product to make next month or the number of units of inventory to hold next month. Linear programming is based on the assumption that decision variables are *continuous*; they can be fractional quantities and need not be whole numbers. Often, this assumption is realistic, as when the decision variable is expressed in dollars, hours, or some other continuous measure. Even when the decision variables represent nondivisible units, such as workers, tables, or trucks, we sometimes can simply round the linear

decision variables
Variables that represent the choices the decision maker can control.

programming solution up or down to get a reasonable solution that does not violate any constraints, or we can use a more advanced technique, called *integer programming*.

Constraints Limitations that restrict the permissible choices for the decision variables are called *constraints*. Each limitation can be expressed mathematically in one of three ways: a less-than-or-equal-to (≤), an equal-to (=), or a greater-than-or-equal-to (≥) constraint. A ≤ constraint puts an upper limit on some function of decision variables and most often is used with maximization problems. For example, a ≤ constraint may specify the maximum number of customers who can be served or the capacity limit of a machine. An = constraint means that the function must equal some value. For example, 100 (not 99 or 101) units of one product must be made. An = constraint often is used for certain mandatory relationships, such as the fact that ending inventory always equals beginning inventory plus production minus sales. A ≥ constraint puts a lower limit on some function of decision variables. For example, a ≥ constraint may specify that production of a product must exceed or equal demand.

feasible region
A region that represents all permissible combinations of the decision variables in a linear programming model.

Feasible Region Every linear programming problem must have one or more constraints. Taken together, the constraints define a **feasible region**, which represents all permissible combinations of the decision variables. In some unusual situations, the problem is so tightly constrained that there is only one possible solution—or perhaps none. However, in the usual case, the feasibility region contains infinitely many possible solutions, assuming that the feasible combinations of the decision variables can be fractional values. The goal of the decision maker is to find the best possible solution.

parameter
A value that the decision maker cannot control and that does not change when the solution is implemented.

Parameters The objective function and constraints are functions of decision variables and parameters. A **parameter**, also known as a *coefficient* or *given constant*, is a value that the decision maker cannot control and that does not change when the solution is implemented. Each parameter is assumed to be known with **certainty**. For example, a computer programmer may know that running a software program will take 30 minutes—no more, no less.

certainty
The word that is used to describe that a fact is known without doubt.

linearity
A characteristic of linear programming models that implies proportionality and additivity—there can be no products or powers of decision variables.

Linearity The objective function and constraint equations are assumed to be linear. **Linearity** implies proportionality and additivity—there can be no products (e.g., $10x_1x_2$) or powers (e.g., x_1^3) of decision variables. Suppose that the profit gained by producing two types of products (represented by decision variables x_1 and x_2) is $2x_1 + 3x_2$. Proportionality implies that one unit of x_1 contributes \$2 to profits and two units contribute \$4, regardless of how much of x_1 is produced. Similarly, each unit of x_2 contributes \$3, whether it is the first or the tenth unit produced. Additivity means that the total objective function value equals the profits from x_1 plus the profits from x_2.

nonnegativity
An assumption that the decision variables must be positive or zero.

Nonnegativity Finally, we make an assumption of **nonnegativity**, which means that the decision variables must be positive or zero. A firm that makes spaghetti sauce, for example, cannot produce a negative number of jars. To be formally correct, a linear programming formulation should show a ≥ 0 constraint for each decision variable.

Although the assumptions of linearity, certainty, and continuous variables are restrictive, linear programming can help managers analyze many complex resource allocation problems. The process of building the model forces managers to identify the important decision variables and constraints, which is a useful step in its own right. Identifying the nature and scope of the problem represents a major step toward solving it. In a later section, we show how sensitivity analysis can help the manager deal with uncertainties in the parameters and answer "what-if" questions.

Formulating a Linear Programming Model

Linear programming applications begin with the formulation of a *model* of the problem with the general characteristics just described. We illustrate the modeling process here with the **product-mix problem**, which is a one-period type of planning problem, the solution of which yields optimal output quantities (or product mix) of a group of services or products subject to resource capacity and market demand constraints. This problem was first introduced in Chapter 6, "Constraint Management," and now we take it up more formally. Formulating a model to represent each unique problem, using the following three-step sequence, is the most creative and perhaps the most difficult part of linear programming.

product-mix problem
A one-period type of planning problem, the solution of which yields optimal output quantities (or product mix) of a group of services or products subject to resource capacity and market demand constraints.

Step 1. *Define the Decision Variables.* What must be decided? Define each decision variable specifically, remembering that the definitions used in the objective function must be equally useful in the constraints. The definitions should be as specific as possible. Consider the following two alternative definitions:

x_1 = product 1

x_1 = number of units of product 1 to be produced and sold next month

The second definition is much more specific than the first, making the remaining steps easier.

Step 2. *Write Out the Objective Function.* What is to be maximized or minimized? If it is next month's profits, write out an objective function that makes next month's profits a linear function of the decision variables. Identify parameters to go with each decision variable. For example, if each unit of x_1 sold yields a profit of \$7, the total profit from product $x_1 = 7x_1$. If a variable has no impact on the objective function, its objective function coefficient is 0. The objective function often is set equal to Z, and the goal is to maximize or minimize Z.

Step 3. *Write Out the Constraints.* What limits the values of the decision variables? Identify the constraints and the parameters for each decision variable in them. As with the objective function, the parameter for a variable that has no impact in a constraint is 0. To be formally correct, also write out the nonnegativity constraints.

As a consistency check, make sure that the same unit of measure is being used on both sides of each constraint and in the objective function. For example, suppose that the right-hand side of a constraint is hours of capacity per month. Then, if a decision variable on the left-hand side of the constraint measures the number of units produced per month, the dimensions of the parameter that is multiplied by the decision variable must be hours per unit because

$$\left(\frac{\text{Hours}}{\cancel{\text{Unit}}}\right)\left(\frac{\cancel{\text{Units}}}{\text{Month}}\right) = \left(\frac{\text{Hours}}{\text{Month}}\right)$$

Of course, you can also skip around from one step to another, depending on the part of the problem that has your attention. If you cannot get past step 1, try a new set of definitions for the decision variables. Often the problem can be modeled correctly in more than one way.

Example D.1 demonstrates the approach to formulating a linear programming model for a company that produces plastic pipe.

EXAMPLE D.1 Formulating a Linear Programming Model

The Stratton Company produces two basic types of plastic pipe. Three resources are crucial to the output of pipe: extrusion hours, packaging hours, and a special additive to the plastic raw material. The following data represent next week's situation. All data are expressed in units of 100 feet of pipe.

	PRODUCT		
Resource	**Type 1**	**Type 2**	**Resource Availability**
Extrusion	4 hr	6 hr	48 hr
Packaging	2 hr	2 hr	18 hr
Additive mix	2 lb	1 lb	16 lb

The contribution to profits and overhead per 100 feet of pipe is \$34 for type 1 and \$40 for type 2. Formulate a linear programming model to determine how much of each type of pipe should be produced to maximize contribution to profits and to overhead, assuming that everything produced can be sold.

SOLUTION

Step 1. To define the decision variables that determine product mix, we let

x_1 = amount of type 1 pipe to be produced and sold next week, measured in 100-foot increments (*e.g.*, $x_1 = 2$ means 200 feet of type 1 pipe)

and

x_2 = amount of type 2 pipe to be produced and sold next week, measured in 100-foot increments

Step 2. Next, we define the objective function. The goal is to maximize the total contribution that the two products make to profits and overhead. Each unit of x_1 yields \$34, and each unit of x_2 yields \$40. For specific values of x_1 and x_2, we find the total profit by multiplying the number of units of each product produced by the profit per unit and adding them. Thus, our objective function becomes

$$\text{Maximize: } \$34x_1 + \$40x_2 = Z$$

Step 3. The final step is to formulate the constraints. Each unit of x_1 and x_2 produced consumes some of the critical resources. In the extrusion department, a unit of x_1 requires 4 hours and a unit of x_2 requires 6 hours. The total must not exceed the 48 hours of capacity available, so we use the $\leq$ sign. Thus, the first constraint is

$$4x_1 + 6x_2 \leq 48$$

Similarly, we can formulate constraints for packaging and raw materials:

$$2x_1 + 2x_2 \leq 18 \text{ (packaging)}$$
$$2x_1 + x_2 \leq 16 \text{ (additive mix)}$$

These three constraints restrict our choice of values for the decision variable because the values we choose for x_1 and x_2 must satisfy all of the constraints. Negative values for x_1 and x_2 do not make sense, so we add nonnegativity restrictions to the model:

$$x_1 \geq 0 \text{ and } x_2 \geq 0 \text{ (nonnegativity restrictions)}$$

We can now state the entire model, made complete with the definitions of variables.

$$\begin{aligned} \text{Maximize: } \$34x_1 + \$40x_2 &= Z \\ \text{Subject to: } 4x_1 + 6x_2 &\leq 48 \\ 2x_1 + 2x_2 &\leq 18 \\ 2x_1 + x_2 &\leq 16 \\ x_1 \geq 0 \text{ and } x_2 &\geq 0 \end{aligned}$$

where

x_1 = amount of type 1 pipe to be produced and sold next week, measured in 100-foot increments

x_2 = amount of type 2 pipe to be produced and sold next week, measured in 100-foot increments

Graphic Analysis

graphic method of linear programming
A type of graphic analysis that involves the following five steps: plotting the constraints, identifying the feasible region, plotting an objective function line, finding a visual solution, and finding the algebraic solution.

With the model formulated, we now seek the optimal solution. In practice, linear programming problems are solved with a computer. However, insight into the meaning of the computer output—and linear programming concepts in general—can be gained by analyzing a simple two-variable problem with the **graphic method of linear programming**. Hence, we begin with the graphic method, even though it is not a practical technique for solving problems that have three or more decision variables. The five basic steps are (1) *plot the constraints*, (2) *identify the feasible region*, (3) *plot an objective function line*, (4) *find the visual solution*, and (5) *find the algebraic solution*.

Plot the Constraints

We begin by plotting the constraint equations, disregarding the inequality portion of the constraints ($<$ or $>$). Making each constraint an equality ($=$) transforms it into the equation for a straight line. The line can be drawn as soon as we identify two points on it. Any two points reasonably spread out may be chosen; the easiest ones to find are the *axis intercepts*, where the line intersects each axis. To find the x_1 axis intercept, set x_2 equal to 0 and solve the equation for x_1. For the Stratton Company in Example D.1, the equation of the line for the extrusion process is

$$4x_1 + 6x_2 = 48$$

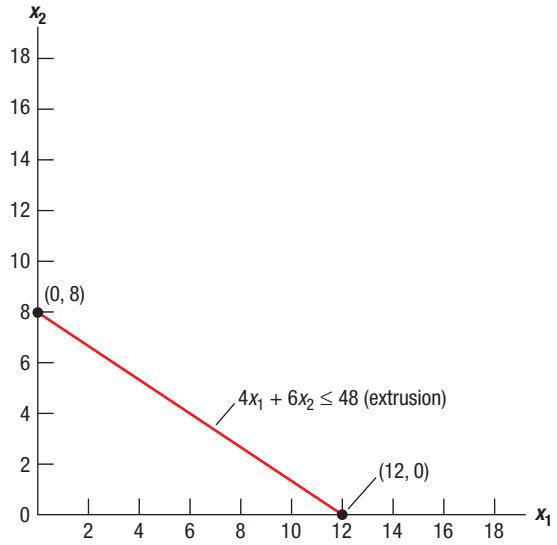
For the x_1 axis intercept, $x_2 = 0$, so

$$\begin{aligned} 4x_1 + 6(0) &= 48 \\ x_1 &= 12 \end{aligned}$$

To find the x_2 axis intercept, set $x_1 = 0$ and solve for x_2:

$$\begin{aligned} 4(0) + 6x_2 &= 48 \\ x_2 &= 8 \end{aligned}$$

We connect points (0, 8) and (12, 0) with a straight line, as shown in Figure D.1.



◀ FIGURE D.1
Graph of the Extrusion Constraint

Example D.2 shows how to plot the constraints for the Stratton Company.

EXAMPLE D.2 Plotting the Constraints

For the Stratton Company problem, plot the other constraints: one constraint for packaging and one constraint for the additive mix.

SOLUTION

The equation for the packaging process's line is $2x_1 + 2x_2 = 18$. To find the x_1 intercept, set $x_2 = 0$:

$$2x_1 + 2(0) = 18$$
$$x_1 = 9$$

To find the x_2 axis intercept, set $x_1 = 0$:

$$2(0) + 2x_2 = 18$$
$$x_2 = 9$$

The equation for the additive mix's line is $2x_1 + x_2 = 16$. To find the x_1 intercept, set $x_2 = 0$:

$$2x_1 + 0 = 16$$
$$x_1 = 8$$

To find the x_2 axis intercept, set $x_1 = 0$:

$$2(0) + x_2 = 16$$
$$x_2 = 16$$

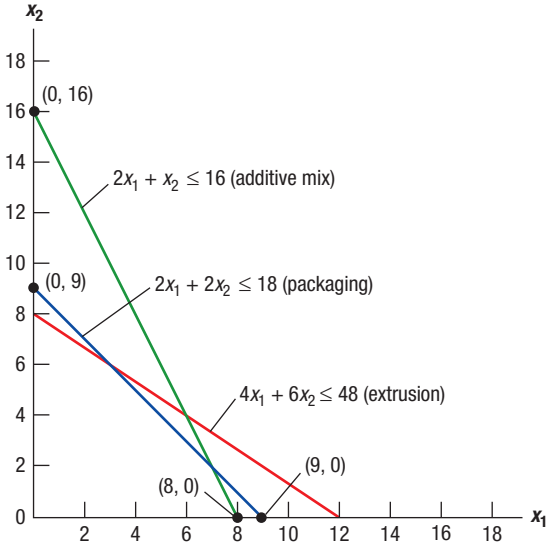
With a straight line, we connect points (0, 9) and (9, 0) for the packaging constraint and points (0, 16) and (8, 0) for the additive mix constraint. Figure D.2 shows the graph with all three constraints plotted.

Online Resources

Active Model D.1 offers many insights on graphic analysis and sensitivity analysis. Use it when studying Examples D.2 through D.4.

Tutor D.1 in OM Explorer provides a new practice example for plotting the constraints.

▼ FIGURE D.2
Graph of the Three Constraints



Identify the Feasible Region

The feasible region is the area on the graph that contains the solutions that satisfy all the constraints simultaneously, including the nonnegativity restrictions. To find the feasible region, first locate the feasible points for each constraint and then the area that satisfies all constraints. Generally, the following three rules identify the feasible points for a given constraint:

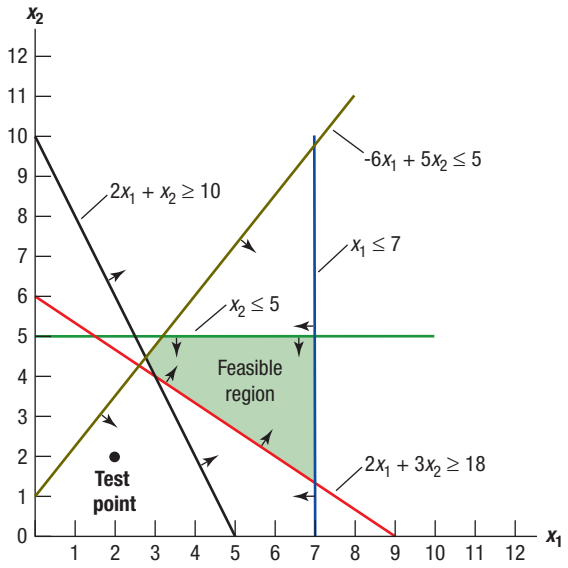
1. For the $=$ constraint, only the points on the line are feasible solutions.
2. For the $\leq$ constraint, the points on the line and the points below or to the left of the line are feasible solutions.
3. For the $\geq$ constraint, the points on the line and the points above or to the right of the line are feasible solutions.

Exceptions to these rules occur when one or more of the parameters on the left-hand side of a constraint are negative. In such cases, we draw the constraint line and test a point on one side of it. If the point does not satisfy the constraint, it is in the infeasible part of the graph. Suppose that a linear programming model has the following five constraints plus the two nonnegativity constraints:

$$\begin{aligned} 2x_1 + x_2 &\geq 10 \\ 2x_1 + 3x_2 &\geq 18 \\ x_1 &\leq 7 \\ x_2 &\leq 5 \\ -6x_1 + 5x_2 &\leq 5 \\ x_1, x_2 &\geq 0 \end{aligned}$$

The feasible region is the shaded portion of Figure D.3. The arrows shown on each constraint identify which side of each line is feasible. The rules work for all but the fifth constraint, which has a negative parameter, -6, for x_1. We arbitrarily select (2, 2) as the test point, which Figure D.3 shows is below the line and to the right. At this point, we find $-6(2) + 5(2) = -2$. Because -2 does not exceed 5, the portion of the figure containing (2, 2) is feasible, at least for this fifth constraint.

FIGURE D.3 ▶
Identifying the Feasible Region



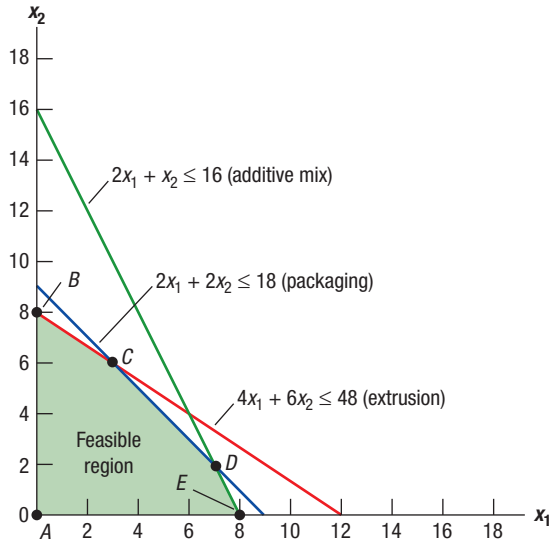
Example D.3 shows that the feasible region is the space that satisfies all the constraints in a problem.

EXAMPLE D.3 **Identifying the Feasible Region**

Identify the feasible region for the Stratton Company problem.

SOLUTION

Because the problem contains only ≤ constraints, and the parameters on the left-hand side of each constraint are not negative, the feasible portions are to the left of and below each constraint. The feasible region, shaded in Figure D.4, satisfies all three constraints simultaneously.



◀ **FIGURE D.4**
Identifying the Feasible Region

Plot the Objective Function Line

Now we want to find the solution that optimizes the objective function. Even though all the points in the feasible region represent possible solutions, we can limit our search to the corner points. A **corner point** lies at the intersection of two (or possibly more) constraint lines on the boundary of the feasible region. No interior points in the feasible region need be considered because at least one corner point is better than any interior point. Similarly, other points on the boundary of the feasible region can be ignored because a corner point is at least as good as any of them.

corner point
A point that lies at the intersection of two (or possibly more) constraint lines on the boundary of the feasible region.

In Figure D.4, the five corner points are marked *A*, *B*, *C*, *D*, and *E*. Point *A* is the origin (0, 0) and can be ignored because any other feasible point is a better solution. We could try each of the other corner points in the objective function and select the one that maximizes *Z*. For example, corner point *B* lies at (0, 8). If we substitute these values into the objective function, the resulting *Z* value is 320:

$$34x_1 + 40x_2 = Z$$
$$34(0) + 40(8) = 320$$

However, we may not be able to read accurately the values of x_1 and x_2 for some of the points (e.g., *C* or *D*) on the graph. Algebraically solving two linear equations for each corner point also is inefficient when there are many constraints and, thus, many corner points.

The best approach is to plot the objective function on the graph of the feasible region for some arbitrary *Z* values. From these objective function lines, we can spot the best solution visually. If the objective function is profits, each line is called an *iso-profit line* and every point on that line will yield the same profit. If *Z* measures cost, the line is called an *iso-cost line* and every point on it represents the same cost. We can simplify the search by plotting the first line in the feasible region—somewhere near the optimal solution, we hope. For the Stratton Company example, let us pass a line through point *E* (8, 0). This point is a corner point. It might even be the optimal solution because it is far from the origin. To draw the line, we first identify its *Z* value as 34(8) + 40(0) = 272. Therefore, the equation for the objective function line passing through *E* is

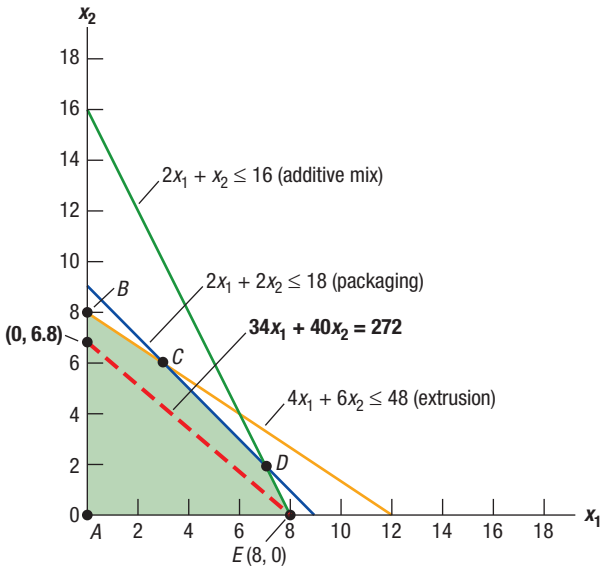
$$34x_1 + 40x_2 = 272$$

Every point on the line defined by this equation has an objective function Z value of 272. To draw the line, we need to identify a second point on it and then connect the two points. Let us use the x_2 intercept, where $x_1 = 0$:

$$34(0) + 40x_2 = 272$$
$$x_2 = 6.8$$

Figure D.5 shows the iso-profit line that connects points (8, 0) and (0, 6.8). A series of other dashed lines could be drawn parallel to this first line. Each would have its own Z value. Lines above the first line we drew would have higher Z values. Lines below it would have lower Z values.

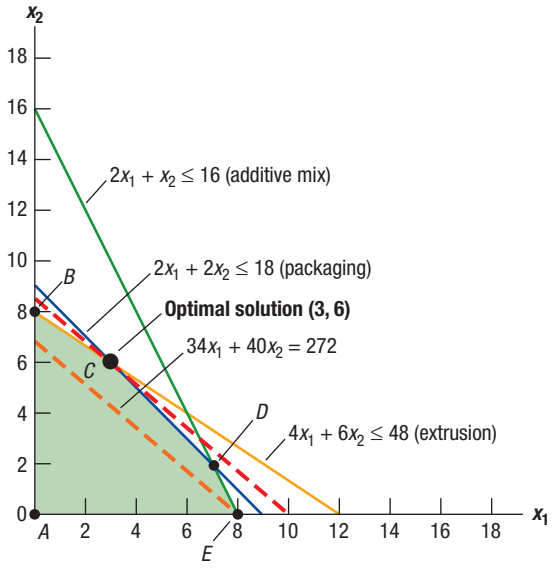
FIGURE D.5 ▶
Passing an Iso-Profit Line Through (8, 0)



Find the Visual Solution

We now eliminate corner points A and E from consideration as the optimal solution because better points lie above and to the right of the $Z = 272$ iso-profit line. Our goal is to maximize profits, so the best solution is a point on the iso-profit line *farthest* from the origin but still touching the feasible region. (For minimization problems, it is a point in the feasible region on the iso-cost line *closest* to the origin.)[1] To identify which of the remaining corner points is optimal (B, C, or D), we draw, parallel to the first line, one or more iso-profit lines that give better Z values (higher for maximization and lower for minimization). The line that just touches the feasible region identifies the optimal solution. For the Stratton Company problem, Figure D.6 shows the second iso-profit

FIGURE D.6 ▶
Drawing the Second Iso-Profit Line



[1]The statements "farthest from the origin" or "closest to the origin" would no longer be true if there are negative coefficients in the objective function.

line. The optimal solution is the last point touching the feasible region: point *C*. It appears to be in the vicinity of (3, 6), but the visual solution is not exact.

A linear programming problem can have more than one optimal solution. This situation occurs when the objective function is parallel to one of the faces of the feasible region. Such would be the case if our objective function in the Stratton Company problem were $\$38x_1 + \$38x_2$. Points (3, 6) and (7, 2) would be optimal, as would any other point on the line connecting these two corner points. In such a case, management probably would base a final decision on nonquantifiable factors. It is important to understand, however, that we need to consider only the corner points of the feasible region when optimizing an objective function.

Find the Algebraic Solution

To find an exact solution, we must use algebra. We begin by identifying the pair of constraints that define the corner point at their intersection. We then list the constraints as equations and solve them simultaneously to find the coordinates x_1, x_2 of the corner point. Simultaneous equations can be solved several ways. For small problems, the easiest way is as follows:

Step 1. Develop an equation with just one unknown. Start by multiplying both sides of one equation by a constant so that the coefficient for one of the two decision variables is *identical* in both equations. Then, subtract one equation from the other and solve the resulting equation for its single unknown variable.

Step 2. Insert this decision variable's value into either one of the original constraints and solve for the other decision variable.

Finding the optimal solution to the Stratton Company problem amounts to solving for the intersection of two of the constraints, as shown in Example D.4.

EXAMPLE D.4 Finding the Optimal Solution Algebraically

Find the optimal solution algebraically for the Stratton Company problem. What is the value of *Z* when the decision variables have optimal values?

Online Resource

Tutor D.2 in OM Explorer provides a new practice example for finding the optimal solution.

SOLUTION

Step 1. Figure D.6 showed that the optimal corner point lies at the intersection of the extrusion and packaging constraints. Listing the constraints as equalities, we have

$$4x_1 + 6x_2 = 48 \text{ (extrusion)}$$
$$2x_1 + 2x_2 = 18 \text{ (packaging)}$$

We multiply each term in the packaging constraint by 2. The packaging constraint now is $4x_1 + 4x_2 = 36$. Next, we subtract the packaging constraint from the extrusion constraint. The result will be an equation from which x_1 has dropped out. (Alternatively, we could multiply the second equation by 3 so that x_2 drops out after the subtraction.) Thus,

$$\begin{aligned} 4x_1 + 6x_2 &= 48 \\ -(4x_1 + 4x_2 &= 36) \\ \hline 2x_2 &= 12 \\ x_2 &= 6 \end{aligned}$$

Step 2. Substituting the value of x_2 into the extrusion equation, we get

$$\begin{aligned} 4x_1 + 6(6) &= 48 \\ 4x_1 &= 12 \\ x_1 &= 3 \end{aligned}$$

Thus, the optimal point is (3, 6). This solution gives a total profit of $34(3) + 40(6) = \$342$.

DECISION POINT

Management at the Stratton Company decided to produce 300 feet of type 1 pipe and 600 feet of type 2 pipe for the next week for a total profit of $342.

Slack and Surplus Variables

Figure D.6 shows that the optimal product mix will exhaust all the extrusion and packaging resources because at the optimal corner point (3, 6) the two constraints are equalities. Substituting the values of x_1 and x_2 into these constraints shows that the left-hand sides equal the right-hand sides:

$$4(3) + 6(6) = 48 \text{ (extrusion)}$$
$$2(3) + 2(6) = 18 \text{ (packaging)}$$

binding constraint

A constraint that helps form the optimal corner point; it limits the ability to improve the objective function.

A constraint (such as the one for extrusion) that helps form the optimal corner point is called a **binding constraint** because it limits the ability to improve the objective function. If a binding constraint is relaxed, or made less restrictive, a better solution is possible. Relaxing a constraint means increasing the right-hand-side parameter for a $\leq$ constraint or decreasing it for a $\geq$ constraint. No improvement is possible from relaxing a constraint that is not binding, such as the additive mix constraint in Figure D.6. If the right-hand side was increased from 16 to 17 and the problem was solved again, the optimal solution would not change. In other words, there is already more additive mix than needed.

slack

The amount by which the left-hand side of a linear programming constraint falls short of the right-hand side.

surplus

The amount by which the left-hand side of a linear programming constraint exceeds the right-hand side.

For nonbinding inequality constraints, knowing how much the left and right sides differ is helpful. Such information tells us how close the constraint is to becoming binding. For a $\leq$ constraint, the amount by which the left-hand side falls short of the right-hand side is called **slack**. For a $\geq$ constraint, the amount by which the left-hand side exceeds the right-hand side is called **surplus**. To find the slack for a $\leq$ constraint algebraically, we *add* a slack variable to the constraint and convert it to an equality. Then, we substitute in the values of the decision variables and solve for the slack. For example, the additive mix constraint in Figure D.6, $2x_1 + x_2 \leq 16$, can be rewritten by adding slack variable s_1:

$$2x_1 + x_2 + s_1 = 16$$

We then find the slack at the optimal solution (3, 6):

$$2(3) + 6 + s_1 = 16$$
$$s_1 = 4$$

The procedure is much the same to find the surplus for a $\geq$ constraint, except that we *subtract* a surplus variable from the left-hand side. Suppose that $x_1 + x_2 \geq 6$ was another constraint in the Stratton Company problem, representing a lower bound on the number of units produced. We would then rewrite the constraint by subtracting a surplus variable s_2:

$$x_1 + x_2 - s_2 = 6$$

Online Resource

Tutor D.3 in OM Explorer provides another practice example for finding slack.

The surplus at the optimal solution (3, 6) would be

$$3 + 6 - s_2 = 6$$
$$s_2 = 3$$

Sensitivity Analysis

Rarely are the parameters in the objective function and constraints known with certainty. Often, they are just estimates of actual values. For example, the available packaging and extrusion hours for the Stratton Company are estimates that do not reflect the uncertainties associated with absenteeism or personnel transfers, and the required hours per unit to package and extrude may be time estimates that essentially are averages. Likewise, profit contributions used for the objective function coefficients do not reflect uncertainties in selling prices and such variable costs as wages, raw materials, and shipping.

Despite such uncertainties, initial estimates are needed to solve the problem. Accounting, marketing, and time-standard information systems (see online Supplement H, "Measuring Output Rates") often provide these initial estimates. After solving the problem using these estimated values, the analyst can determine how much the optimal values of the decision variables and the objective function value Z would be affected if certain parameters had different values. This type of postsolution analysis for answering "what-if" questions is called *sensitivity analysis*.

One way of conducting sensitivity analysis for linear programming problems is the brute-force approach of changing one or more parameter values and resolving the entire problem. This approach may be acceptable for small problems, but it is inefficient if the problem involves many parameters. For example, brute-force sensitivity analysis using three separate values for each of 20 objective function coefficients requires 3^{20}, or 3,486,784,401, separate solutions! Fortunately, efficient methods are available for getting sensitivity information without resolving the entire problem, and they are routinely used in most linear programming computer software packages. Table D.1 describes the four basic types of sensitivity analysis information provided by linear programming.

TABLE D.1 | SENSITIVITY ANALYSIS INFORMATION PROVIDED BY LINEAR PROGRAMMING

Key Term	Definition
Reduced cost	How much the objective function coefficient of a decision variable must improve (increase for maximization or decrease for minimization) before the optimal solution changes and the decision variable "enters" the solution with some positive number.
Shadow price	The marginal improvement in Z (increase for maximization and decrease for minimization) caused by relaxing the constraint by one unit.
Range of optimality	The interval (lower and upper bounds) of an objective function coefficient over which the optimal values of the decision variables remain unchanged.
Range of feasibility	The interval (lower and upper bounds) over which the right-hand-side parameter of a constraint can vary while its shadow price remains valid.

Computer Analysis

Most real-world linear programming problems are solved on a computer, so we concentrate here on understanding the use of linear programming and the logic on which it is based. The solution procedure in computer codes is some form of the **simplex method**, which is an iterative algebraic procedure for solving linear programming problems.

simplex method
An iterative algebraic procedure for solving linear programming problems.

Simplex Method

The graphic analysis gives insight into the logic of the simplex method, beginning with the focus on corner points. If there is any feasible solution to a problem, at least one corner point will always be the optimum, even when multiple optimal solutions are available. Thus, the simplex method starts with an initial corner point and then systematically evaluates other corner points in such a way that the objective function improves (or, at worst, stays the same) at each iteration. In the Stratton Company problem, an improvement would be an increase in profits. When no more improvements are possible, the optimal solution has been found.[2] The simplex method also helps generate the sensitivity analysis information that we developed graphically.

Each corner point has no more than m variables that are greater than 0, where m is the number of constraints (not counting the nonnegativity constraints). The m variables include slack and surplus variables, not just the original decision variables. Because of this property, we can find a corner point by simultaneously solving m constraints, where all but m variables are set equal to 0. For example, point B in Figure D.6 has three nonzero variables: x_2, the slack variable for packaging, and the slack variable for the additive mix. Their values can be found by simultaneously solving the three constraints, with x_1 and the slack variable for extrusion equal to 0. After finding this corner point, the simplex method applies information similar to the reduced costs to decide which new corner point to find next that gives an even better Z value. It continues in this way until no better corner point is possible. The final corner point evaluated is the optimal one.

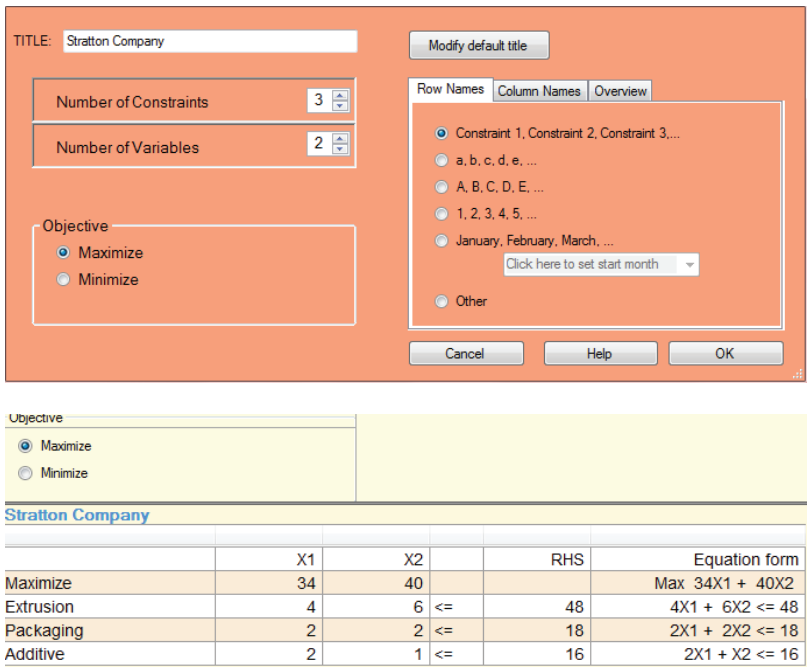
Computer Output

Computer programs dramatically reduce the amount of time required to solve linear programming problems. The capabilities and displays of software packages are not uniform. For example, POM for Windows can handle small to midsize linear programming problems. Inputs are made easily and nonnegativity constraints need not be entered. Microsoft's *Excel* Solver offers a second option for similar problem sizes. More advanced software for larger problems is available from multiple sources.

Here we show output from POM for Windows when applied to the Stratton Company. Figure D.7 shows the two *data entry* screens. The first screen allows you to enter the problem's name, specify the number of constraints and decision variables, and choose between maximization and minimization. After making these inputs and clicking the "OK" button, the data table screen is shown. Enter the parameters, give names to each constraint and decision variable (as desired), and specify the type of relationship ($\leq$, $=$, $\geq$) for each constraint. The second screen in Figure D.7 shows the completed data table. The user may customize labels for the decision variables, right-hand-side values, and constraints. Here, the first decision variable is labeled "X1," the right-hand-side values "RHS," and the extrusion constraint "Extrusion." Slack and surplus variables will be added automatically as needed. When all of the inputs are made, click the arrow labeled "Solve" in the upper-right corner.

[2]For more information on how to perform the simplex method manually, see Render, Barry, Ralph M. Stair, Michael E. Hanna, and Trevor S. Hale, *Quantitative Analysis for Management* (13th ed.) or any other current textbook on management science.

FIGURE D.7 ▶
Data Entry Screens



	X1	X2		RHS	Equation form
Maximize	34	40			Max 34X1 + 40X2
Extrusion	4	6	<=	48	4X1 + 6X2 <= 48
Packaging	2	2	<=	18	2X1 + 2X2 <= 18
Additive	2	1	<=	16	2X1 + X2 <= 16

Figure D.8 displays the solution with the *Results* screen. All output confirms our earlier calculations and the graphic analysis. Of particular interest is the bottom row that gives the optimal values of the decision variables ($x_1 = 3$ and $x_2 = 6$), and also the optimal value of the objective function ($342). The shadow prices for each constraint are given in the last column.

FIGURE D.8 ▶
Results Screen

Stratton Company Solution

	X1	X2		RHS	Shadow Price
Maximize	34	40			
Constraint 1	4	6	<=	48	3
Constraint 2	2	2	<=	18	11
Constraint 3	2	1	<=	16	0
Solution	3	6		342	

Click on the Window icon and select the second option in the drop-down menu to switch to the *Ranging* screen, as shown in Figure D.9. The top half deals with the decision variables. Of particular interest are the reduced costs and the lower and upper bounds. Two tips on interpreting the *reduced cost* information are as follows:

1. It is relevant only for a decision variable that is 0 in the optimal solution. If the decision variable is greater than 0, ignore the reduced cost number. Thus, for the Stratton Company problem the reduced cost numbers provide no new insight because they are always 0 when decision variables have positive values in the optimal solution. Look instead at the lower and upper bounds on the objective function coefficients.
2. It tells how much the objective function coefficient of a decision variable that is 0 in the optimal solution must *improve* (increase for maximization problems or decrease for minimization problems) before the optimal solution would change. At that point, the decision variable associated with the coefficient enters the optimal solution at some positive level. To learn the new solution, apply POM for Windows again with a coefficient improved by slightly more than the reduced cost number.

The top half of this screen also gives the *range of optimality*, or the lower and upper bound over which the objective function coefficients can range without affecting the optimal values of the decision variables. Note that the objective function coefficient for x_1, which currently has a value of $34, has a range of optimality from $26.67 to $40. While the objective function's Z value would change with coefficient changes over this range, the optimal values of the decision variables remain the same.

The bottom half of Figure D.9 deals with the constraints, including the slack or surplus variables and the original right-hand-side values. Of particular interest are the shadow prices. Two tips on interpreting a *shadow price* follow:

1. The number is relevant only for a binding constraint, where the slack or surplus variable is 0 in the optimal solution. For a nonbinding constraint, the shadow price is 0.
2. The sign of the shadow price can be positive or negative. The sign depends on whether the objective function is being maximized or minimized, and whether it is a $\leq$ constraint or $\geq$ constraint. If you simply ignore the sign, interpret the shadow price as the benefit of increasing the right-hand side by one unit of resource for a $\leq$ constraint and reducing it by one unit of resource for a $\geq$ constraint. The benefit is a reduction in the objective function value for minimization problems, and an increase for maximization problems. The shadow price can also be interpreted as the marginal loss (or penalty) in Z caused by making the constraint more restrictive by one unit of resource.

▼ **FIGURE D.9**
Ranging Screen

Variable	Value	Reduced Cost	Original Val	Lower Bound	Upper Bound
X1	3	0	34	26.67	40
X2	6	0	40	34	51
	Shadow Price	Slack/Surplus	Original Val	Lower Bound	Upper Bound
Constraint 1	3	0	48	40	54
Constraint 2	11	0	18	16	20
Constraint 3	0	4	16	12	Infinity

Thus, the Stratton Company problem has 4 pounds of the additive mix slack, so the shadow price is $0. Packaging, in contrast, is a binding constraint because it has no slack. The shadow price of one more packaging hour is $11. Example D.5 shows how shadow prices can be used for decision making.

EXAMPLE D.5 Using Shadow Prices for Decision Making

The Stratton Company needs answers to three important questions: (1) Would increasing capacities in the extrusion or packaging area pay if it cost an extra $8 per hour over and above the normal costs already reflected in the objective function coefficients? (2) Would increasing packaging capacity pay if it cost an additional $6 per hour? (3) Would buying more raw materials pay?

SOLUTION

Expanding extrusion capacity would cost a premium of $8 per hour, but the shadow price for that capacity is only $3 per hour. However, expanding packaging hours would cost only $6 per hour more than the price already reflected in the objective function, and the shadow price is $11 per hour. Finally, buying more raw materials would not pay because a surplus of 4 pounds already exists; the shadow price is $0 for that resource.

DECISION POINT

Management decided to increase its packaging capacity but did not decide to expand extrusion capacity or buy more raw materials.

Finally, Figure D.9 reports the lower and upper bounds for the *range of feasibility*, over which the right-hand-side parameters can range without changing the shadow prices. For example, the $11 shadow price for packaging is valid over the range from 16 to 20 hours.

The number of variables in the optimal solution (counting the decision variables, slack variables, and surplus variables) that are greater than 0 never exceeds the number of constraints. Such is the case for the Stratton Company problem, with its three constraints (not counting the implicit nonnegativity constraints) and three nonzero variables in the optimal solution (x_1, x_2, and the additive mix slack variable). On some rare occasions, the number of nonzero variables in the optimal solution can be less than the number of constraints—a condition called **degeneracy**. When degeneracy occurs, the sensitivity analysis information is suspect. If you want more "what-if" information, simply run your software package again using the new parameter values that you want to investigate.

degeneracy
A condition that occurs when the number of nonzero variables in the optimal solution is less than the number of constraints.

The Transportation Method

transportation problem
A special case of linear programming that has linear constraints for capacity limitations and demand requirements.

A special case of linear programming is the **transportation problem**, which can be represented as a standard table, sometimes called a *tableau*. Figure D.10 is an example, where the rows are supply sources and the columns are demands. Both the supplies and demands can be broken down into several periods into the future. Typically, the rows of the table are linear constraints that impose capacity limitations, and the columns are linear constraints that require certain demand levels to be met. Each cell in the tableau is a decision variable, and a per-unit cost is shown in the upper-right corner of each cell. Figure D.10 implies 52 decision variables (13 rows × 4 columns) and 17 constraints (13 rows + 4 columns).

transportation method
A more efficient solution technique than the simplex method for solving transportation problems.

Transportation problems can be formulated as a conventional linear programming problem and solved as usual. The **transportation method** simplifies data input and is a more efficient solution technique, but it does not provide sensitivity analysis as in Figure D.9, nor can you add any constraints on the decision variables beyond capacity and demand. Here we show how production-planning problems can be formulated as transportation problems. Chapter 13, "Supply Chain Logistic Networks," shows an entirely different application of the transportation method: how to solve location problems. We focus on the setup and interpretation of the problem, leaving the rest of the solution process to a computer software package.

Transportation Method for Sales and Operations Planning

Making sure that demand and supply are in balance is central to sales and operations planning (S&OP), so it is no surprise that the transportation method can be applied to it. The *transportation method for sales and operations planning* is particularly helpful in determining anticipation inventories. Thus, it relates more to manufacturers' production plans than to service providers' staffing plans. In fact, the workforce levels for each period are inputs to the transportation method rather than outputs from it. Different workforce adjustment plans should be evaluated. Thus, several transportation method solutions may be obtained before a final plan is selected.

FIGURE D.10 ▶
Example of Transportation Tableau

Source of Supply		Time Period 1	2	3	4	Capacity
Period	Initial Inventory					
1	Type 1					
	Type 2					
	Type 3					
2	Type 1					
	Type 2					
	Type 3					
3	Type 1					
	Type 2					
	Type 3					
4	Type 1					
	Type 2					
	Type 3					
Demand						

Using the transportation method for production planning is based on the assumption that a demand forecast is available for each period, along with a possible workforce adjustment plan. Capacity limits on overtime and the use of subcontractors also are needed for each period. Another assumption is that all costs are linearly related to the amount of goods produced; that is, a change in the amount of goods produced creates a proportionate change in costs.

To develop a sales and operations plan for a manufacturer, we do the following:

1. Obtain the demand forecasts for each period to be covered by the sales and operations plan and identify the initial inventory level currently available that can be used to meet future demand.
2. Select a candidate workforce adjustment plan, using a chase strategy, level strategy, or a mixed strategy. Specify the capacity limits of each production alternative (regular time, overtime, and subcontracting) for each period covered by the plan.
3. Estimate the cost of holding inventory and the cost of possible production alternatives (regular-time production, overtime production, and subcontracting). Translate all costs to a common unit of measure, such as a unit of product. For example, regular-time wages, overtime wages, inventory holding costs, and so on could be expressed as dollars per unit. Identify the cost of undertime, if idle regular-time capacity is paid.
4. Input the information gathered in steps 1 through 3 into a computer routine that solves the transportation problem. After getting the solution, calculate the anticipation inventory levels and identify high-cost elements of the plan.
5. Repeat the process with other plans for regular-time, overtime, and subcontracting capacities until you find the solution that best balances cost and qualitative considerations. Even though this process involves trial and error, the transportation method yields the best mix of regular time, overtime, and subcontracting for each supply plan.

Example D.6 demonstrates this approach using the *Transportation Method (Production Planning)* module in the POM for Windows package.

EXAMPLE D.6 Preparing a Production Plan with the Transportation Method

The Tru-Rainbow Company produces a variety of paint products for both commercial and private use. The demand for paint is highly seasonal, peaking in the third quarter. Initial inventory is 250,000 gallons, and ending inventory should be 300,000 gallons.

Tru-Rainbow's manufacturing manager wants to determine the best production plan using the following demand requirements and capacity plan. Demands and capacities here are expressed in thousands of gallons (rather than employee-period equivalents). The manager knows that the regular-time cost is $1.00 per unit, overtime cost is $1.50 per unit, subcontracting cost is $1.90 per unit, and inventory holding cost is $0.30 per unit per quarter. Undertime is paid and the cost is $0.50 per unit. It is less than the regular-time cost because only labor costs are involved, not materials and variable overhead going into paint production.

	Demand	Regular-time Capacity	Overtime Capacity	Subcontractor Capacity
Quarter 1	300	450	90	200
Quarter 2	850	450	90	200
Quarter 3	1,500	750	150	200
Quarter 4	350	450	90	200
Totals	3,000	2,100	420	800

The following constraints apply:

a. The maximum allowable overtime in any quarter is 20 percent of the regular-time capacity in that quarter.
b. The subcontractor can supply a maximum of 200,000 gallons in any quarter. Production can be subcontracted in one period and the excess held in inventory for a future period to avoid a stockout.
c. No planned backorders or stockouts are permitted.

SOLUTION

Figure D.11 shows the POM for Windows screen of data inputs. Figure D.12 shows the POM for Windows screen that displays the optimal solution for this particular workforce adjustment plan. It looks much like the table shown previously, but with one exception. The demand for quarter 4 is shown to be 650,000 gallons rather than the demand forecast of only 350,000. The larger number reflects the desire of the manager to have an ending inventory in quarter 4 of 300,000 gallons. Some points to note in Figure D.12 include the following:

1. There is a row in Figure D.12 for each supply alternative (instead of the "source of supply" in Figure D.10) on a quarter-by-quarter basis. The first row is the initial inventory available, and the rows that follow are for regular-time, overtime, and subcontracting production in each of the four quarters. The initial inventory can be used to satisfy demand in any of the four quarters. The second row (regular-time production in period 1) can also be used to satisfy demand in any of the four periods the plan will cover, and so on. The numbers in the last column give the maximum capacity made available for the supply alternatives. For example, the regular-time capacity for quarter 3 increases from the usual 450,000 gallons to 750,000 gallons, to help with the peak demand forecasted to be 1,500,000 gallons.
2. A column indicates each future quarter of demand, and the last row gives its demand forecast. The demand for the fourth quarter is shown to be 650 units, because it includes the desired amount of ending inventory. The Excess Capacity column shows the unused capacity, and the number in the last row (270 units) is the amount by which total capacity exceeds total demand.

▼ **FIGURE D.11**
POM for Windows Screen for Tru-Rainbow Company

Period	Demand	Regular tm Capacity	Overtime Capacity	Subcontract Capacity		Unit costs	Value
Quarter 1	300	450	90	200		Regular time	1
Quarter 2	850	450	90	200		Overtime	1.5
Quarter 3	1500	750	150	200		Subcontracting	1.9
Quarter 4	650	450	90	200		Holding/carrying cost	.3
						Backorder cost	Not allowed
						Idle RT Capacity cost	.5
						Initial Inventory	250

▼ **FIGURE D.12**
Solution Screen for Prospective Tru-Rainbow Company Production Plan

Tru-Rainbow Company Solution

Optimal cost = $4,010	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Excess Capacity	Capacity
Init Inventory	230		20			250
Quarter 1 RegTime	50	400				450
Quarter 1 Overtime			90			90
Quarter 1 Subcontract	20				180	200
Quarter 2 RegTime		450				450
Quarter 2 Overtime			90			90
Quarter 2 Subcontract			200			200
Quarter 3 RegTime			750			750
Quarter 3 Overtime			150			150
Quarter 3 Subcontract			200			200
Quarter 4 RegTime				450		450
Quarter 4 Overtime				90		90
Quarter 4 Subcontract				110	90	200
Demand	300	850	1500	650	270	

3. The least expensive alternatives are those in which the output is produced and sold in the same period. For example, the cost for quarter 4 overtime production is only $1.50 per gallon because it is designated to meet demand in quarter 4 (row 12, column 4). The cost of overtime in quarter 2 increases to $1.80 because it is designated for quarter 3 demand. However, we may not always be able to avoid alternatives that create inventory because of capacity restrictions.
4. The first row in Figure D.12 shows that 230 units of the initial inventory are used to help satisfy the demand in quarter 1. The remaining 20 units in the first row are earmarked for helping supply the demand in quarter 3. The sum of the allocations across row 1 for the four quarters (230 + 0 + 20 + 0) does not exceed the maximum capacity of 250, given in the right column. With the transportation method, this result must occur with each row. Any shortfalls are unused capacity, given in the "Excess Capacity" column. In this case, the undertime cost of $0.50 per unit was sufficiently large that no regular-time capacity went unused.

   Similarly, the sum of the allocations down each column must equal the total demand for the quarter. For example, the demand for quarter 1 is supplied from 230 units of the initial inventory, 50 units of quarter 1 regular-time production, and 20 units of quarter 1 subcontracting production. Summed together, they equal the forecasted demand of 300 units.

To further interpret the solution, we can convert Figure D.12 into the following table. For example, the total regular-time production in quarter 1 is 450,000 gallons (50,000 gallons to help meet demand in quarter 1 and 400,000 gallons to help satisfy demand in quarter 2).

The anticipation inventory held at the end of each quarter is obtained in the last column. For any quarter, it is the quarter's beginning inventory plus total supply (regular-time and overtime production, plus subcontracting) minus demand. For example, for quarter 1 the beginning inventory (250,000) plus the total from production and subcontracting (560,000) minus quarter 1 demand (300,000) results in an ending inventory of 510,000, which also is the beginning inventory for quarter 2.

Quarter	Regular-time Production	Overtime Production	Subcontracting	Total Supply	Anticipation Inventory
1	450	90	20	560	250 + 560 − 300 = 510
2	450	90	200	740	510 + 740 − 850 = 400
3	750	150	200	1,100	400 + 1,100 − 1,500 = 0
4	450	90	110	650	0 + 650 − 350 = 300
Totals	2,100	420	530	3,050	

Note: Anticipation inventory is the amount at the end of each quarter, where Beginning inventory + Total production − Actual Demand = Ending inventory.

The breakdown of costs can be found by multiplying the allocation in each cell of Figure D.12 by the cost per unit in that cell in the last column of Figure D.11. Computing the cost column by column (it can also be done on a row-by-row basis) yields a total cost of $4,010,000, or $4,010 × 1,000.

	Cost Calculations by Column	
Quarter 1	230($0) + 50($1.00) + 20($1.90)	= $ 88
Quarter 2	400($1.30) + 450($1.00)	= $ 970
Quarter 3	20($0.60) + 90($2.10) + 90($1.80) + 200($2.20)+ 750($1.00) + 150($1.50) + 200($1.90)	= $2,158
Quarter 4	450($1.00) + 90($1.50) + 110($1.90)	= $ 794
		Total = $4,010

DECISION POINT

This plan requires too much overtime and subcontracting, and the anticipation inventory cost is substantial. The manager decided to search for a better capacity plan—with increases in the workforce to boost regular-time production capacity—that could lower production costs, perhaps even low enough to offset the added capacity costs.

Many problems in operations and supply chain management, and in other functional areas, lend themselves to linear programming and the transportation method. In addition to the examples already introduced in this supplement, applications also exist in process management, constraint management, shipping assignments, inventory control, and shift scheduling. The review problems at the end of this supplement and at the end of previous chapters illustrate many of these types of problems. Once the decision maker knows how to formulate a problem generally, he or she can then adapt it to the situation at hand.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
D.1 Define the seven characteristics of all linear programming models.	See the section "Characteristics of Linear Programming Models."	
D.2 Formulate a linear programming model.	Review the section "Formulating a Linear Programming Model" and pay particular attention to Example D.1.	
D.3 Perform a graphic analysis and derive a solution for a two-variable linear programming model.	See the section "Graphic Analysis," where we show how to plot the constraints, identify the feasible region, plot the objective function, and find the solution. Do not overlook the sections on slack and surplus variables and sensitivity analysis because they will set the foundation for the use of computers. Review Solved Problem 1.	**Active Model Exercise:** D.1: LP Graph **POM for Windows:** Linear Programming **OM Explorer Tutors:** D.1: Plotting the Constraints; D.2: Finding the Optimal Solution; D.3: Finding Slack at the Optimal Solution; D.4: Graphic and Algebraic Solution
D.4 Use a computer routine to solve a linear programming problem.	The section "Computer Analysis" goes into detail as to how computers can be used to solve linear programming problems. Computer output from POM for Windows is displayed and interpreted. Key information relates to the optimal values of the decision variables, objective function value, slack variables, and surplus variables. The shadow prices, reduced costs, lower bounds, and upper bounds can be valuable information for sensitivity analysis.	**POM for Windows:** Linear Programming
D.5 Apply the transportation method to Sales and Operations Planning (S&OP) problems.	The section "The Transportation Method" gives a step-by-step description on how to set up the problem as a transportation problem and then how to interpret the POM for Windows output. Pay particular attention to Figures D.11 and D.12. Example D.6 and Solved Problem 2 are also helpful.	**POM for Windows:** Transportation Method (Production Planning)

Key Terms

binding constraint 460
certainty 452
corner point 457
decision variables 451
degeneracy 463
feasible region 452
graphic method of linear programming 454
linearity 452
linear programming 451
nonnegativity 452
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Solved Problem 1

Online Resource

Tutor D.4 in OM Explorer provides a practice example for finding the graphic and algebraic solution.

O'Connel Airlines is considering air service from its hub of operations in Cicely, Alaska, to Rome, Wisconsin, and Seattle, Washington. O'Connel has one gate at the Cicely Airport, which operates 12 hours per day. Each flight requires 1 hour of gate time. Each flight to Rome consumes 15 hours of pilot crew time and is expected to produce a profit of $2,500. Serving Seattle uses 10 hours of pilot crew time per flight and will result in a profit of $2,000 per flight. Pilot crew labor is limited to 150 hours per day. The market for service to Rome is limited to nine flights per day.

a. Use the graphic method of linear programming to maximize profits for O'Connel Airlines.

b. Identify positive slack and surplus variables, if any.

SOLUTION

a. The objective function is to maximize profits, Z:

$$\text{Maximize:} \quad \$2{,}500x_1 + \$2{,}000x_2 = Z$$

where

x_1 = number of flights per day to Rome, Wisconsin
x_2 = number of flights per day to Seattle, Washington

The constraints are

$$\begin{aligned} x_1 + x_2 &\le 12 \text{ (gate capacity)} \\ 15x_1 + 10x_2 &\le 150 \text{ (labor)} \\ x_1 &\le 9 \text{ (market)} \\ x_1 \ge 0 &\text{ and } x_2 \ge 0 \end{aligned}$$

A careful drawing of iso-profit lines parallel to the one shown in Figure D.13 will indicate that point D is the optimal solution. It is at the intersection of the labor and gate capacity constraints. Solving algebraically, we get

$$\begin{aligned} 15x_1 + 10x_2 &= 150 \text{ (labor)} \\ -10x_1 - 10x_2 &= -120 \text{ (gate} \times -10) \\ 5x_1 + 0x_2 &= 30 \\ x_1 &= 6 \\ 6 + x_2 &= 12 \text{ (gate)} \\ x_2 &= 6 \end{aligned}$$

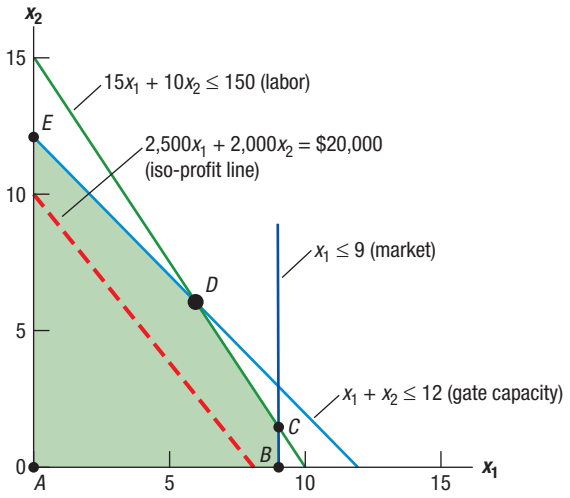
The maximum profit results from making six flights to Rome and six flights to Seattle:

$$\$2{,}500(6) + \$2{,}000(6) = \$27{,}000$$

b. The market constraint has three units of slack, so the demand for flights to Rome is not fully met:

$$\begin{aligned} x_1 &\le 9 \\ x_1 + s_3 &= 9 \\ 6 + s_3 &= 9 \\ s_3 &= 3 \end{aligned}$$

▼ **FIGURE D.13**
Graphic Solution for O'Connel Airlines



Solved Problem 2

The Arctic Air Company produces residential air conditioners. The manufacturing manager wants to develop a sales and operations plan for the next year based on the following demand and capacity data (in hundreds of product units):

	Demand	Regular-time Capacity	Overtime Capacity	Subcontractor Capacity
Jan–Feb (1)	50	65	13	10
Mar–Apr (2)	60	65	13	10
May–Jun (3)	90	65	13	10
Jul–Aug (4)	120	80	16	10
Sep–Oct (5)	70	80	16	10
Nov–Dec (6)	40	65	13	10
Totals	430	420	84	60

Undertime is unpaid, and no cost is associated with unused overtime or subcontractor capacity. Producing one air conditioning unit on regular time costs $1,000, including $300 for labor. Producing a unit on overtime costs $1,150. A subcontractor can produce a unit to Arctic Air specifications for $1,250. Holding an air conditioner in stock costs $60 for each 2-month period, and 200 air conditioners are currently in stock. The plan calls for 400 units to be in stock at the end of period 6. No backorders are allowed. Use the transportation method to develop a plan that minimizes costs.

SOLUTION

The following tables identify the optimal production and inventory plans. Figure D.14 shows the tableau that corresponds to this solution. An arbitrarily large cost ($99,999 per period) was used for backorders, which effectively ruled them out. Again, all production quantities are in hundreds of units. Note that demand in period 6 is 4,400. That amount is the period 6 demand plus the desired ending inventory of 400. The anticipation inventory is measured as the amount at the end of each period. Cost calculations are based on the assumption that workers are not paid for undertime or are productively put to work elsewhere in the organization whenever they are not needed for this work.

FIGURE D.14 ▶
Tableau for Optimal Production and Inventory Plans

Alternatives		Time Period 1	2	3	4	5	6	Unused Capacity	Total Capacity
Period	Initial Inventory	0	60	120	180 2	240	300	0	2
1	Regular time	1,000 50	1,060 15	1,120	1,180	1,240	1,300	0	65
	Overtime	1,150	1,210	1,270	1,330	1,390	1,450	13	13
	Subcontract	1,250	1,310	1,370	1,430	1,490	1,550	10	10
2	Regular time	99,999	1,000 41	1,060 12	1,120 12	1,180	1,240	0	65
	Overtime	99,999	1,150 4	1,210	1,270	1,330	1,390	9	13
	Subcontract	99,999	1,250	1,310	1,370	1,430	1,490	10	10
3	Regular time	99,999	99,999	1,000 65	1,060	1,120	1,180	0	65
	Overtime	99,999	99,999	1,150 13	1,210	1,270	1,330	0	13
	Subcontract	99,999	99,999	1,250	1,310	1,370	1,430	10	10
4	Regular time	99,999	99,999	99,999	1,000 80	1,060	1,120	0	80
	Overtime	99,999	99,999	99,999	1,150 16	1,210	1,270	0	16
	Subcontract	99,999	99,999	99,999	1,250 10	1,310	1,370	0	10
5	Regular time	99,999	99,999	99,999	99,999	1,000 70	1,060	10	80
	Overtime	99,999	99,999	99,999	99,999	1,150	1,210	16	16
	Subcontract	99,999	99,999	99,999	99,999	1,250	1,310	10	10
6	Regular time	99,999	99,999	99,999	99,999	99,999	1,000 44	21	65
	Overtime	99,999	99,999	99,999	99,999	99,999	1,150	13	13
	Subcontract	99,999	99,999	99,999	99,999	99,999	1,250	10	10
Demand		50	60	90	120	70	44	132	566

One initially puzzling aspect of this solution is that it allocates the initial inventory of 200 units to meet demand in period 4 rather than in period 1. The explanation is that multiple optimal solutions exist and this solution is only one of them. However, all solutions result in the same production and anticipation inventory plans derived as follows:

PRODUCTION PLAN

Period	Regular-time Production	Overtime Production	Subcontracting	Total
1	6,500	—	—	6,500
2	6,500	400	—	6,900
3	6,500	1,300	—	7,800
4	8,000	1,600	1,000	10,600
5	7,000	—	—	7,000
6	4,400	—	—	4,400

ANTICIPATION INVENTORY

Period	Beginning Inventory Plus Total Production Minus Demand	Anticipation (Ending) Inventory
1	200 + 6,500 − 5,000	1,700
2	1,700 + 6,900 − 6,000	2,600
3	2,600 + 7,800 − 9,000	1,400
4	1,400 + 10,600 − 12,000	0
5	0 + 7,000 − 7,000	0
6	0 + 4,400 − 4,000	400

Discussion Questions

1. A particular linear programming maximization problem has the following less-than-or-equal-to constraints: (1) raw materials, (2) labor hours, and (3) storage space. The optimal solution occurs at the intersection of the raw materials and labor hours constraints, so those constraints are binding. Management is considering whether to authorize overtime. What useful information could the linear programming solution provide to management in making this decision? Suppose a warehouse becomes available for rent at bargain rates. What would management need to know to decide whether to rent the warehouse? How could the linear programming model be helpful?
2. Linear programming and the transportation method promise optimal solutions. However, wise managers sometimes, after seeing the optimal results such as in Figure D.8 or D.12, might decide to implement different plans. How do you explain such decision making?

Problems

The OM Explorer and POM for Windows software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download the software and how best to use these resources. For linear programming problems with more than two variables, and for transportation problems, use POM for Windows to solve your model formulations. The emphasis in these cases is on modeling problems and interpreting computer output.

Formulating a Linear Programming Model

1. Happy Dog Inc. produces three types of dog food. Puppy Blend is produced for dogs that are less than a year old, Adult Blend for dogs between 1 and 8 years old, and Geriatric Blend for dogs older than 8 years. Each blend, sold in 5-pound bags, has a unique recipe that requires, among other ingredients, exact quantities of certain raw materials.

	Chicken	Fish Meal	Soy Flour	Demand (in 5-lb bags)
Puppy Blend	2.5 lb	1.0 lb	0.5 lb	2,000
Adult Blend	1.5 lb	2.0 lb	0.5 lb	8,000
Geriatric Blend	1.0 lb	2.0 lb	1.0 lb	1,000
Availability of raw material	10,000 lb	20,000 lb	5,000 lb	

a. Formulate a linear programming model that produces as many bags of dog food as possible without exceeding the demand or the available supply of raw material.

b. Reformulate the linear programming model if the company is now interested in maximizing its profit (price − raw material cost) from dog food production. Assume that Puppy Blend sells for $9.50 per bag, Adult Blend sells for $8.50 per bag, and Geriatric Blend sells for $9.00 per bag. Further, chicken costs $2.50 per pound, fish meal costs $1.25 per pound, and soy flour costs $2.00 per pound. How does this new information change your linear programming model?

2. Amazing Dairy produces yogurt, sour cream, kefir, and cottage cheese in 10-pound containers for the food-service industry. Each product is made in 10-pound batches and requires similar processing through three machines. Details on Amazing Dairy's product line, including the processing time in minutes at each machine, follows.

	Yogurt	Sour Cream	Kefir	Cottage Cheese
Price per pound	$1.50	$2.00	$3.50	$1.25
Weekly demand	200 lb	350 lb	50 lb	150 lb
Processing Time at Machine 1	15 minutes per 10-lb batch	10 minutes per 10-lb batch	15 minutes per 10-lb batch	5 minutes per 10-lb batch
Processing Time at Machine 2	25 minutes per 10-lb batch	10 minutes per 10-lb batch	15 minutes per 10-lb batch	5 minutes per 10-lb batch
Processing Time at Machine 3	5 minutes per 10-lb batch	15 minutes per 10-lb batch	30 minutes per 10-lb batch	20 minutes per 10-lb batch

Amazing Dairy has 2,400 minutes of processing time available for each machine each week. Develop a linear program that maximizes total revenue.

3. The town of Lexington purchases gasoline from three vendors to fuel its fleet of municipal vehicles. Each vendor delivers gasoline in 6,000-gallon quantities. Since vendors must deliver the fuel, a transportation fee (based on the distance the vendor must travel) is added to each delivery. The number of deliveries required by each location, the cost of supplying a truckload of gasoline to each location from each vendor, and the number of truckloads each vendor can deliver are provided here:

	Police Station	Fire Station	Bus Depot	Public Works Garage	Deliveries (truckloads) Available
Vendor A	$500	$525	$550	$600	20
Vendor B	$350	$425	$450	$575	14
Vendor C	$400	$375	$625	$475	10
Deliveries (truckloads) required	12	2	18	6	

Assuming that the price per gallon of fuel is the same for each vendor, develop a linear programming model that minimizes the total transportation fee that Lexington must pay for supplying all of its facilities' fuel needs.

4. JPMorgan Chase has a scheduling problem. Operators work 8-hour shifts and can begin work at midnight, 4 A.M., 8 A.M., noon, 4 P.M., or 8 P.M. Operators are needed to satisfy the following demand pattern. Formulate a linear programming model to cover the demand requirements with the minimum number of operators.

Time Period	Operators Needed
Midnight to 4 A.M.	4
4 A.M. to 8 A.M.	6
8 A.M. to noon	90
Noon to 4 P.M.	85
4 P.M. to 8 P.M.	55
8 P.M. to 12 midnight	20

Graphic Analysis

5. The Sports Shoe Company is a manufacturer of basketball and football shoes. The manager of marketing must decide the best way to spend advertising resources. Each football team sponsored requires 120 pairs of shoes. Each basketball team requires 32 pairs of shoes. Football coaches receive $300,000 for shoe sponsorship, and basketball coaches receive $1,000,000. The manager's promotional budget is $30,000,000. The company has a limited supply (4 liters, or 4,000 cubic centimeters) of flubber, a rare and costly compound used in promotional athletic shoes. Each pair of basketball shoes requires 3 cc of flubber, and each pair of football shoes requires 1 cc. The manager wants to sponsor as many basketball and football teams as resources will allow.

a. Create a set of linear equations to describe the objective function and the constraints.

b. Use graphic analysis to find the visual solution.

c. What is the maximum number of each type of team that the company can sponsor?

6. A business student at Nowledge College must complete a total of 65 courses to graduate. The number of business courses must be greater than or equal to 23. The number of nonbusiness courses must be greater than or equal to 20. The average business course requires a textbook costing $60 and 120 hours of study. Nonbusiness courses require a textbook costing $24 and 200 hours of study. The student has $3,000 to spend on books.

a. Create a set of linear equations to describe the objective function and the constraints.

b. Use graphic analysis to find the visual solution.

c. What combination of business and nonbusiness courses minimizes total hours of study?

d. Identify the slack or surplus variables.

7. In Problem 6, suppose that the objective is to minimize the cost of books and that the student's total study time is limited to 12,600 hours.

a. Use graphic analysis to determine the combination of courses that minimizes the total cost of books.

b. Identify the slack or surplus variables.

8. Mile-High Microbrewery makes a light beer and a dark beer. Mile-High has a limited supply of barley, limited bottling capacity, and a limited market for light beer. Profits are $0.20 per bottle of light beer and $0.50 per bottle of dark beer.

a. The following table shows resource availability of products at the Mile-High Microbrewery. Use the graphic method of linear programming to maximize profits. How many bottles of each product should be produced per month?

	PRODUCT		
Resource	**Light Beer (x_1)**	**Dark Beer (x_2)**	**Resource Availability (per month)**
Barley	0.1 gram	0.6 gram	2,000 grams
Bottling	1 bottle	1 bottle	6,000 bottles
Market	1 bottle	—	4,000 bottles

b. Identify any constraints with slack or surplus.

9. The plant manager of a plastic pipe manufacturer has the opportunity to use two different routings for a particular type of plastic pipe. Routing 1 uses extruder A and routing 2 uses extruder B. Both routings require the same melting process. The following table shows the time requirements and capacities of these processes:

	TIME REQUIREMENTS (HR/100 FT)		
Process	**Routing 1**	**Routing 2**	**Capacity (hr)**
Melting	1	1	45
Extruder A	3	0	90
Extruder B	0	1	160

Each 100 feet of pipe processed on routing 1 uses 5 pounds of raw material, whereas each 100 feet of pipe processed on routing 2 used only 4 pounds. This difference results from differing scrap rates of the extruding machines. Consequently, the profit per 100 feet of pipe processed on routing 1 is $60 and on routing 2 is $80. A total of 200 pounds of raw material is available.

a. Create a set of linear equations to describe the objective function and the constraints.

b. Use graphic analysis to find the visual solution.

c. What is the maximum profit?

10. A manufacturer of textile dyes can use two different processing routings for a particular type of dye. Routing 1 uses drying press A and routing 2 uses drying press B. Both routings require the same mixing vat to blend chemicals for the dye before drying. The following table shows the time requirements and capacities of these processes:

	TIME REQUIREMENTS (HR/KG)		
Process	**Routing 1**	**Routing 2**	**Capacity (hr)**
Mixing	2	2	54
Dryer A	6	0	120
Dryer B	0	8	180

Each kilogram of dye processed on routing 1 uses 20 liters of chemicals, whereas each kilogram of dye processed on routing 2 uses only 15 liters. The difference results from differing yield rates of the drying presses. Consequently, the profit per kilogram processed on routing 1 is $50 and on routing 2 is $65. A total of 450 liters of input chemicals is available.

a. Write the constraints and objective function to maximize profits.

b. Use the graphic method of linear programming to find the optimal solution.

c. Identify any constraints with slack or surplus.

Computer Analysis

11. The Trim-Look Company makes several lines of skirts, dresses, and sport coats. Recently, a consultant suggested that the company reevaluate its South Islander line and allocate its resources to products that would maximize contribution to profits and to overhead. Each product requires the same polyester fabric and must pass through the cutting and sewing departments. The following data were collected for the study:

	PROCESSING TIME (HR)		
Product	**Cutting**	**Sewing**	**Material (yd)**
Skirt	1	1	1
Dress	3	4	1
Sport coat	4	6	4

The cutting department has 100 hours of capacity, sewing has 180 hours of capacity, and 60 yards of material are available. Each skirt contributes $5 to profits and overhead; each dress, $17; and each sport coat, $30.

a. Specify the objective function and constraints for this problem.

b. Use a computer package such as POM for Windows to solve the problem.

12. Consider Problem 11 further.

a. How much would you be willing to pay for an extra hour of cutting time? For an extra hour of sewing time? For an extra yard of material? Explain your response to each question.

b. Determine the range of right-hand-side values over which the shadow price would be valid for the cutting constraint and for the material constraint.

13. Polly Astaire makes fine clothing for big and tall men. A few years ago, Astaire entered the sportswear market with the Sunset line of shorts, pants, and shirts. Management wants to make the amount of each product that will maximize profits. Each type of clothing is routed through two departments, A and B. The relevant data for each product are as follows:

	PROCESSING TIME (HR)		
Product	**Department A**	**Department B**	**Material (yd)**
Shirts	2	1	2
Shorts	2	3	1
Pants	3	4	4

Department A has 120 hours of capacity, department B has 160 hours of capacity, and 90 yards of material are available. Each shirt contributes $10 to profits and overhead; each pair of shorts, $10; and each pair of pants, $23.

a. Specify the objective function and constraints for this problem.

b. Use a computer package such as POM for Windows to solve the problem.

c. How much should Astaire be willing to pay for an extra hour of department A capacity? How much for an extra hour of department B capacity? For what range of right-hand values are these shadow prices valid?

14. The Butterfield Company makes a variety of knives. Each knife is processed on four machines. The processing times required are as follows: Machine capacities (in hours) are 1,500 for machine 1; 1,400 for machine 2; 1,600 for machine 3; and 1,500 for machine 4.

	PROCESSING TIME (HR)			
Knife	**Machine 1**	**Machine 2**	**Machine 3**	**Machine 4**
A	0.05	0.10	0.15	0.05
B	0.15	0.10	0.05	0.05
C	0.20	0.05	0.10	0.20
D	0.15	0.10	0.10	0.10
E	0.05	0.10	0.10	0.05

Each product contains a different amount of two basic raw materials. Raw material 1 costs $0.50 per ounce, and raw material 2 costs $1.50 per ounce. There are 75,000 ounces of raw material 1 and 100,000 ounces of raw material 2 available.

	REQUIREMENTS (OZ/UNIT)		
Knife	**Raw Material 1**	**Raw Material 2**	**Selling Price per Unit**
A	4	2	$15.00
B	6	8	$25.50
C	1	3	$14.00
D	2	5	$19.50
E	6	10	$27.00

a. If the objective is to maximize profit, specify the objective function and constraints for the problem. Assume that labor costs are negligible.

b. Solve the problem with a computer package such as POM for Windows.

15. The Nutmeg Corporation produces three different products, each in a 1-pound can: Almond-Lovers Mix, Walnut-Lovers Mix, and the Thrifty Mix. Three types of nuts are used in Nutmeg's products: almonds, walnuts, and peanuts. Nutmeg currently has 350 pounds of almonds, 150 pounds of walnuts, and 1,000 pounds of peanuts. Each of Nutmeg's products must contain a certain percentage of each type of nut, as shown in the following table. The table also shows the revenue per can as well as the cost per pound to purchase nuts.

	PERCENTAGE REQUIREMENTS PER CAN			
	Almonds	**Walnuts**	**Peanuts**	**Revenue per Can**
Almond-Lovers Mix	80%	20%	0%	$8.00
Walnut-Lovers Mix	20%	80%	0%	$10.00
Thrifty Mix	10%	10%	80%	$4.50
Cost per pound	$4.50	$6.00	$3.00	

a. Given Nutmeg's current stock of nuts, how many cans of each product should be produced to maximize revenue?

b. Does the solution you developed in part (a) change if Nutmeg is interested in maximizing contribution margin (defined as revenue per unit − raw material cost)?

c. If 50 additional pounds of walnuts became available, how would your contribution-margin maximizing solution from part (b) change?

16. A problem often of concern to managers in processing industries is blending. The Nutmeg Corporation, from Problem 15, is considering a new product it intends to sell to active and health-concerned adults. This new product will be a 4-ounce package of nuts that conforms to specific heath requirements. First, the 4-ounce package can contain no more than 720 calories. It must deliver at least 20 grams of protein. Finally, the package must provide at least 15 percent of the adult daily requirement (ADR) of calcium and 20 percent of the ADR of iron. Nutmeg would like to use only almonds, walnuts, and peanuts in this new product. The following table provides nutritional data on each of these ingredients as well as their cost to Nutmeg.

Ingredients	Calories per Ounce	Grams of Protein per Ounce	Percent ADR of Calcium per Ounce	Percent ADR of Iron per Ounce	Cost per Ounce
Almonds	180	6	8%	6%	$0.28
Walnuts	190	4	2%	6%	$0.38
Peanuts	170	7	0%	4%	$0.12

a. Use linear programming to find the cost-minimizing number of ounces of each ingredient that Nutmeg should use in each 4-ounce package. What is the per-package cost of raw materials?

b. The marketing department at Nutmeg insists that each package should contain at least 0.5 ounce of almonds, at least 0.5 ounce of walnuts, and no more than 1 ounce of peanuts. Does the solution developed for part (a) satisfy these new constraints? If not, use linear programming to find a solution that includes these marketing requirements. What is the new cost of raw materials?

17. A small fabrication firm makes three basic types of components for use by other companies. Each component is processed on three machines. The processing times follow. Total capacities (in hours) are 1,600 for machine 1; 1,400 for machine 2; and 1,500 for machine 3.

	PROCESSING TIME (HR)		
Component	Machine 1	Machine 2	Machine 3
A	0.25	0.10	0.05
B	0.20	0.15	0.10
C	0.10	0.05	0.15

Each component contains a different amount of two basic raw materials. Raw material 1 costs $0.20 per ounce, and raw material 2 costs $0.35 per ounce. At present, 200,000 ounces of raw material 1 and 85,000 ounces of raw material 2 are available.

	REQUIREMENT (OZ/UNIT)		
Component	Raw Material 1	Raw Material 2	Selling Price per Unit
A	32	12	$40
B	26	16	$28
C	19	9	$24

a. Assume that the company must make at least 1,200 units of component B, that labor costs are negligible, and that the objective is to maximize profits. Specify the objective function and constraints for the problem.

b. Use a computer package such as POM for Windows to solve the problem.

18. The following is a linear programming model for analyzing the product mix of Maxine's Hat Company, which produces three hat styles:

$$\begin{aligned}
\text{Maximize:} \quad & \$7x_1 + \$8x_2 + \$6x_3 = Z \\
\text{Subject to:} \quad & 2x_1 + 4x_2 + 2x_3 \leq 120 \text{ (machine A time)} \\
& 5x_1 + 3x_2 + 2x_3 \leq 400 \text{ (machine B time)} \\
& 2x_1 + 2x_2 + 4x_3 \leq 110 \text{ (machine C time)} \\
& x_1 \geq 0,\ x_2 \geq 0, \text{ and } x_3 \geq 0
\end{aligned}$$

The POM for Windows printout in Figure D.15 shows the optimal solution to the problem.

Consider each of the following statements independently, and state whether it is true or false. Explain each answer.

a. If the price of hat 3 were increased to $11.50, it would be part of the optimal product mix. *Hint:* Hat 3 is represented by x_3 and its optimal value currently is 0, which means that it is not to be produced (and not part of the optimal product mix).

b. The capacity of machine B can be reduced to 280 hours without affecting profits.

c. If machine C had a capacity of 115 hours, the production output would remain unchanged.

19. The Washington Chemical Company produces chemicals and solvents for the glue industry. The production process is divided into several "focused factories," each producing a specific set of products. The time has come to prepare the production plan for one of the focused factories. This particular factory produces five products, which must pass through both the reactor and the separator. Each product also requires a certain combination of raw materials. Production data are shown in Table D.2.

The Washington Chemical Company has a long-term contract with a major glue manufacturer that requires annual production of 3,000 pounds of both products 3 and 4. More of these products could be produced because demand currently exceeds production capacity.

Maxine's Hat Company Solution

	X1	X2	X3		RHS	Shadow Price
Maximize	7	8	6			
machine A time	2	4	2	<=	120	.5
machine B time	5	3	2	<=	400	0
machine C time	2	2	4	<=	110	3
Solution	50	5	0		390	

Variable	Value	Reduced Cost	Original Val	Lower Bound	Upper Bound
X1	50	0	7	4.67	8
X2	5	0	8	7	14
X3	0	7	6	–Infinity	13
	Shadow Price	Slack/Surplus	Original Val	Lower Bound	Upper Bound
Machine A Time	.5	0	120	110	220
Machine B Time	0	135	400	265	Infinity
Machine C Time	3	0	110	60	120

▲ **FIGURE D.15**
Solution Screens for Maxine's Hat Company

TABLE D.2 | **PRODUCTION DATA FOR WASHINGTON CHEMICAL**

	PRODUCT					
Resource	**1**	**2**	**3**	**4**	**5**	**Total Resources Available**
Reactor (hr/lb)	0.05	0.10	0.80	0.57	0.15	7,500 hr*
Separator (hr/lb)	0.20	0.02	0.20	0.09	0.30	7,500 hr*
Raw material 1 (lb)	0.20	0.50	0.10	0.40	0.18	10,000 lb
Raw material 2 (lb)	—	0.70	—	0.50	—	6,000 lb
Raw material 3 (lb)	0.10	0.20	0.40	—	—	7,000 lb
Profit contribution ($/lb)	4.00	7.00	3.50	4.00	5.70	

*The total time available has been adjusted to account for setups. The five products have a prescribed sequence owing to the cost of changeovers between products. The company has a 35-day cycle (or 10 changeovers per year per product). Consequently, the time for these changeovers has been deducted from the total time available for these machines.

a. Determine the annual production quantity of each product that maximizes contribution to profits. Assume the company can sell all it can produce.

b. Specify the lot size for each product.

The Transportation Method

20. The Warwick Manufacturing Company produces shovels for industrial and home use. Sales of the shovels are seasonal, and Warwick's customers refuse to stockpile them during slack periods. In other words, the customers want to minimize inventory, insist on shipments according to their schedules, and will not accept backorders.

Warwick employs manual, unskilled laborers who require only basic training. Producing 1,000 shovels costs $3,500 on regular time and $3,700 on overtime. These amounts include materials, which account for more than 85 percent of the cost. Overtime is limited to production of 15,000 shovels per quarter. In addition, subcontractors can be hired at $4,200 per thousand shovels, but Warwick's labor contract restricts this type of production to 5,000 shovels per quarter.

The current level of inventory is 30,000 shovels, and management wants to end the year at that level. Holding 1,000 shovels in inventory costs $280 per quarter. The latest annual demand forecast is as follows:

Quarter	Demand
1	70,000
2	150,000
3	320,000
4	100,000
Totals	640,000

Use the Transportation Method (Production Planning) module in POM for Windows to determine the *best* regular-time capacity plan. Assume the following:

- The firm has 30 workers now, and management wants to have the same number in quarter 4.
- Each worker can produce 4,000 shovels per quarter.
- Hiring a worker costs $1,000, and laying off a worker costs $600.

21. The management of Warwick Manufacturing Company is willing to give price breaks to its customers as an incentive to purchase shovels in advance of the traditional seasons. Warwick's sales and marketing staff estimates that the demand for shovels resulting from the price breaks would be as follows:

Quarter	Demand	Original Demand
1	120,000	70,000
2	180,000	150,000
3	180,000	320,000
4	160,000	100,000
Totals	640,000	640,000

Use the Transportation Method (Production Planning) module in POM for Windows to calculate the optimal production plan (including the workforce staffing plan) under the new demand schedule. Compare it to the optimal production plan under the original demand schedule. Evaluate the potential effects of demand management.

22. The Bull Grin Company produces a feed supplement for animal foods produced by a number of other companies. Producing 1,000 pounds of supplement costs $810 on regular time and $900 on overtime. These amounts include materials, which account for more than 80 percent of the cost. The plant can produce 400,000 pounds of supplement per quarter using regular time, but overtime is limited to the production of 40,000 pounds per quarter. The current level of inventory is 40,000 pounds, and management wants to end the year at that level. Holding 1,000 pounds of feed supplement in inventory costs $110 per quarter. Assume hiring and layoff costs are negligible. The latest annual demand forecast follows:

Quarter	Demand (in Pounds)
1	100,000
2	410,000
3	770,000
4	440,000

a. Formulate this production-planning problem as a linear program after defining all decision variables.

b. Solve your formulation using a computer package such as POM for Windows.

c. Assume that subcontractors can be hired at $1,100 per thousand pounds to produce as much supplement as Bull Grin requires. Does this change the cost-minimizing solution found in part (b)?

d. If Bull Grin realizes that the current level of inventory is actually 0 pounds, are the resources assumed in part (c) adequate to satisfy all demand and still end the year with 40,000 pounds in ending inventory? If so, how much will the cost of Bull Grin's production plan increase?

23. Supertronics, Inc., would like to know how the firm's profitability is altered by product mix. Currently, product mix is determined by giving priority to the product with the highest per-unit contribution margin (defined as the difference between price and material cost). Details on the Supertronics product line, including processing time at each workstation, follow:

	PRODUCT			
	Alpha	Beta	Delta	Gamma
Price	$350.00	$320.00	$400.00	$500.00
Material Cost	$50.00	$40.00	$125.00	$150.00
Weekly Demand in Units	100	60	50	80
Processing Time at Machine 1 in Minutes	20	0	40	10
Processing Time at Machine 2 in Minutes	25	20	0	50
Processing Time at Machine 3 in Minutes	0	20	60	30

a. Assume that Supertronics has 5,500 minutes of capacity available at each workstation each week. Develop a linear program to define the production mix that maximizes contribution margin.

b. Solve your formulation using a computer package such as POM for Windows.

c. Given your solution for part (b), which machine is the bottleneck?

d. How would your formulation and solution in part (b) change if 50 units of each product were already committed to customers and thereby had to be produced?

24. Revisit Problem 22 on the Bull Grin Company. Some cost and demand parameters have changed. Producing 1,000 pounds of supplement now costs $830 on regular time and $910 on overtime. No additional cost is incurred for unused regular-time, overtime, or subcontractor capacity. Overtime is limited to production of a total of 20,000 pounds per quarter. In addition, subcontractors can be hired at $1,000 per 1,000 pounds, but only 30,000 pounds per quarter can be produced this way.

The current level of inventory is 40,000 pounds, and management wants to end the year at that level. Holding 1,000 pounds of feed supplement in inventory per quarter costs $100. The latest annual forecast is shown in Table D.3.

Use the transportation method of production planning in POM for Windows to find the optimal production plan and calculate its cost, or use the spreadsheet approach to find a good production plan and calculate its cost.

TABLE D.3 | FORECASTS AND CAPACITIES

	PERIOD				
	Quarter 1	**Quarter 2**	**Quarter 3**	**Quarter 4**	**Total**
Demand (pounds)	130,000	400,000	800,000	470,000	1,800,000
Capacities (pounds)					
Regular time	390,000	400,000	460,000	380,000	1,630,000
Overtime	20,000	20,000	20,000	20,000	80,000
Subcontract	30,000	30,000	30,000	30,000	30,000

25. The Cut Rite Company is a major producer of industrial lawn mowers. The cost to Cut Rite for hiring a semi-skilled worker for its assembly plant is $3,000, and the cost for laying off one is $2,000. The plant averages an output of 36,000 mowers per quarter with its current workforce of 720 employees. Regular-time capacity is directly proportional to the number of employees. Overtime is limited to a maximum of 3,000 mowers per quarter, and subcontracting is limited to 1,000 mowers per quarter. The costs to produce one mower are $2,430 on regular time (including materials), $2,700 on overtime, and $3,300 via subcontracting. Unused regular-time capacity costs $270 per mower. No additional cost is incurred for unused overtime or subcontractor capacity. The current level of inventory is 4,000 mowers, and management wants to end the year at that level. Customers do not tolerate backorders, and holding a mower in inventory per quarter costs $300. The demand for mowers this coming year is as follows:

Quarter	1	2	3	4
Demand	10,000	41,000	77,000	44,000

Two workforce plans have been proposed, and management is uncertain as to which one to use. The following table shows the number of employees per quarter under each plan:

Quarter	1	2	3	4
Plan 1	720	780	920	720
Plan 2	860	860	860	860

a. Which plan would you recommend to management? Explain, supporting your recommendation with an analysis using the transportation method of production planning.

b. If management used creative pricing to get customers to buy mowers in nontraditional time periods, the following demand schedule would result:

Quarter	1	2	3	4
Demand	20,000	54,000	54,000	44,000

Which workforce plan would you recommend now?

26. The Holloway Calendar Company produces a variety of printed calendars for both commercial and private use. The demand for calendars is highly seasonal, peaking in the third quarter. Current inventory is 165,000 calendars, and ending inventory should be 200,000 calendars.

Ann Ritter, Holloway's manufacturing manager, wants to determine the best production plan for the demand requirements and capacity plan shown in the following table. (Here, demand and capacities are expressed as thousands of calendars rather than as employee-period equivalents.) Ritter knows that the regular-time cost is $0.50 per unit, overtime cost is $0.75 per unit, subcontracting cost is $0.90 per unit, and inventory holding cost is $0.10 per calendar per quarter. Unused regular-time capacity is not paid.

	QUARTER				
	1	**2**	**3**	**4**	**Total**
Demand	250	515	1,200	325	2,290
Capacities					
Regular time	300	300	600	300	1,500
Overtime	75	75	150	75	375
Subcontracting	150	150	150	150	600

a. Recommend a production plan to Ritter, using the Transportation Method (Production Planning) module of POM for Windows. (Do not allow any stockouts or backorders to occur.)

b. Interpret and explain your recommendation.

c. Calculate the total cost of your recommended production plan.

11

RESOURCE PLANNING

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

11.1 Explain how the concept of dependent demand in material requirements planning is fundamental to resource planning.

11.2 Describe the process of developing a master production schedule (MPS) and compute available-to-promise quantities.

11.3 Apply the logic of an MRP explosion to identify production and purchase orders needed for dependent demand items.

11.4 Explain how enterprise resource planning (ERP) systems can foster better resource planning.

11.5 Apply resource planning principles to the provision of services and distribution inventories.

Philips



testing/Shutterstock

Philips booth during the China International Health Industry Expo (CHINA-HOSPEQ 2017) at the China National Convention Center.

Philips, based in Amsterdam, Netherlands, is a diversified Dutch technology conglomerate whose health care and consumer lifestyle divisions employed 81,000 employees in more than 100 countries in 2019. With sales of 19.48 billion euros in 2019, it is one of the largest electronics company in the world and a leader in cardiac, oral, and home health care devices; flat screen television sets; and personal grooming products such as electric shavers. Philips spun off its lighting division in June 2016 to focus on its health

care division and, in 2017, launched Philips Ventures with a health technology venture fund as its main focus.

Managing over 100 manufacturing plants in different countries around the globe presents management with a complex set of decisions surrounding what needs to be made and when, and which components should be ordered in what quantities to support the production schedules that can satisfy customer demand. Complexity of sourcing and planning for all these material and labor resources increases rapidly due to the large variety of products manufactured on a regular basis by Philips.

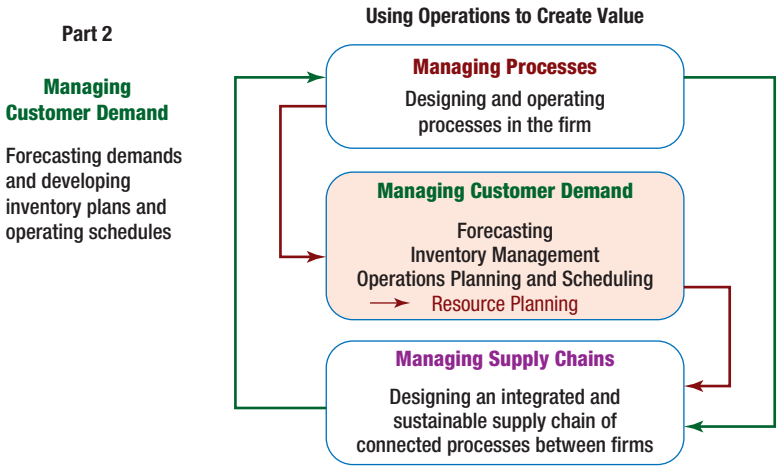
The Medical Systems division in the United States within the health care segment of Philips is located in Andover, Massachusetts. Shanghai APEX Electronics, a small manufacturing company in China, designs, develops, and produces ultrasonic transducers for Philips. Component requirements from Philips plants for suppliers such as APEX are generated through a resource planning process embedded within an enterprise-wide system. These requirements are communicated to APEX and other suppliers through a standardized supply chain management application called Nocturne. In turn, Philips expected and required APEX to install Nocturne and also acquire a material requirements planning (MRP) computer-based system of its own so that it could more readily meet the on-time components commitments requested by Philips. While APEX did not have the resources or the need to acquire large-scale enterprise systems similar to the ones implemented by Philips, it did procure and implement an integrated manufacturing system for small manufacturers called E-Z-MRP from Beach Access Software in Del Mar, California. This MRP system at APEX could use Nocturne to interface downstream with Philips and upstream with suppliers of APEX to communicate its raw materials requirements.

Integrating material requirements planning and all the associated resources up and down the supply chain coordinates product flows, avoids costly delays or shortages, minimizes inventory, and makes every firm within the chain more competitive and profitable. Adopting such sophisticated materials planning and coordination practices across its manufacturing plants and supply chains has allowed Philips to keep pace with technological changes and maintain its leadership position in a rapidly changing industry.[1]

Philips demonstrates that companies can gain a competitive edge by focusing their attention on resource planning even for their upstream suppliers to ensure that all of the resources they need to produce finished services or products are available at the right time. If they are not, a firm risks losing business. For a manufacturer, this task can mean keeping track of thousands of subassemblies, components, and raw materials as well as key equipment capacities. For a service provider, this task can mean keeping track of numerous supplies and carefully scheduling the time and capacity requirements of different employees and types of equipment.

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[1] *Sources:* "Combination of Small MRP System and Large Supply Chain Software Spells Success for Shanghai APEX Electronics," http://www.e-z-mrp.com/combination-small-mrp-system-large-supply-chain-software-spells-success-shanghai-apex-electronics/; http://www.usa.philips.com/about/company/index.page (July 18, 2020); http://en.wikipedia.org/wiki/Philips (July 18, 2020).



Resource planning lies at the heart of any organization, cutting across all of its different functional areas. It takes sales and operations plans; processes information in the way of time standards, routings, and other information on how services or products are produced; and then plans the input requirements. It also can create reports for managers of the firm's major functional areas, such as human resources, purchasing, sales and marketing, and finance and accounting. In essence, resource planning is a process in and of itself that can be analyzed relative to the firm's competitive priorities.

We begin this chapter by first examining material requirements planning (MRP), which is a specific approach to resource planning for manufacturers that includes the master production scheduling of finished products and determines the timing of all orders for components and raw materials in support of that schedule. Subsequently we describe enterprise resource planning (ERP) systems, which have become a valuable tool for, among other things, resource planning. The concluding section of the chapter illustrates how service providers can use the principles of MRP in managing their supplies, human resources, equipment, and financial resources.

resource planning

A process that takes sales and operations plans; processes information in the way of time standards, routings, and other information on how services or products are produced; and then plans the input requirements.

Material Requirements Planning

Understanding resource planning begins with the concept of *dependent demand*, which sets it apart from the techniques covered in Chapter 9, "Inventory Management." **Material requirements planning (MRP)** is a computerized information system developed specifically to help manufacturers manage dependent demand inventory and schedule replenishment orders. The key inputs of an MRP system are a master production schedule, a bill of materials database, and an inventory record database, as shown in Figure 11.1. Using this information, the MRP system identifies the actions planners must take to stay on schedule, such as releasing new production orders, adjusting order quantities, and expediting late orders.

material requirements planning (MRP)

A computerized information system developed specifically to help manufacturers manage dependent demand inventory and schedule replenishment orders.

An MRP system translates the master production schedule and other sources of demand, such as independent demand for replacement parts and maintenance items, into the requirements for all subassemblies, components, and raw materials needed to produce the required parent items. This process is called an **MRP explosion** because it converts the requirements of various final products into a material requirements plan that specifies the replenishment schedules of all the subassemblies, components, and raw materials needed to produce final products.

MRP explosion

A process that converts the requirements of various final products into a material requirements plan that specifies the replenishment schedules of all the subassemblies, components, and raw materials needed to produce final products.

We first explore the nature of dependent demand and how it differs from independent demand, followed by a discussion of the key inputs to the MRP system shown in Figure 11.1.

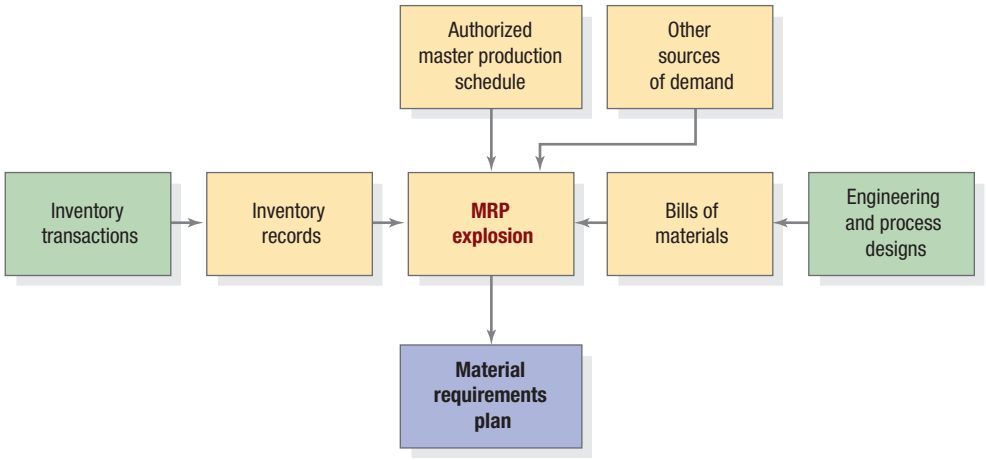
Dependent Demand

For years, many companies tried to manage production and their dependent demand inventories using independent demand systems, similar to those discussed in Chapter 9, "Inventory Management," but the outcome was seldom satisfactory because dependent demand is fundamentally different from independent demand. To illustrate the concept of dependent demand, let us consider a Huffy bicycle produced for retail outlets. Demand for a final product, such as a bicycle, is called *independent demand* because it is influenced only by market conditions. In contrast, the demand for spokes going into the bicycle "depends" on the production planned for its wheels. Huffy must forecast this demand using techniques such as those discussed in Chapter 8, "Forecasting." However, Huffy also keeps many other items in inventory—handlebars, pedals, frames, and wheel rims—used to make completed bicycles. Each of these items has a **dependent demand** because the quantity required varies with the production plans for other items held in the firm's inventory—finished bikes, in this case. For example, the demand for frames, pedals, and wheel rims is *dependent* on the production of completed bicycles. Operations can calculate the demand for dependent demand items once the bicycle production levels are laid out in the sales and operations plan. For example, every bicycle needs two wheel rims, so 1,000 completed bicycles need $1{,}000(2) = 2{,}000$ rims. Forecasting techniques are not needed for the rims.

dependent demand

The demand for an item that occurs because the quantity required varies with the production plans for other items held in the firm's inventory.

FIGURE 11.1 ▶
Material Requirements Plan Inputs



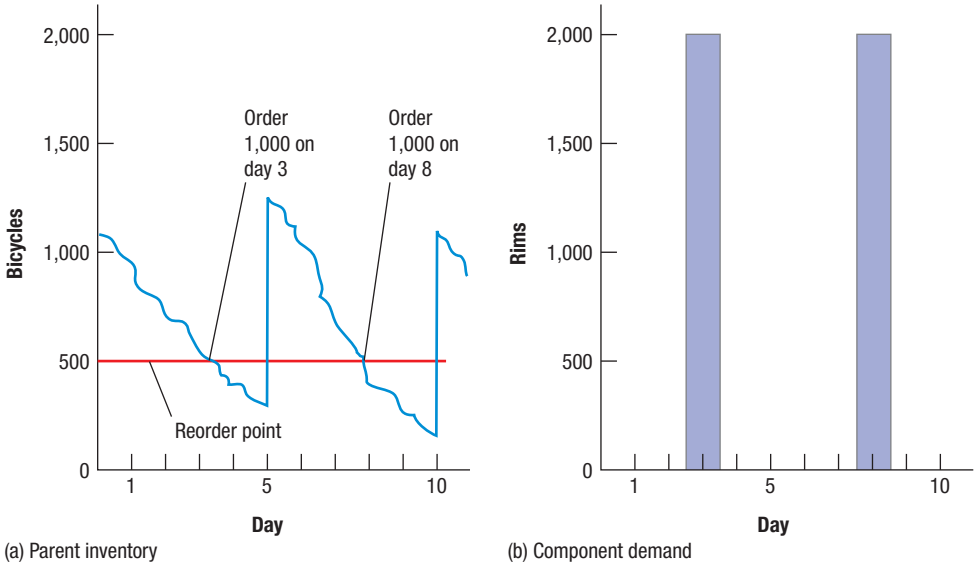
parent
Any product that is manufactured from one or more components.

component
An item that goes through one or more operations to be transformed into or become part of one or more parents.

The bicycle, or any other product that is manufactured from one or more components, is called a **parent**. The wheel rim is an example of a **component**—an item that goes through one or more operations to be transformed into or become part of one or more parents. A wheel rim, for example, will have several different parents if the rim is used to make more than one style of bicycle. This parent–component relationship can cause erratic dependent demand patterns for components. Suppose that every time inventory falls to 500 units (a reorder point), an order for 1,000 more bicycles is placed, as shown in Figure 11.2(a). The assembly supervisor then authorizes the withdrawal of 2,000 rims from inventory, along with other components for the finished product. The demand for the rim is shown in Figure 11.2(b). So, even though customer demand for the finished bicycle is continuous and reasonably uniform, the production demand for wheel rims is "lumpy"; that is, it occurs sporadically, usually in relatively large quantities. Thus, the production decisions for the assembly of bicycles, which account for the costs of assembling the bicycles and the projected assembly capacities at the time the decisions are made, determine the demand for wheel rims.

Managing dependent demand inventories is complicated because some components may be subject to both dependent and independent demand. For example, the shop floor needs 2,000 wheel rims for the new bicycles, but the company also sells replacement rims for old bicycles directly to retail outlets. This practice places an independent demand on the inventory of wheel rims. Material requirements planning can be used in complex situations involving components that may have independent demand as well as dependent demand inventories. As the Managerial Challenge below illustrates, planning for materials and resources to meet dependent and independent demand in a timely fashion is a complex task that requires an understanding of concepts outlined in this chapter.

FIGURE 11.2 ▶
Lumpy Dependent Demand Resulting from Continuous Independent Demand



MANAGERIAL CHALLENGE Operations

Rennselar Industries, Inc., an independent family-owned firm located in Michigan, is an original equipment manufacturer (OEM) of automotive parts. Customers include three major car assemblers, as well as several large dealerships and auto parts stores located throughout the United States. The weekly demand for the made-to-stock OEM parts is dependent on the number of cars manufactured by its three major clients, and is given to the firm for 12 weeks at a time. In addition, orders for the same set of parts from auto stores and dealerships required for maintenance independently arrive every day at the sales office of Rennselar, and are then aggregated on a weekly basis and sent to the manufacturing plants. While Rennselar had been able to maintain on-time OEM deliveries to the assemblers, concerns about a slip in delivery performance have been reflected through falling sales from dealerships and auto parts stores over the past year. Now in its third generation of ownership, Michael Rennselar, the CEO, requested Jennifer Wu, the VP of manufacturing at Rennselar, to take a closer look at the problem and make some recommendations.

Jennifer spoke to the five regional sales managers to understand the problem from the customers' perspective. Rennselar supplies over 250 made-to-stock parts to these independent dealerships and parts stores. She randomly selected a sample of 100 orders over the past 3 months to assess delivery performance. Her analysis showed that delivery delays ranged from as little as 3 to 5 days to 3 weeks. Apart from delayed deliveries, the customers also complained about a lack of visibility into when their order would be delivered if the requested delivery date was not going to be met. Such information, if shared in advance, would allow the customers to better plan their own operations. In desperation, some of them had already started turning to competitor suppliers for these parts.

Jennifer next turned to Pankaj Shah, the divisional operations manager in Chicago who oversaw production at the three manufacturing plants in the Midwest. Pankaj knew that all OEM orders were given top priority for shipment out of their finished goods inventory. The plant managers were using an in-house–developed Excel spreadsheet model to schedule production and order raw materials from their own suppliers. The sales and operations plans (SOP) at each plant were highly aggregated, and there was no system available to create a master production schedule that would accommodate both OEM and other maintenance orders according to their requested delivery dates, be consistent with the SOP, and provide forward visibility on which orders would be delayed and by how many days. Jennifer had explicitly requested Pankaj to develop a capability by which sales managers could let customers know how many units were available to promise and by which due date, and track orders if something goes wrong in the manufacturing or sourcing processes. This would be critical in retaining customers for the future and maintaining Rennselar's market position.

Information contained in the rest of this chapter can help Pankaj better understand what would be needed to resolve this problem and help him to recommend a resource planning solution to Jennifer and Michael that would meet Rennselar's business objectives.

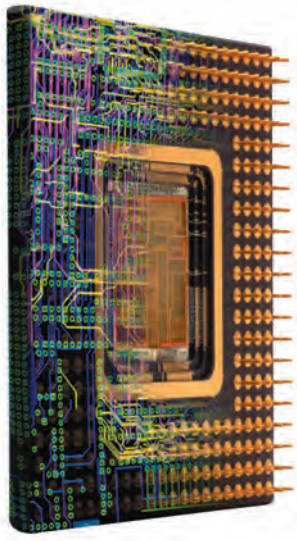
Master Production Scheduling

master production schedule (MPS)

A part of the material requirements plan that details how many end items will be produced within specified periods of time.

The first input into a material requirements plan is the **master production schedule (MPS)**, which details how many end items will be produced within specified periods of time. It breaks the sales and operations plan into specific product schedules. Figure 11.3 shows how a sales and operations plan at a furniture manufacturing firm for a family of chairs breaks down into the weekly MPS for each specific chair type (the time period can be hours, days, weeks, or months). The chair example demonstrates the following aspects of master scheduling:

1. The sums of the quantities in the MPS must equal those in the sales and operations plan. This consistency between the plans is desirable because of the economic analysis done to arrive at the sales and operations plan.
2. The production quantities must be allocated efficiently over time. The specific mix of chair types—the number of each type as a percent of the total family's quantity—is based on historic demand and on marketing and promotional considerations. The planner must select lot sizes for each chair type, taking into consideration economic factors such as production setup costs and inventory carrying costs.
3. Capacity limitations and bottlenecks, such as machine or labor capacity, storage space, or working capital, may determine the timing and size of MPS quantities. The planner must acknowledge these limitations by recognizing that some chair styles require more resources than others and setting the timing and size of the production quantities accordingly.



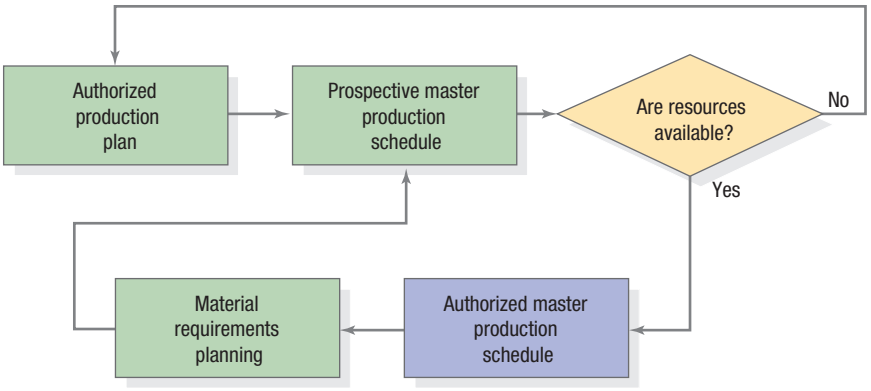
WidStock/Alamy Stock Photo

Cypress Semiconductor, a California-based company that manufactures logic devices, USB controllers, general-purpose programmable clocks, memories, and wireless connectivity solutions for consumer and automotive markets, uses commercial software solutions to manage the complexity of its master production scheduling processes.

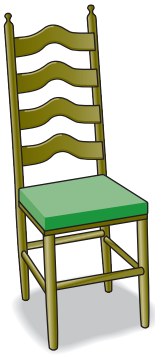
Figure 11.4 shows the MPS process. Operations must first create a prospective MPS to test whether it meets the schedule with the resources (e.g., machine capacities, workforce, overtime, and subcontractors) provided for in the sales and operations plan. Operations then revises the MPS until a schedule that satisfies all of the resource limitations is developed or until it is determined that no feasible schedule can be developed. In the latter event, the production plan must be revised to adjust production requirements or increase authorized resources. Once the firm's managers have accepted a feasible prospective MPS, operations uses the authorized MPS as an input to material requirements planning. Operations can then determine specific schedules for component production and assembly. Actual performance data such as inventory levels and shortages are inputs to preparing the prospective MPS for the next period, and so the master production scheduling process is repeated from one period to the next.

	April				May			
	1	2	3	4	5	6	7	8
Dining-room chair	150					150		
Kitchen chair				120			120	
Desk chair		200	200		200			200
Sales and operations plan for chair family			670				670	

▲ **FIGURE 11.3**
MPS for a Family of Chairs



▲ **FIGURE 11.4**
Master Production Scheduling Process



▲ **FIGURE 11.5**
Dining-room Chair

Developing a Master Production Schedule

The process of developing an MPS includes (1) calculating the projected on-hand inventory and (2) determining the timing and size of the production quantities of specific products. We use the dining-room chair, shown in Figure 11.5, to illustrate the process. For simplicity, we assume that the firm does not utilize safety stocks for end items, even though many firms do. In addition, we use weeks as our planning periods, even though hours, days, or months could be used.

Step 1. *Calculate Projected On-Hand Inventories.* The first step is to calculate the projected on-hand inventory, which is an estimate of the amount of inventory available each week after demand has been satisfied:

$$\left(\begin{array}{c}\text{Projected on-hand}\\ \text{inventory at end}\\ \text{of this week}\end{array}\right) = \left(\begin{array}{c}\text{On-hand}\\ \text{inventory at}\\ \text{end of last week}\end{array}\right) + \left(\begin{array}{c}\text{MPS quantity}\\ \text{due at start}\\ \text{of this week}\end{array}\right) - \left(\begin{array}{c}\text{Projected}\\ \text{requirements}\\ \text{this week}\end{array}\right)$$

In some weeks, no MPS quantity for a product may be needed because sufficient inventory already exists. For the projected requirements for this week, the scheduler uses whichever is larger—the forecast or the customer orders booked—recognizing that the forecast is subject to error. If actual booked orders exceed the forecast, the projection will be more accurate if the scheduler uses the booked orders because booked orders are a known quantity. Conversely, if the forecast exceeds booked orders for a week, the forecast will provide a better estimate of the requirements needed for that week because some orders may yet come in.

The manufacturer of the dining-room chair produces the chair to stock and needs to develop an MPS for it. Marketing has forecasted a demand of 30 chairs for the first week of April, but actual customer orders booked are for 38 chairs. The current on-hand inventory is 55 chairs. No MPS quantity is due in week 1. Figure 11.6 shows an MPS record with these quantities listed. Because actual orders for week 1 are greater than the forecast, the scheduler uses that figure for actual orders to calculate the projected inventory balance at the end of week 1:

Item: Dining-room chair

		April	
Quantity on Hand:	55	1	2
Forecast		30	30
Customer orders (booked)		38	27
Projected on-hand inventory		17	–13
MPS quantity		0	0
MPS start			

Explanation: Forecast is less than booked orders in week 1; projected on-hand inventory balance = 55 + 0 – 38 = 17.

Explanation: Forecast exceeds booked orders in week 2; projected on-hand inventory balance = 17 + 0 – 30 = –13. The shortage signals a need to schedule an MPS quantity for completion in week 2.

▲ **FIGURE 11.6**
Master Production Schedule for Weeks 1 and 2

$$\text{Inventory} = \begin{pmatrix}\text{55 chairs}\\ \text{currently}\\ \text{in stock}\end{pmatrix} + \begin{pmatrix}\text{MPS quantity}\\ \text{(0 for week 1)}\end{pmatrix} - \begin{pmatrix}\text{38 chairs already}\\ \text{promised for}\\ \text{delivery in week 1}\end{pmatrix} = 17 \text{ chairs}$$

In week 2, the forecasted quantity exceeds actual orders booked, so the projected on-hand inventory for the end of week 2 is 17 + 0 − 30 = −13. The shortage signals the need for more chairs to be produced and available for week 2.

Step 2. *Determine the Timing and Size of MPS Quantities.* The goal of determining the timing and size of MPS quantities is to maintain a nonnegative projected on-hand inventory balance. As shortages in inventory are detected, MPS quantities should be scheduled to cover them. The first MPS quantity should be scheduled for the week when the projected on-hand inventory reflects a shortage, such as week 2 in Figure 11.6.[2] The scheduler adds the MPS quantity to the projected on-hand inventory and searches for the next period when a shortage occurs. This shortage signals a need for a second MPS quantity, and so on.

Figure 11.7 shows an MPS for the dining-room chair for the next 8 weeks. The order policy requires production lot sizes of 150 units. A shortage of 13 chairs in week 2 will occur unless the scheduler provides for an MPS quantity for that period. Our convention is to show blanks instead of zeroes

▼ **FIGURE 11.7**
Master Production Schedule for Weeks 1–8

Item: Dining-room chair **Order Policy:** 150 units **Lead Time:** 1 week

		April				May			
Quantity on Hand:	55	1	2	3	4	5	6	7	8
Forecast		30	30	30	30	35	35	35	35
Customer orders (booked)		38	27	24	8				
Projected on-hand inventory		17	137	107	77	42	7	122	87
MPS quantity			150					150	
MPS start		150					150		

Explanation: The time needed to assemble 150 chairs is 1 week. The assembly department must start assembling chairs in week 1 to have them ready by week 2.

Explanation: On-hand inventory balance = 17 + 150 – 30 = 137. The MPS quantity is needed to avoid a shortage of 30 – 17 = 13 chairs in week 2.

[2]In some cases, new orders will be planned before a shortage is encountered. Two such instances occur when safety stocks and anticipation inventories are built up.

in all rows, which improves readability and is often used in practice. The only exception is in the projected on-hand inventory row, where a number is always shown, even if it is a 0 or negative number.

Once the MPS quantity is scheduled, the updated projected inventory balance for week 2 is

$$\text{Inventory} = \begin{pmatrix}\text{17 chairs in}\\ \text{inventory at the}\\ \text{end of week 1}\end{pmatrix} + \begin{pmatrix}\text{MPS quantity}\\ \text{of 150 chairs}\end{pmatrix} - \begin{pmatrix}\text{Forecast of}\\ \text{30 chairs}\end{pmatrix} = 137 \text{ chairs}$$

The scheduler proceeds column by column through the MPS record until it reaches the end, filling in the MPS quantities as needed to avoid shortages. The 137 units will satisfy forecasted demands until week 7, when the inventory shortage in the absence of an MPS quantity is $7 + 0 - 35 = -28$. This shortage signals the need for another MPS quantity of 150 units. The updated inventory balance is $7 + 150 - 35 = 122$ chairs for week 7.

The last row in Figure 11.7 indicates the periods in which production of the MPS quantities must *begin* so that they will be available when indicated in the MPS quantity row. In the upper-right portion of the MPS record, a lead time of 1 week is indicated for the dining-room chair; that is, 1 week is needed to assemble 150 dining-room chairs, assuming that items B, C, D, and E are available. For each MPS quantity, the scheduler works backward through the lead time to determine when the assembly department must start producing chairs. Consequently, a lot of 150 units must be started in week 1 and another in week 6.

available-to-promise (ATP) inventory

The quantity of end items that marketing can promise to deliver on specified dates.

Available-to-Promise Quantities

In addition to providing manufacturing with the timing and size of production quantities, the MPS provides marketing with information useful for negotiating delivery dates with customers. The quantity of end items that marketing can promise to deliver on specified dates is called **available-to-promise (ATP) inventory**. It is the difference between the customer orders already booked and the quantity that operations is planning to produce. As new customer orders are accepted, the ATP inventory is reduced to reflect the commitment of the firm to ship those quantities, but the actual inventory stays unchanged until the order is removed from inventory and shipped to the customer. An available-to-promise inventory is associated with each MPS quantity because the MPS quantity specifies the timing and size of new stock that can be earmarked to meet future bookings.

▼ **FIGURE 11.8**
MPS Record with an ATP Row

Item: Dining-room chair — **Order Policy:** 150 units — **Lead Time:** 1 week

Quantity on Hand: 55	April				May			
	1	2	3	4	5	6	7	8
Forecast	30	30	30	30	35	35	35	35
Customer orders (booked)	38	27	24	8				
Projected on-hand inventory	17	137	107	77	42	7	122	87
MPS quantity		150					150	
MPS start	150					150		
Available-to-promise (ATP) inventory	17	91					150	

Explanation: The total of customer orders booked until the next MPS receipt is 38 units. The ATP = 55 (on-hand) + 0 (MPS quantity) – 38 = 17.

Explanation: The total of customer orders booked until the next MPS receipt is 27 + 24 + 8 = 59 units. The ATP = 150 (MPS quantity) – 59 = 91 units.

Figure 11.8 shows an MPS record with an additional row for the ATP quantities. The ATP in week 2 is the MPS quantity minus booked customer orders until the next MPS quantity, or $150 - (27 + 24 + 8 + 0 + 0) = 91$ units. The ATP indicates to marketing that, of the 150 units scheduled for completion in week 2, 91 units are uncommitted, and total new orders up to that quantity can be promised for delivery as early as week 2. In week 7, the ATP is 150 units because there are no booked orders in week 7 and beyond.

The procedure for calculating ATP information is slightly different for the first (current) week of the schedule than for other weeks because it accounts for the inventory currently in stock. The ATP inventory for the first week equals *current on-hand inventory* plus the MPS quantity for the first week, minus the cumulative total of booked orders up to (but not including) the week in which the next MPS quantity arrives. So, in Figure 11.8, the ATP for the first week is $55 + 0 - 38 = 17$. This information

indicates to the sales department that it can promise as many as 17 units this week, 91 more units sometime in weeks 2 through 6, and 150 more units in week 7 or 8. If customer order requests exceed ATP quantities in those time periods, the MPS must be changed before the customer orders can be booked or the customers must be given a later delivery date—when the next MPS quantity arrives. See Solved Problem 2 at the end of this chapter for an example of decision making using the ATP quantities.

Inventory planners do not create master production plans manually, although they thoroughly understand the logic built into them. Figure 11.9 is typical of the computer support available. It was created with the *Master Production Scheduling* Solver in OM Explorer, and confirms the output shown in Figure 11.8.

Lot Size	150								
Lead Time	1								
Quantity on Hand	55	1	2	3	4	5	6	7	8
Forecast		30	30	30	30	35	35	35	35
Customer Orders (Booked)		38	27	24	8				
Projected On-Hand Inventory		17	137	107	77	42	7	122	87
MPS Quantity			150					150	
MPS Start		150					150		
Available-to-Promise Inv (ATP)		17	91					150	

▲ **FIGURE 11.9**
Master Production Scheduling Solver Output Using *OM Explorer*

Freezing the MPS

The MPS is the basis of all end item, subassembly, component, and materials schedules. For this reason, changes to the MPS can be costly, particularly if they are made to MPS quantities soon to be completed. Increases in an MPS quantity can result in material shortages, delayed shipments to customers, and excessive expediting costs. Decreases in MPS quantities can result in unused materials or components (at least until another need for them arises) and valuable capacity being used to create products not needed. Similar costs occur when forecasted need dates for MPS quantities are changed. For these reasons, many firms, particularly those with a make-to-stock strategy and a focus on low-cost operations, *freeze*, or disallow changes to, the near-term portion of the MPS.

Reconciling the MPS with Sales and Operations Plans

Because the MPS is based on both forecasts and actual orders received, it can differ from the sales and operations plan when summed across different periods in a month. It is important for the MPS and the S&OP plans to be consistent because the MPS specifies actual outputs, while the S&OP determines the aggregate resources needed to produce those outputs. For instance, in Figure 11.3, if the sum total MPS quantities of the three models of chairs in the month of April was 725 instead of 670, then either the management must revise the sales and operations plan upwards by authorizing additional resources to match supply with demand, or reduce the quantities of MPS in the month of April to match the sales and operations plan. MPSs drive plant and supplier activity, so they must be synchronized with actual customer demands and the sales and operations plans to ensure that the firm's planning decisions are actually being implemented on an ongoing basis.

Online Resource
Tutor 11.1 in OM Explorer provides a new example to practice completing a master production schedule.

MRP Explosion

Having understood how an authorized MPS and other sources of independent demand create a time-phased statement of what is needed on a weekly basis, we next turn to exploring other inputs to the MRP system shown in Figure 11.1. These include the bills of materials and the information contained in inventory records, which in conjunction with the planning factors come together within the MRP logic to create the MRP explosion. The outputs of this explosion process and the reports that form the resultant material requirements plan are also described, along with the environments in which MRP works best.

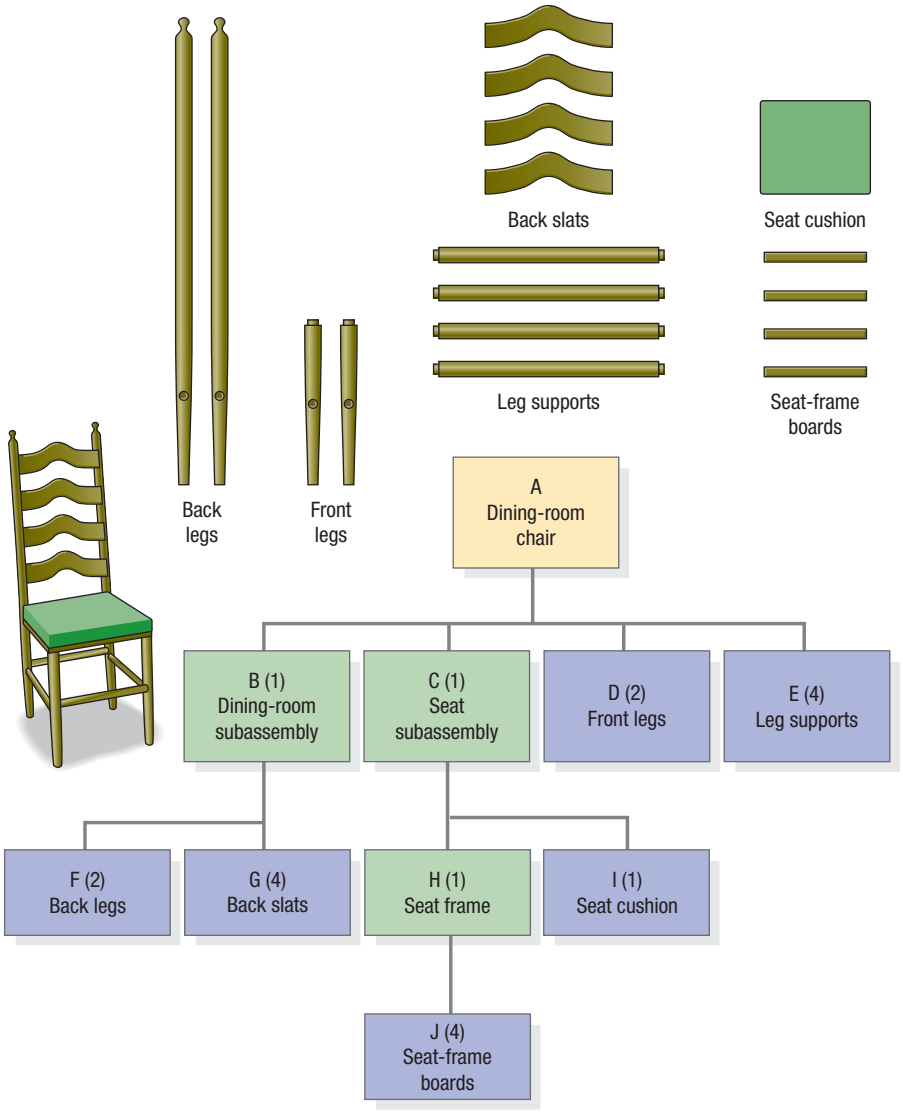
Bill of Materials

The replenishment schedule for a component is determined from the production schedules of its parents. Hence, the system needs accurate information on parent–component relationships. A **bill of materials (BOM)** is a record of all the components of an item, the parent–component relationships, and the usage quantities derived from engineering and process designs. In Figure 11.10, the BOM of our dining-room chair from our discussion of the MPS shows that the chair is made from a dining-room subassembly, a seat subassembly, front legs, and leg supports. In turn, the dining-room subassembly is made from back legs and back slats, and the seat subassembly is made from a seat frame and a seat cushion. Finally, the seat frame is made from seat-frame boards. For convenience, we refer to these items by the letters shown in Figure 11.10.

All items except item A are components because they are needed to make a parent. Items A, B, C, and H are parents because they all have at least one component. The BOM also specifies the **usage quantity**, or the number of units of a component that are needed to make one unit of its immediate parent. Figure 11.10 shows usage quantities for each parent–component relationship in parentheses. Note that one chair (item A) is made from one dining-room subassembly (item B), one

bill of materials (BOM)
A record of all the components of an item, the parent–component relationships, and the usage quantities derived from engineering and process designs.

usage quantity
The number of units of a component that are needed to make one unit of its immediate parent.



▲ **FIGURE 11.10**
BOM for a Dining-room Chair

seat subassembly (item C), two front legs (item D), and four leg supports (item E). In addition, item B is made from two back legs (item F) and four back slats (item G). Item C needs one seat frame (item H) and one seat cushion (item I). Finally, item H needs four seat-frame boards (item J).

Four terms frequently used to describe inventory items are *end items*, *intermediate items*, *subassemblies*, and *purchased items*. An **end item** typically is the final product sold to the customer; it is a parent but not a component. Item A in Figure 11.10, the completed dining-room chair, is an end item. Accounting statements classify inventory of end items as either work-in-process (WIP), if work remains to be done, or finished goods. An **intermediate item**, such as item B, C, or H, has at least one parent and at least one component. Some products have several levels of intermediate items; the parent of one intermediate item can also be an intermediate item. Inventory of intermediate items—whether completed or still on the shop floor—is classified as WIP. A **subassembly** is an intermediate item that is assembled (as opposed to being transformed by other means) from more than one component. Items B and C are subassemblies. A **purchased item** has no components in the buyer's inventory because it comes from a supplier, but it has one or more parents. Examples are items D, E, F, G, I, and J in Figure 11.10. Inventory of purchased items is treated as raw materials in accounting statements.

A component may have more than one parent. **Part commonality**, sometimes called *standardization of parts* or *modularity*, is the degree to which a component has more than one immediate parent. As a result of commonality, the same item may appear in several

end item
The final product sold to a customer.

intermediate item
An item that has at least one parent and at least one component.

subassembly
An intermediate item that is *assembled* (as opposed to being transformed by other means) from more than one component.

purchased item
An item that has one or more parents but no components because it comes from a supplier.

part commonality
The degree to which a component has more than one immediate parent.



iurii/Shutterstock

An image of a disassembled car to show its bill of materials.

places in the BOM for a product, or it may appear in the BOM for several different products. For example, the seat subassembly in Figure 11.10 is a component of the dining-room chair and of a kitchen chair that is part of the same family of products. The usage quantity specified in the BOM relates to a specific parent–component relationship. The usage quantity for any component can therefore change, depending on the parent item. Part commonality, or using the same part in many parents, increases its volume and repeatability, which provides several process advantages and helps minimize inventory costs.

When the popular iPad and iPad 2 products from Apple were released a few years back, careful dissections of their BOMs showed that the two different generation products differed in their enclosure and battery, but were otherwise remarkably similar in their components and design. The same suppliers were used for many components, and costs were very comparable for new revisions of chips found in the previous iPad and iPhones. Standardization of designs and components across different products and generations allowed Apple to be very competitive and profitable.

Inventory Record

Inventory records are a third major input to MRP, and inventory transactions are the basic building blocks of up-to-date records (see Figure 11.1). These transactions include releasing new orders, receiving scheduled receipts, adjusting due dates for scheduled receipts, withdrawing inventory, canceling orders, correcting inventory errors, rejecting shipments, and verifying scrap losses and stock returns. Recording the transactions accurately is essential if the firm's on-hand inventory balances are to be correct and its MRP system is to operate effectively.

The **inventory record** divides the future into time periods called *time buckets*. In our discussion, we use weekly time buckets for consistency with our MPS example, although other time periods could as easily be used. The inventory record shows an item's lot-size policy, lead time, and various time-phased data. The purpose of the inventory record is to keep track of inventory levels and component replenishment needs. The time-phased information contained in the inventory record consists of (1) *gross requirements*, (2) *scheduled receipts*, (3) *projected on-hand inventory*, (4) *planned receipts*, and (5) *planned order releases*.

We illustrate the discussion of inventory records with the seat subassembly, item C that was shown in Figure 11.10. Suppose that it is used in two products: a dining-room chair and a kitchen chair.

▼ **FIGURE 11.11**
MRP Record for the Seat Subassembly

Item: C
Description: Seat subassembly
Lot Size: 230 units
Lead Time: 2 weeks

		Week							
		1	2	3	4	5	6	7	8
Gross requirements		150			120		150	120	
Scheduled receipts		230							
Projected on-hand inventory	37	117	117	117	–3	–3	–153	–273	–273
Planned receipts									
Planned order releases									

Explanation:
Gross requirements are the total demand for the two chairs. Projected on-hand inventory in week 1 is 37 + 230 – 150 = 117 units.

Gross Requirements The **gross requirements** are the total demand derived from *all* parent production plans. They also include demand not otherwise accounted for, such as demand for replacement parts for units already sold. Figure 11.11 shows an inventory record for item C, the seat subassembly. Item C is produced in lots of 230 units and has a lead time of 2 weeks. The inventory record also shows item C's gross requirements for the next 8 weeks, which come from the MPS for the dining-room and kitchen chairs (see Figure 11.3). The MPS start quantities for each parent are added to arrive at each week's gross requirements. The seat subassembly's gross requirements exhibit lumpy demand: Operations will withdraw seat subassemblies from inventory in only 4 of the 8 weeks.

The MRP system works with release dates to schedule production and delivery for components and subassemblies. Its program logic anticipates the removal of all materials required by a parent's production order from inventory at the beginning of the parent item's lead time—when the scheduler first releases the order to the shop.

Scheduled Receipts Recall that *scheduled receipts* (sometimes called open orders) are orders that have been placed but not yet completed. For a purchased item, the scheduled receipt could be in one of several stages: being processed by a supplier, being transported to the purchaser, or being inspected by the purchaser's receiving department. If the firm is making the item in-house, the order could be on the shop floor being processed, waiting for components, waiting for a machine

inventory record
A record that shows an item's lot-size policy, lead time, and various time-phased data.

gross requirements
The total demand derived from *all* parent production plans.

to become available, or waiting to be moved to its next operation. According to Figure 11.11, one 230-unit order of item C is due in week 1. Given the 2-week lead time, the inventory planner probably released the order 2 weeks ago. Scheduled receipts due beyond the item's lead time are unusual, caused by events such as a last-minute change in the MPS.

projected on-hand inventory
An estimate of the amount of inventory available each week after gross requirements have been satisfied.

Projected On-Hand Inventory The **projected on-hand inventory** is an estimate of the amount of inventory available each week after gross requirements have been satisfied. The beginning inventory, shown as the first entry (37) in Figure 11.11, indicates the on-hand inventory available at the time the record was computed. As with scheduled receipts, entries are made for each actual withdrawal and receipt to update the MRP database. Then, when the MRP system produces the revised record, the correct inventory will appear.

Other entries in the row show inventory expected in future weeks. Projected on-hand inventory is calculated as

$$\begin{pmatrix}\text{Projected on-hand}\\ \text{inventory balance}\\ \text{at end of week } t\end{pmatrix} = \begin{pmatrix}\text{Inventory on}\\ \text{hand at end of}\\ \text{week } t-1\end{pmatrix} + \begin{pmatrix}\text{Scheduled}\\ \text{or planned}\\ \text{receipts in}\\ \text{week } t\end{pmatrix} - \begin{pmatrix}\text{Gross}\\ \text{requirements}\\ \text{in week } t\end{pmatrix}$$

planned receipts
Orders that are not yet released to the shop or the supplier.

The projected on-hand calculation includes the consideration of **planned receipts**, which are orders not yet released to the shop or the supplier. Planned receipts should not be confused with scheduled receipts. Planned receipts are still at the planning stage and can still change from one week to the next, whereas scheduled receipts are actual orders that are being acted upon by the shop or supplier. In Figure 11.11, the planned receipts are all zero. The on-hand inventory calculations for each week are as follows:

Week 1:	37 + 230 − 150 = 117
Weeks 2 and 3:	117 + 0 − 0 = 117
Week 4:	117 + 0 − 120 = −3
Week 5:	−3 + 0 − 0 = −3
Week 6:	−3 + 0 − 150 = −153
Week 7:	−153 + 0 − 120 = −273
Week 8:	−273 + 0 − 0 = −273

In week 4, the balance drops to −3 units, which indicates that a shortage of 3 units will occur unless more seat subassemblies are built. This condition signals the need for a planned receipt to arrive in week 4. In addition, unless more stock is received, the shortage will grow to 273 units in weeks 7 and 8.[3]

Planned Receipts Planning for the receipt of new orders will keep the projected on-hand balance from dropping below zero. The planned receipt row is developed as follows:

1. Weekly on-hand inventory is projected until a shortage appears. Completion of the initial planned receipt is scheduled for the week in which the shortage is projected. The addition of the newly planned receipt should increase the projected on-hand balance so that it equals or exceeds zero. It will exceed zero when the lot size exceeds requirements in the week it is planned to arrive.
2. The projection of on-hand inventory continues until the next shortage occurs. This shortage signals the need for the second planned receipt.

This process is repeated until the end of the planning horizon by proceeding column by column through the MRP record—filling in planned receipts as needed and completing the projected on-hand inventory row. Figure 11.12 shows the planned receipts for the seat subassembly. In week 4, the projected on-hand inventory will drop below zero, so a planned receipt of 230 units is scheduled for week 4. The updated inventory on-hand balance is 117 inventory at end of week 3 + 230 (planned receipts) − 120 (gross requirements) = 227 units. The projected on-hand inventory remains at 227 for week 5 because no scheduled receipts or gross requirements are

[3]There is an exception to the rule of scheduling a planned receipt whenever the projected inventory otherwise becomes negative. When a scheduled receipt is coming in *after* the inventory becomes negative, the first recourse is to expedite the scheduled receipt (giving it an earlier due date), rather than scheduling a new planned receipt.

anticipated. In week 6, the projected on-hand inventory is 227 (inventory at end of week 5) − 150 (gross requirements) = 77 units. This quantity is greater than zero, so no new planned receipt is needed. In week 7, however, a shortage will occur unless more seat subassemblies are received. With a planned receipt in week 7, the updated inventory balance is 77 (inventory at end of week 6) + 230 (planned receipts) − 120 (gross requirements) = 187 units.

Planned Order Releases A **planned order release** indicates when an order for a specified quantity of an item is to be issued. We must place the planned order release quantity in the proper time bucket. To do so, we must assume that all inventory flows—scheduled receipts, planned receipts, and gross requirements—occur at the same point of time in a time period. Some firms assume that all flows occur at the beginning of a time period; other firms assume that they occur at the end of a time period or at the middle of the time period. Regardless of when the flows are assumed to occur, we find the release date by subtracting the lead time from the receipt date. For example, the release date for the first planned order release in Figure 11.12 is 4 (planned receipt date) − 2 (lead time) = 2 (planned order release date). Figure 11.12 shows the planned order releases for the seat subassembly. If all goes according to the plan, we will release an order for 230 seat assemblies next week (in week 2). This order release sets off a series of updates to the inventory record. First, the planned order release for the order is removed. Next, the planned receipt for 230 units in week 4 is also removed. Finally, a new scheduled receipt for 230 units will appear in the scheduled receipt row for week 4.

Item: C
Description: Seat subassembly
Lot Size: 230 units
Lead Time: 2 weeks

		Week							
		1	2	3	4	5	6	7	8
Gross requirements		150			120		150	120	
Scheduled receipts		230							
Projected on-hand inventory	37	117	117	117	227	227	77	187	187
Planned receipts					230			230	
Planned order releases			230			230			

Explanation:
Without a planned receipt in week 4, a shortage of 3 units will occur: 117 – 120 = –3 units. Adding the planned receipt brings the balance to 117 + **230** – 120 = 227 units. Offsetting for a 2-week lead time puts the corresponding planned order release back to week 2.

Explanation:
The first planned receipt lasts until week 7, when projected inventory would drop to 77 – 120 = –43 units. Adding the second planned receipt brings the balance to 77 + **230** – 120 = 187 units.
The corresponding planned order release is for week 5 (or week 7 minus 2 weeks).

▲ **FIGURE 11.12**
Completed Inventory Record for the Seat Subassembly

planned order release
An indication of when an order for a specified quantity of an item is to be issued.

Planning Factors

The planning factors in an MRP inventory record play an important role in the overall performance of the MRP system. By manipulating these factors, managers can fine-tune inventory operations. In this section, we discuss planning lead time, lot-sizing rules, and safety stock.

Planning Lead Time Planning lead time is an estimate of the time between placing an order for an item and receiving the item in inventory. Accuracy is important in planning lead time. If an item arrives in inventory sooner than needed, inventory holding costs increase. If an item arrives too late, stockouts, excessive expediting costs, or both may occur.

For purchased items, the planning lead time is the time allowed for receiving a shipment from the supplier after the order has been sent, including the normal time to place the order. Often, the purchasing contract stipulates the delivery date. For items manufactured in-house, a rough-cut estimate of the planning lead time can be obtained by keeping track of the actual lead times for recent orders and computing an average. A more extensive estimating process consists of breaking down each of the following factors:

- Setup time
- Processing time
- Materials handling time between operations
- Waiting time

Each of these times must be estimated for every operation along the item's route. Estimating setup, processing, and materials handling times can be relatively easy, but estimating the waiting time for materials handling equipment or for a workstation to perform a particular operation can be more difficult. In a facility that uses a make-to-order strategy, such as a machine shop, the load on the shop varies considerably over time, causing actual waiting times for a particular order to fluctuate widely. Therefore, being able to accurately estimate the waiting time is especially



Jonathan Weiss/Shutterstock

Winnebago regularly introduces new models of motorhomes, many of which have received the Readers' Choice award from *MotorHome Magazine*. With a constant change in product variety, Winnebago uses a homegrown MRP system running on an IBM mainframe that can be easily modified to structure its Bill of Materials (BOM) and support production schedules of the new vehicles.

important when it comes to estimating the planning lead time. However, in a facility that uses a make-to-stock strategy, such as an assembly plant, product routings are more standard and waiting time is more predictable; hence, waiting time generally is a less troublesome part of planning lead times.

Lot-Sizing Rules A lot-sizing rule determines the timing and size of order quantities. A lot-sizing rule must be assigned to each item before planned receipts and planned order releases can be computed. The choice of lot-sizing rules is important because they determine the number of setups required and the inventory holding costs for each item. We present three lot-sizing rules: (1) fixed order quantity, (2) periodic order quantity, and (3) lot for lot.

Fixed Order Quantity The **fixed order quantity (FOQ)** rule maintains the same order quantity each time an order is issued.[4] For example, the lot size might be the size dictated by equipment capacity limits, such as when a full lot must be loaded into a furnace at one time. For purchased items, the FOQ could be determined by the quantity discount level, truckload capacity, or minimum purchase quantity. Alternatively, the lot size could be determined by the economic order quantity (EOQ) formula (see Chapter 9, "Inventory Management"). Figure 11.12 illustrated the FOQ rule. However, if an item's gross requirement within a week is particularly large, the FOQ might be insufficient to avoid a shortage. In such unusual cases, the inventory planner must increase the lot size beyond the FOQ, typically to a size large enough to avoid a shortage. Another option is to make the order quantity an integer multiple of the FOQ. This option is appropriate when capacity constraints limit production to FOQ sizes (at most).

fixed order quantity (FOQ)
A rule that maintains the same order quantity each time an order is issued.

Periodic Order Quantity The **periodic order quantity (POQ)** rule allows a different order quantity for each order issued but issues the order for predetermined time intervals, such as every 2 weeks. The order quantity equals the amount of the item needed during the predetermined time between orders and must be large enough to prevent shortages. Specifically, the POQ is

periodic order quantity (POQ)
A rule that allows a different order quantity for each order issued but issues the order for predetermined time intervals.

$$\begin{pmatrix}\text{POQ lot size}\\ \text{to arrive in}\\ \text{week } t\end{pmatrix} = \begin{pmatrix}\text{Total gross requirements}\\ \text{for } P \text{ weeks, including}\\ \text{week } t\end{pmatrix} - \begin{pmatrix}\text{Projected On-hand}\\ \text{inventory balance at}\\ \text{end of week } t-1\end{pmatrix}$$

This amount exactly covers P weeks' worth of gross requirements. That is, the projected on-hand inventory should equal zero at the end of the Pth week.

Online Resource
Tutor 11.2 in OM Explorer provides a new example to practice lot-sizing decisions using FOQ, POQ, and L4L rules.

Suppose that we want to switch from the FOQ rule used in Figure 11.12 to the POQ rule. Figure 11.13 was created with the *Single-Item MRP* Solver in OM Explorer. It shows the application of the POQ rule, with $P = 3$ weeks, to the seat subassembly inventory. The first order is required in week 4 because it is the first week that projected inventory balance will fall below zero. The first order using $P = 3$ weeks is

$$(\text{POQ lot size}) = \begin{pmatrix}\text{Gross requirements}\\ \text{for weeks}\\ 4, 5, \text{ and } 6\end{pmatrix} - \begin{pmatrix}\text{Inventory at}\\ \text{end of week } 3\end{pmatrix}$$

$$= (120 + 0 + 150) - 117 = 153 \text{ units}$$

The second order must arrive in week 7 with a lot size of $(120 + 0) - 0 = 120$ units. This second order reflects only 2 weeks' worth of gross requirements—to the end of the planning horizon.

The POQ rule does not mean that the planner must issue a new order every P weeks. Rather, when an order is planned, its lot size must be enough to cover P successive weeks. One way to

[4]The Kanban system essentially uses an FOQ rule, except that the order quantity is very small.

Periods 8

Item Description: Seat Assembly | Period (P) for POQ: 3 | Lot Size (FOQ) / Lead Time: 2

POQ Rule

		1	2	3	4	5	6	7	8
Gross requirements		150			120		150	120	
Scheduled receipts		230							
Projected on-hand inventory	37	117	117	117	150	150			
Planned receipts					153			120	
Planned order releases			153			120			

FIGURE 11.13
Single-Item MRP Solver Output in OM Explorer using the POQ ($P = 3$) Rule for the Seat Subassembly

select a P value is to divide the average lot size desired, such as the EOQ or some other applicable lot size, by the average weekly demand. That is, express the target lot size as the desired weeks of supply (P) and round to the nearest integer.

Lot for Lot A special case of the POQ rule is the **lot-for-lot (L4L) rule**, under which the lot size ordered covers the gross requirements of a single week. Thus, $P = 1$, and the goal is to minimize inventory levels. This rule ensures that the planned order is just large enough to prevent a shortage in the single week it covers. The L4L lot size is

lot-for-lot (L4L) rule
A rule under which the lot size ordered covers the gross requirements of a single week.

$$\begin{pmatrix}\text{L4L lot size}\\ \text{to arrive in}\\ \text{week } t\end{pmatrix} = \begin{pmatrix}\text{Gross requirements}\\ \text{for week } t\end{pmatrix} - \begin{pmatrix}\text{Projected On-hand}\\ \text{inventory balance at}\\ \text{end of week } t-1\end{pmatrix}$$

The projected on-hand inventory combined with the new order will equal zero at the end of week t. Following the first planned order, an additional planned order will be used to match each subsequent gross requirement.

This time we want to switch from the FOQ rule to the L4L rule. Figure 11.14 shows the application of the L4L rule to the seat subassembly inventory. As before, the first order is needed in week 4:

$$\text{(L4L lot size)} = \begin{pmatrix}\text{Gross requirements}\\ \text{in week 4}\end{pmatrix} - \begin{pmatrix}\text{Inventory balance}\\ \text{at end of week 3}\end{pmatrix}$$
$$= 120 - 117 = 3$$

Item: Dining-room chair **Order Policy:** L4L **Lead Time:** 2 weeks

		Week 1	2	3	4	5	6	7	8
Gross requirements		150			120		150	120	
Scheduled receipts		230							
Projected on-hand inventory	37	117	117	117					
Planned receipts					3		150	120	
Planned order releases			3		150	120			

FIGURE 11.14
The L4L Rule for the Seat Subassembly

The stockroom must receive additional orders in weeks 6 and 7 to satisfy each of the subsequent gross requirements. The planned receipt for week 6 is 150 and for week 7 is 120.

Comparing Lot-Sizing Rules Choosing a lot-sizing rule can have important implications for inventory management. Lot-sizing rules affect inventory costs and setup and ordering costs. The FOQ, POQ, and L4L rules differ from one another in one or both respects. In our example, each rule took effect in week 4, when the first order was placed. Let us compare the projected on-hand inventory averaged over weeks 4 through 8 of the planning horizon. The data are shown in Figures 11.12, 11.13, and 11.14, respectively.

$$\text{FOQ: } \frac{227 + 227 + 77 + 187 + 187}{5} = 181 \text{ units}$$

$$\text{POQ: } \frac{150 + 150 + 0 + 0 + 0}{5} = 60 \text{ units}$$

$$\text{L4L: } \frac{0 + 0 + 0 + 0 + 0}{5} = 0 \text{ units}$$

The performance of the L4L rule with respect to average inventory levels comes at the expense of an additional planned order and its accompanying setup time and cost. We can draw three conclusions from this comparison:

1. The FOQ rule generates a high level of average inventory because it creates inventory *remnants*. A remnant is inventory carried into a week, but it is too small to prevent a shortage. Remnants occur because the FOQ does not match requirements exactly. For example,

according to Figure 11.12, the stockroom must receive a planned order in week 7, even though 77 units are on hand at the beginning of that week. The remnant is the 77 units that the stockroom will carry for 3 weeks, beginning with receipt of the first planned order in week 4. Although they increase average inventory levels, inventory remnants introduce stability into the production process by buffering unexpected scrap losses, capacity bottlenecks, inaccurate inventory records, or unstable gross requirements.

2. The POQ rule reduces the amount of average on-hand inventory because it does a better job of matching order quantity to requirements. It adjusts lot sizes as requirements increase or decrease. Figure 11.13 shows that in week 7, when the POQ rule has fully taken effect, the projected on-hand inventory is zero—no remnants.
3. The L4L rule minimizes inventory investment, but it also maximizes the number of orders placed. This rule is most applicable to expensive items or items with small ordering or setup costs. It is the only rule that can be used for a low-volume item made to order. It can also approximate the small-lot inventory levels of a lean system.

By avoiding remnants, both the POQ and the L4L rule may introduce instability by tying the lot-sizing decision so closely to requirements. If any requirement changes, so must the lot size, which can disrupt component schedules. Last-minute increases in parent orders may be hindered by missing components.

Safety Stock An important managerial decision is the quantity of safety stock to carry. It is more complex for dependent demand items than for independent demand items. Safety stock for dependent demand items with lumpy demand (gross requirements) is helpful only when future gross requirements, the timing or size of scheduled receipts, and the amount of scrap that will be produced are uncertain. As these uncertainties are resolved, safety stock should be reduced and ultimately eliminated. The usual policy is to use safety stock for end items and purchased items to protect against fluctuating customer orders and unreliable suppliers of components but to avoid using it as much as possible for intermediate items. Safety stocks can be incorporated into the MRP logic by using the following rule: Schedule a planned receipt whenever the projected on-hand inventory balance drops below the desired safety stock level (rather than zero, as before). The objective is to keep a minimum level of planned inventories equal to the safety stock quantity. Figure 11.15 shows what happens when the safety stock requirement has just been increased from 0 units to 80 units of safety stock for the seat assembly using an FOQ of 230 units. The beginning projected on-hand quantity is still 37 units when the safety stock policy is introduced, and cannot fall below 80 units in any future period thereafter. Compare the results in Figure 11.15 to those in Figure 11.12. The net effect is to move the second planned order release from week 5 to week 4 to avoid dropping below 80 units in week 6.

FOQ Rule — **Lot Size:** 230 units; **Lead Time:** 2 weeks; **Safety Stock:** 80 units

	Week							
	1	2	3	4	5	6	7	8
Gross requirements	150			120		150	120	
Scheduled receipts	230							
Projected on-hand inventory 37	117	117	117	227	227	307	187	187
Planned receipts				230		230		
Planned order releases		230		230				

▲ **FIGURE 11.15**
Inventory Record for the Seat Subassembly Showing the Application of a Safety Stock

Outputs from MRP

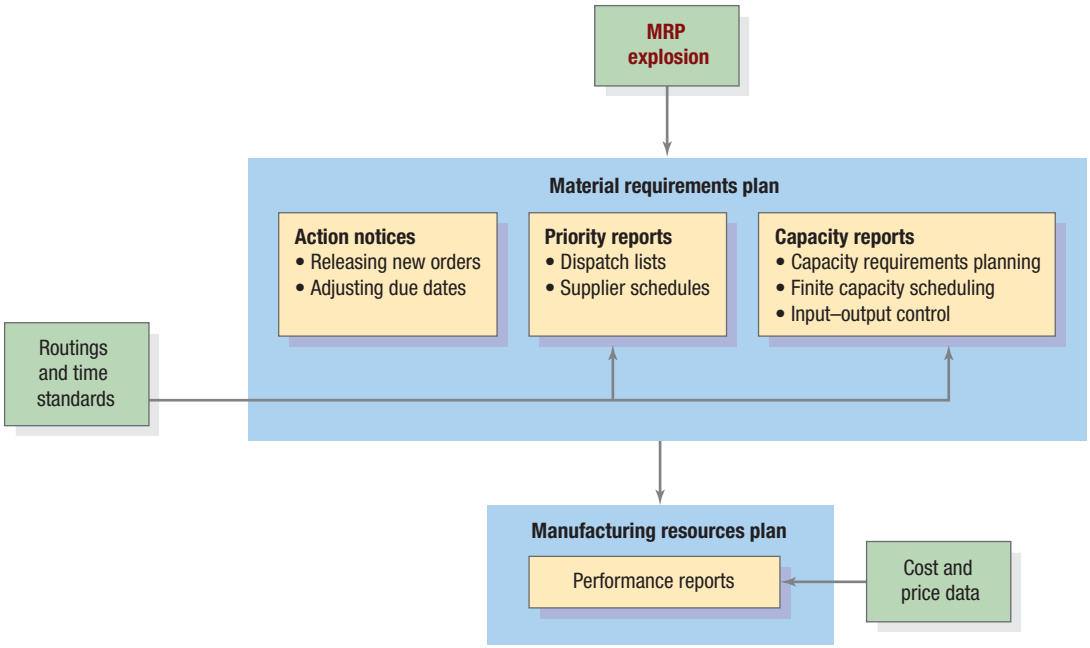
MRP systems provide many reports, schedules, and notices to help planners control dependent demand inventories, as indicated in Figure 11.16. In this section, we discuss the MRP explosion process that generates the material requirements, notices that alert planners to items needing attention, resource requirement reports, and performance reports.

Material Requirements MRP translates, or *explodes*, the MPS and other sources of demand into the requirements needed for all of the subassemblies, components, and raw materials the firm needs to produce parent items. This process generates the material requirements plan for each component item.

An item's gross requirements are derived from three sources:

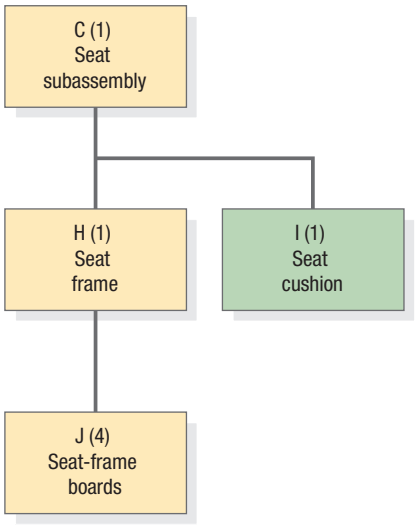
1. The MPS for immediate parents that are end items
2. The planned order releases (*not* the gross requirements, scheduled receipts, or planned receipts) for immediate parents below the MPS level
3. Any other requirements not originating in the MPS, such as the demand for replacement parts

Consider the seat subassembly and its inventory record shown in Figure 11.12. The seat subassembly requires a seat cushion and a seat frame, which in turn needs four seat-frame boards.



◀ **FIGURE 11.16**
MRP Outputs

Its BOM is shown in Figure 11.17 (see also Figure 11.10, which shows how the seat subassembly BOM relates to the product as a whole). How many seat cushions should we order from the supplier? How many seat frames should we produce to support the seat subassembly schedule? How many seat-frame boards do we need to make? The answers to these questions depend on the existing inventories of these items and the replenishment orders already in progress. MRP can help answer these questions through the explosion process.



▲ **FIGURE 11.17**
BOM for the Seat Subassembly

Figure 11.18 shows the MRP records for the seat subassembly and its components. We already showed how to develop the MRP record for the seat subassembly. We now concentrate on the MRP records of its components. The lot-size rules are an FOQ of 300 units for the seat frame, L4L for the seat cushion, and an FOQ of 1,500 for the seat-frame boards. All three components have a 1-week lead time. The key to the explosion process is to determine the proper timing and size of the gross requirements for each component. After we make those determinations, we can derive the planned order release schedule for each component by using the logic already demonstrated.

In our example, the components have no independent demand for replacement parts. Consequently, in Figure 11.18 the gross requirements of a component come from the planned order releases of its parents. The seat frame and the seat cushion get their gross requirements from the planned order release schedule of the seat subassembly. Both components have gross requirements of 230 units in weeks 2 and 5, the same weeks in which we will be releasing orders to make more seat subassemblies. In week 2, for example, the materials handler for the assembly department will withdraw 230 seat frames and 230 seat cushions from inventory so that the assembly department can produce the seat subassemblies in time to avoid a stockout in week 4. The materials plans for the seat frame and the seat cushion must allow for that.

Using the gross requirements in weeks 2 and 5, we can develop the MRP records for the seat frame and the seat cushion, as shown in Figure 11.18. For a scheduled receipt of 300 seat frames in week 2, an on-hand quantity of 40 units, and a lead time of 1 week, we need to release an order of 300 seat frames in week 4 to cover the assembly schedule for the seat subassembly. The seat cushion has no scheduled receipts and no inventory on hand; consequently, we must place orders for 230 units in weeks 1 and 4, using the L4L logic with a lead time of 1 week.

After determining the replenishment schedule for the seat frame, we can calculate the gross requirements for the seat-frame boards. We plan to begin producing 300 seat frames in week 4. Each frame requires 4 boards, so we need to have 300(4) = 1,200 boards available in week 4. Consequently, the gross requirement for seat-frame boards is 1,200 in week 4. Given no scheduled

Item: Seat subassembly
Lot size: 230 units
Lead time: 2 weeks

	Week							
	1	2	3	4	5	6	7	8
Gross requirements	150			120		150	120	
Scheduled receipts	230							
Projected inventory 37	117	117	117	227	227	77	187	187
Planned receipts				230			230	
Planned order releases		230			230			

Usage quantity: 1 — Usage quantity: 1

Item: Seat frames
Lot size: 300 units
Lead time: 2 weeks

	Week							
	1	2	3	4	5	6	7	8
Gross requirements		230			230			
Scheduled receipts		300						
Projected inventory 40	40	110	110	110	180	180	180	180
Planned receipts					300			
Planned order releases			300					

Item: Seat cushion
Lot size: L4L
Lead time: 1 week

	Week							
	1	2	3	4	5	6	7	8
Gross requirements		230			230			
Scheduled receipts								
Projected inventory 0	0	0	0	0	0	0	0	0
Planned receipts		230			230			
Planned order releases	230			230				

Usage quantity: 4

Item: Seat-frame boards
Lot size: 1,500 units
Lead time: 1 week

	Week							
	1	2	3	4	5	6	7	8
Gross requirements			1,200					
Scheduled receipts								
Projected inventory 200	200	200	500	500	500	500	500	500
Planned receipts			1,500					
Planned order releases		1,500						

▲ **FIGURE 11.18**
MRP Explosion of Seat Assembly Components

receipts, 200 boards in stock, a lead time of 1 week, and an FOQ of 1,500 units, we need a planned order release of 1,500 in week 3.

The questions posed earlier can now be answered. We should plan to release the following orders: 300 seat frames in week 4; 230 seat cushions in each of weeks 1 and 4; and 1,500 seat-frame boards in week 3. If MRP plans are updated weekly, only the planned order for week 1 should be released now. Releasing it creates a scheduled receipt of 230 seat cushions that will appear in the updated inventory record. The other orders remain in the planning stage, and even might be revised by the MRP explosion done next week.

In practice, a company can have thousands of dependent demand items with an average of six bills of materials levels. Time horizons often stretch out for 30 or more time periods into the future. Doing a MRP explosion by hand, as shown in Figure 11.18, would be impractical. What is needed is massive data processing, the very thing that computers do best, leaving the decision making to the inventory analyst. The *Material Requirements Planning* Solver of OM Explorer represents a small example of what is done on a much larger scale by commercial packages. It can compute requirements for up to two end items, and has the ability to develop inventory records up to 18 items deep with little effort, and can easily recompute these requirements if there is any change in planning parameters.

Action Notices Once computed, inventory records for any item appearing in the BOM can be printed in hard copy or displayed on a computer video screen. Inventory planners use a computer-generated memo called an **action notice** to make decisions about releasing new orders and adjusting the due dates of scheduled receipts. For instance, based on the output in Figure 11.18, an action notice would be issued to bring to the attention of the inventory planner the planned order release of 230 units for seat cushions. Its planned order release is now "mature" for release this week. Unless the planner knows of a problem, the planner would place the order with the supplier. At the same time, the planner would input a transaction that automatically eliminates the planned order release in period 1, removes the planned receipt in period 2, and inserts a scheduled receipt for 230 units in period 2. The planner need not look at the records for seat frames or seat-frame boards, because no action is needed for them.

action notice

A computer-generated memo alerting planners about releasing new orders and adjusting the due dates of scheduled receipts.

Action notices are generated every time the system is updated, typically once per week. The action notice alerts planners to only the items that need their attention, such as those items that have a planned order release in the current period or a scheduled receipt that needs its due date revised. Planners can then view the full records for those items and take the necessary actions. An action notice can simply be a list of part numbers for items that need attention; or it can be the full record for such items, with a note at the bottom identifying the action needed.

Resource Requirements Reports By itself, the MRP system does not recognize capacity limitations when computing planned orders; that is, it may call for a planned order release that exceeds the amount that can be physically produced. An essential role of planners is to monitor the capacity requirements of material requirements plans, adjusting a plan when it cannot be met. Particular attention is paid to bottlenecks. The planner can apply theory of constraints (TOC) principles (see Chapter 6, "Constraint Management") to keep bottleneck operations fed by adjusting some lot-sizing rules or occasionally overriding planned order releases. To facilitate this process, various types of capacity reports can be provided. For example, **capacity requirements planning (CRP)** reports project time-phased capacity requirements for workstations. They calculate workload according to the work required to complete the scheduled receipts already in the shop and to complete the planned order releases not yet released. Bottlenecks are those workstations at which the projected loads exceed station capacities.

capacity requirements planning (CRP)

A technique used for projecting time-phased capacity requirements for work stations; its purpose is to match the materials requirements plan with the capacity of key processes.

Performance Reports Other types of outputs are also possible, such as priority reports on orders already placed to the shop or with suppliers. Priority reports begin with the due dates assigned to scheduled receipts, which planners keep up to date so that they continue to reflect when receipt is really needed. On a broader scale, the information in an MRP system is useful to functional areas other than operations. MRP evolved into **manufacturing resource planning (MRP II)**, a system that ties the basic MRP system to the company's financial system and to other core and supporting processes. For example, management can project the dollar value of shipments, product costs, overhead allocations, inventories, backlogs, and profits by using the MRP plan along with prices and product and activity costs from the accounting system. Also, information from the MPS, scheduled receipts, and planned orders can be converted into cash flow projections, which are broken down by product families. Similar computations are possible for other performance measures of interest to management. Some firms may, however, forgo the cost of vendor-delivered MRP systems because of the huge budgets and company resources involved in their deployment, and instead create their own MRP system implementations in-house.

manufacturing resource planning (MRP II)

A system that ties the basic MRP system to the company's financial system and to other core and supporting processes.

MRP and the Environment

Consumer and governmental concern about the deterioration of the natural environment has driven manufacturers to reengineer their processes to become more environmentally friendly. The recycling of base materials is becoming more commonplace, and products are being designed in

such a way that they can be remanufactured after their useful lives. Nonetheless, manufacturing processes often produce a number of waste materials that need to be properly disposed of. Wastes come in many forms:

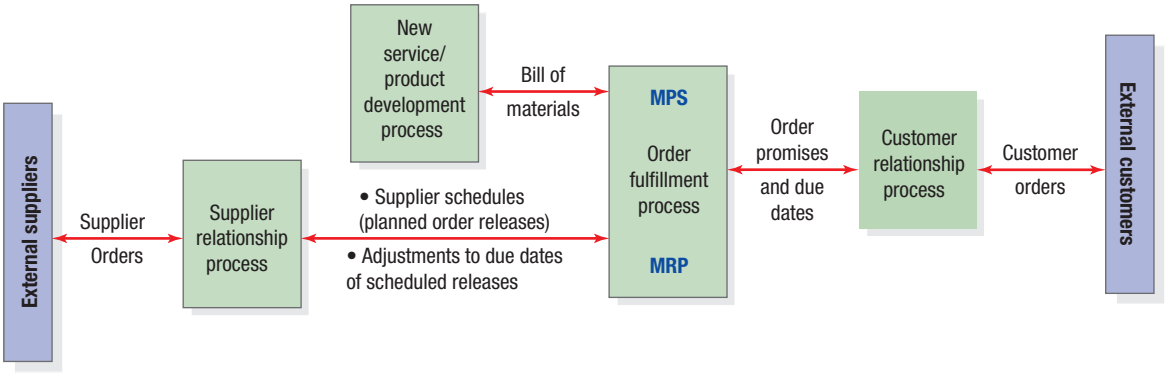
- Effluents, such as carbon monoxide, sulfur dioxide, and hazardous chemicals associated with the processes used to manufacture the product
- Materials, such as metal shavings, oils, and chemicals associated with specific operations
- Packaging materials, such as unusable cardboard and plastics associated with certain products or purchased items
- Scrap associated with unusable products or component defects generated by the manufacturing process

Companies can modify their MRP systems to help them track these wastes and plan for their disposal. The type and amount of waste associated with each item can be entered into its BOM by treating the waste much like you would a component of the item. When the MPS is developed for a product, reports can be generated that project the amount of waste expected during the production process and when it will occur. Although this approach can require that a firm's BOM be modified substantially, the benefits are also substantial. Firms can identify their waste problems in advance to eliminate them in some cases (through process improvement efforts) or plan for their proper disposal in others. It also gives the firm a way to generate any formal documentation required by the government to verify that it has complied with environmental laws and policies. See Chapter 15, "Supply Chain Sustainability," for added discussion of the need for recognizing the environment in supply chain operations.

MRP, Core Processes, and Supply Chain Linkages

Among the four core processes of an organization that link activities within and across firms in a supply chain, the MRP system interacts with all of them through either its inputs or its outputs. It all begins with customer orders, which consist of orders for end items as well as replacement parts. MRP and resource planning typically reside inside the order fulfillment process. The MPS is an integral part of MRP (see Figure 11.1). As shown schematically in Figure 11.19, the MPS drives the feedback between the order fulfillment process and the customer relationship process through confirmation of order receipts and promised due dates. The MPS also provides guidance to the sales group within the customer relationship process with respect to when future orders can be promised, and whether the due dates for existing orders can be adjusted in the time frame requested. The new service and product development process provides an updated BOM to the MRP system, and makes sure that every component and assembly needed for manufacturing of end items is properly recognized.

FIGURE 11.19 ▼
MRP Related Information Flows in the Supply Chain



In a similar vein on the inbound side, orders to external suppliers are based on the planned order releases, which come directly from the output of MRP reports. The power of MRP, however, becomes evident when changes to an existing schedule are needed. These changes can be generated, for example, by changes to the MPS because a customer wants to change the timing or size of future orders, by some internal failure such as material shortages or unexpected machine downtime, or by supplier failure. In a supply chain, schedule changes have implications for customers as well as suppliers. Some firms, in partnership with their suppliers, have MRP systems that can actually "see" into their suppliers' inventory to determine if a particular item is in stock or, if not, when it can be expected. This is an advantage when contemplating a change to the original schedule of order releases. While systems such as this are powerful tools for making changes, care must be taken to avoid unnecessary fluctuations in the timing and size of planned

order releases because of the choice of lot-sizing policy. As we have seen, lot-sizing rules such as POQ or L4L are susceptible to changes in requirements, and using them indiscriminately can cause instability in replenishment orders. In turn, this instability can be transmitted up the supply chain if the firm's MRP system is electronically linked to the production planning and control systems of its immediate suppliers.

Execution of MRP-based plans using the information flows between core processes as shown in Figure 11.19 properly links a firm with its upstream and downstream supply chain partners. Valid customer and supplier priorities would not be effectively recognized without such an MRP-based framework, which in many firms is actually implemented through an ERP system that we discuss next in this chapter.

enterprise process

A company-wide process that cuts across functional areas, business units, geographical regions, and product lines.

enterprise resource planning (ERP) systems

Large, integrated information systems that support many enterprise processes and data storage needs.

Enterprise Resource Planning

An **enterprise process** is a company-wide process that cuts across functional areas, business units, geographical regions, product lines, suppliers, and customers. **Enterprise resource planning (ERP) systems** are large, integrated information systems that support many enterprise processes and data storage needs. By integrating the firm's functional areas, ERP systems allow an organization to view its operations as a whole rather than having to try to put together the different information pieces produced by its various functions and divisions. Today, ERP systems are being used by traditional brick-and-mortar organizations such as manufacturers, restaurants, hospitals, and hotels, as well as by Internet companies that rely extensively on Web connectivity to link their customers and suppliers.

How ERP Systems Are Designed



Pavel L. Photo and Video/Shutterstock

Golden Road, a small brewery making craft beer, is using a cloud-based ERP system to compete in Los Angeles—without breaking the bank.

ERP revolves around a single comprehensive database that can be made available across the entire organization (or enterprise). Security restricts system usage to allow personnel access to certain areas of the system. Having a single database for all of the firm's information makes it much easier for managers to monitor all of the company's products at all locations and at all times. The database collects data and feeds them into the various modular applications (or suites) of the software system. As new information is entered as a *transaction* in one application, related information is automatically updated in the other applications, including the firm's financial and accounting databases, its human resource and payroll databases, sales, supplier and customer databases, and so forth. In this way, the ERP system streamlines the data flows throughout the organization and supply chain and provides employees with direct access to a wealth of real-time operating information scattered across different functions in the organization. Figure 11.20 shows some of the typical applications with a few subprocesses nested within each one. Some of the applications are for back-office operations such as manufacturing and payroll, while others are for front-office operations such as customer service. The Manufacturing and Supply Chain Management modules in Figure 11.20 specifically deal with resource planning. In fact, for many firms, MRP II ultimately evolved into ERP.

Amazon.com is one company that uses an ERP system. The supply chain application of Amazon's system is particularly important because it allows **Amazon.com** to link customer orders to warehouse shipments and, ultimately, to supplier replenishment orders. Other applications are more important in other businesses. For example, universities put particular emphasis on the human resources and accounting and finance applications, and manufacturers have an interest in almost every application suite. Not all applications in Figure 11.20 need to be integrated into an ERP system, but those left out will not share their information with the ERP system. Sometimes, however, ERP systems are designed to interface with a firm's existing, older information systems (called "legacy systems").

Designing an ERP system requires that a company carefully analyze its major processes so that appropriate decisions about the coordination of legacy systems and new software can be made. Sometimes, a company's processes that involve redundancies and convoluted information flows must be completely reengineered before the firm can enjoy the benefits of an integrated information system. However, a recent study showed that companies reap the greatest rewards when they keep

their ERP implementations simple, work with a small number of software vendors, and use standardized systems rather than customizing them extensively. Firms can otherwise end up spending excessive amounts of money on ERP systems that are complex to use and costly to manage.

FIGURE 11.20 ▶
Examples of ERP II Modules



Most ERP systems today use a graphical user interface, although the older, keyboard-driven, text-based systems are still popular because of their dependability and technical simplicity. Users navigate through various screens and menus. Training, such as during ERP implementation, focuses on these screens and how users can utilize them to get their jobs done. The biggest suppliers of these off-the-shelf commercial ERP packages are SAP AG, followed by Oracle Corporation. Managerial Practice 11.1 illustrates the challenges and benefits associated with implementing an ERP system by SAP at the Valle del Lili Foundation Hospital in Cali, Colombia.

MANAGERIAL PRACTICE 11.1 ERP Implementation at Valle del Lili Foundation

Valle del Lili Foundation (VLF) is a private nonprofit organization founded in 1982 to deliver tertiary medical care in Cali, Colombia. The founding partners who were cardiologists identified a need for local health care providers specializing in complex and critical medical cases in Cali. Based on public funding from local civic and political leaders and donors, VLF gradually expanded its services beyond cardiology cases and also became a teaching hospital. Using the latest technology and cutting-edge health care practices, the 500-bed facility provides health care solutions in more than 60 medical specialties, including preventive checkups and cancer and cardiovascular care, for its estimated 600,000 patients every year.

At a hospital, patients usually pass through many hands during their stay, which requires close coordination between administrative and patient care personnel. This coordination is based primarily on medical records, which contain the information of every medical and clinical procedure performed and all supplies and medicines used for a given patient. The traditional paper and pencil method would sometimes lead to omitted information that may hinder the patient from getting the right supplies and even stall surgery schedules. Sometimes notes were recorded by physicians and then transcribed by an office assistant. Errors could occur from the transcription process, and documents could be lost, mislaid, or filed with the wrong patient. The results of these mistakes can be significant.

For example, in the United States alone, a study by the Institute of Medicine concluded that more people die from human error in hospitals than in car accidents.

At VLF, there were 30 or more information systems in place that were handling various tasks. Most of these systems were supporting administrative back-office processes such as accounting or billing, rather than procedures that are directly related to patient care. Since many countries were adopting electronic systems for managing hospital information to provide cost-effective and timely medical services, VLF also decided to manage medical records electronically to improve patient safety, care delivery efficiency, and labor productivity. The search for the information system solution started back in 2008, by a team made up of cardiologists, a chief medical director, a chief nursing officer, a chief administrative officer, and a head of insurance contract management. VLF hired a local SAP partner firm to implement SAP enterprise resource planning (ERP) system within a 13-month schedule.

Because the implementation would take away all paper-based processes, the hospital would face major process changes at all levels within the organization. VLF faced numerous challenges during the implementation project, not the least of which was overcoming the organizational and cultural resistance. The implementation team had to relieve the workers' anxiety about losing jobs. Workers allocated to disappearing jobs such as Dictaphone typists were reallocated to other units. The hospital also informed health insurers about the project by holding several communication meetings. The second challenge was to reach the goal of designing a unified system configuration. VLF involved key decision makers at all levels of the organization. Not only did the project include top management support, but also involved the best nurses from both clinical and administrative units. Third, VLF had to disseminate system use knowledge to the end users quickly and efficiently. VLF installed computer labs with SAP modules that were available 24/7 to facilitate familiarization with basic transactions. Also, several training sessions were conducted for each functionality.

In such a large-scale IT system implementation project, a firm can choose between a phased introduction and a simultaneous launch. The calibration and stabilization period for the simultaneous approach is shorter than the step-by-step approach, but the risks associated with inadequate end-user familiarization and learning are higher. Processes in hospitals involve the frequent transfer of personnel between departments and time is a precious resource, especially to patients. After deliberations, VLF chose to launch the system simultaneously. The hospital chose December 31, 2010, midnight to make the transition after building various contingency plans that would prevent critical patient care delays. Although the new system significantly slowed the workflow initially, learning by doing brought the workflow back up to speed and the new system was stabilized 6 months after the launch.



LUIS ROBAYO/Stringer/AFP/Getty Images

Uruguayan goalkeeper Alexis Viera of Colombia's Depor FC team is seen during an interview with AFP at his room at the Valle del Lili clinic in Cali, Colombia.

VLF saw several benefits after going online with the new ERP system. First, the nurses were able to check patient drug administration compliance easier than before. Second, lost and misfiled records fell to almost zero. Third, reduction in many administrative activities allowed the clerks to focus on more preemptive and analytical tasks. Fourth, throughput in terms of the number of bills processed per year increased significantly by 43 percent, even as the workforce increased by only 20 percent. Fifth, since the ER patient's prior interactions with the hospital were readily available, it reduced drug prescription risks. Sixth, the hospital could keep track of all patient vital signs even during surgery. Finally, data input for patients who have a long medical history was also easier. Among other factors, this ERP implementation by SAP improved the hospital's performance and financial results. Operating margin grew from 3 percent in 2010 to 9 percent in 2014. Reported revenues in 2014 grew to US$200 million. VLF became ranked as the third best hospital in Latin America and the best in Colombia, and was also recognized as one of the most important hospitals in the region based on 2015 rankings published in *América Economía* magazine.[5]

Resource Planning for Service Providers

We have seen how manufacturing companies can disaggregate an MPS of finished products, which in turn must be translated into the needs for resources, such as staff, equipment, components, and financial assets. The driver for these resource requirements is a material requirements plan. Service providers, of course, must plan their resources just as manufacturers do. However, unlike finished goods, services cannot be inventoried. They must be provided on demand. In terms of resource planning then, service organizations must focus on maintaining the *capacity* to serve their customers. In this section, we will discuss how service providers use the concept of dependent demand and a bill of resources in managing capacity.

Dependent Demand for Services

When we discussed planning and control systems for manufacturers earlier in this chapter, we introduced the concept of *dependent demand*, which is demand for an item that is a function of the production plans for some other item the company produces. For service resource planning,

[5] *Sources:* J. Cajiao and Enrique Ramirez, "Surviving SAP Implementation in a Hospital," *International Journal of Case Studies in Management,* Vol. 14, No. 2 (2016), pp.1–25; Molla S. Donaldson, Janet M. Corrigan, and Linda T. Kohn, eds., "To err is human: Building a safer health system," National Academies Press, Vol. 6 (2000), pp. 93–95; https://www.gs1co.org/Portals/0/Contenido/Caso_de_exito_Valle_de_Lili.pdf (July 18, 2020).

it is useful to define the concept of dependent demand to include demands for resources that are driven by forecasts of customer requests for services or by plans for various activities in support of the services the company provides. Here are some other examples of dependent demands for service providers.

Restaurants Every time you order from the menu at a restaurant, you initiate the restaurant's need for certain types of goods (uncooked food items, plates, and napkins), staff (chef, servers, and dishwashers), and equipment (stoves, ovens, and cooking utensils). Using a forecast of the demand for each type of meal, the manager of the restaurant can estimate the need for these resources. Many restaurants, for example, feature "specials" on certain days, say, fish on Fridays or prime rib on Saturdays. Specials improve the accuracy of the forecasts managers need to make for different types of meals (and the food products that are required to make them) and typically signal the need for above-average staffing levels. How much of these resources will be needed, however, depends on the number of meals the restaurant ultimately expects to serve. As such, these items—food products and staff members—are dependent demands.

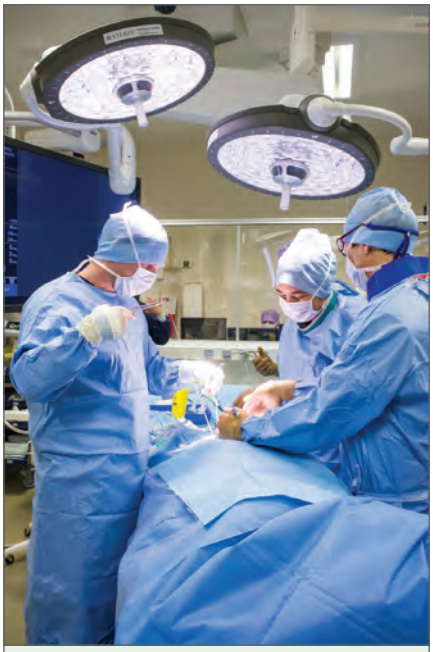
Airlines Whenever an airline schedules a flight, certain supporting goods are needed (beverages, snacks, and fuel), labor (pilots, flight attendants, and airport services), and equipment (a plane and airport gate). The number of flights and passengers the airline forecasts it will serve determines the amount of these resources needed. Just like a manufacturer, the airline can translate its master schedule of flights into resource requirements.

Hospitals With the exception of the emergency room services, hospitals can use their admission appointments to create a master schedule. The master schedule can be exploded to determine the resources the hospital will need during a certain period. For example, when you schedule a surgical procedure, you generate a need for facilitating goods such as medicines, surgical gowns, linens, staff (a surgeon, nurses, and an anesthesiologist), and equipment (an operating room, surgical tools, and a recovery bed). As they build their master schedules, hospitals must ensure that certain equipment and personnel do not become overcommitted—that capacity is maintained, in other words. For example, an appointment for a key operation might have to be scheduled in advance at a time a surgeon is available to do it, even though the hospital's other resources—operating room, nurses, and so forth—might be currently be available.

bill of resources (BOR)

A record of a service firm's parent–component relationships and all of the materials, equipment time, staff, and other resources associated with them, including usage quantities.

Hotels A traveler who makes a reservation at a hotel generates demand for facilitating goods (soap and towels), staff (front desk, housekeeping, and concierge), and equipment (fax, television, and exercise bicycle). To determine its dependent resource needs, a hotel adds the number of reservations already booked to the number of "walk-in" customers it forecasts it will have. This figure is used to create the hotel's master schedule. One resource a hotel cannot easily adjust, however, is the number of rooms it has. If the hotel is overbooked, for instance, it cannot simply add more rooms. If it has too few guests, it cannot "downsize" its number of rooms. Given the high capital costs needed for this resource, hotels try to maintain as high a utilization rate as possible by offering group rates or special promotions at certain times of the year. In other words, they try to drive up dependent demand for this particular resource.



BSIP/Universal Images Group Editorial/Getty Images

Treatment of a thoraco-abdominal aortic aneurysm by endovascular means by Professor Stephan Haulon and his teammates at the Hybrid cardiac surgery operating theatre at the Lille hospital, France.

Bill of Resources

The service analogy to the bill of materials in a manufacturing company is the **bill of resources (BOR)**, which is a record of a service firm's parent–component relationships and all of the materials, equipment time, staff, and other resources associated with them, including usage quantities. Once the service firm has completed its master schedule, the BOR can be used to determine what resources the firm will need, how much of them it will need, and when. A BOR for a service provider can be as complex as a BOM for a manufacturer.

Consider a comprehensive regional hospital that, among many other procedures, also performs aneurysm treatment at its state-of-the-art facility. As shown in Figure 11.21(a), the BOR for treatment of an aneurysm has seven levels, starting at the top (end item): (1) discharge, (2) intermediate care, (3) postoperative care (step down), (4) postoperative care (intensive), (5) surgery, (6) preoperative care (angiogram), and (7) preoperative care (testing). Each level of the BOR has a set of material and resource requirements and an associated lead time. For example, at level 6, shown in Figure 11.21(b), the patient needs 6 hours of nurses' time, 1 hour of the primary MD's time, 1 hour of the respiratory therapist's time, 24 hours of bed time, three different lab tests, one meal, and 10 different medicines from the pharmacy. The lead time for this level is 1 day. As shown in Figure 11.21, the cumulative lead time, or the patient stay time at the hospital, across all seven levels for the entire duration of the aneurysm treatment, is 10 days.

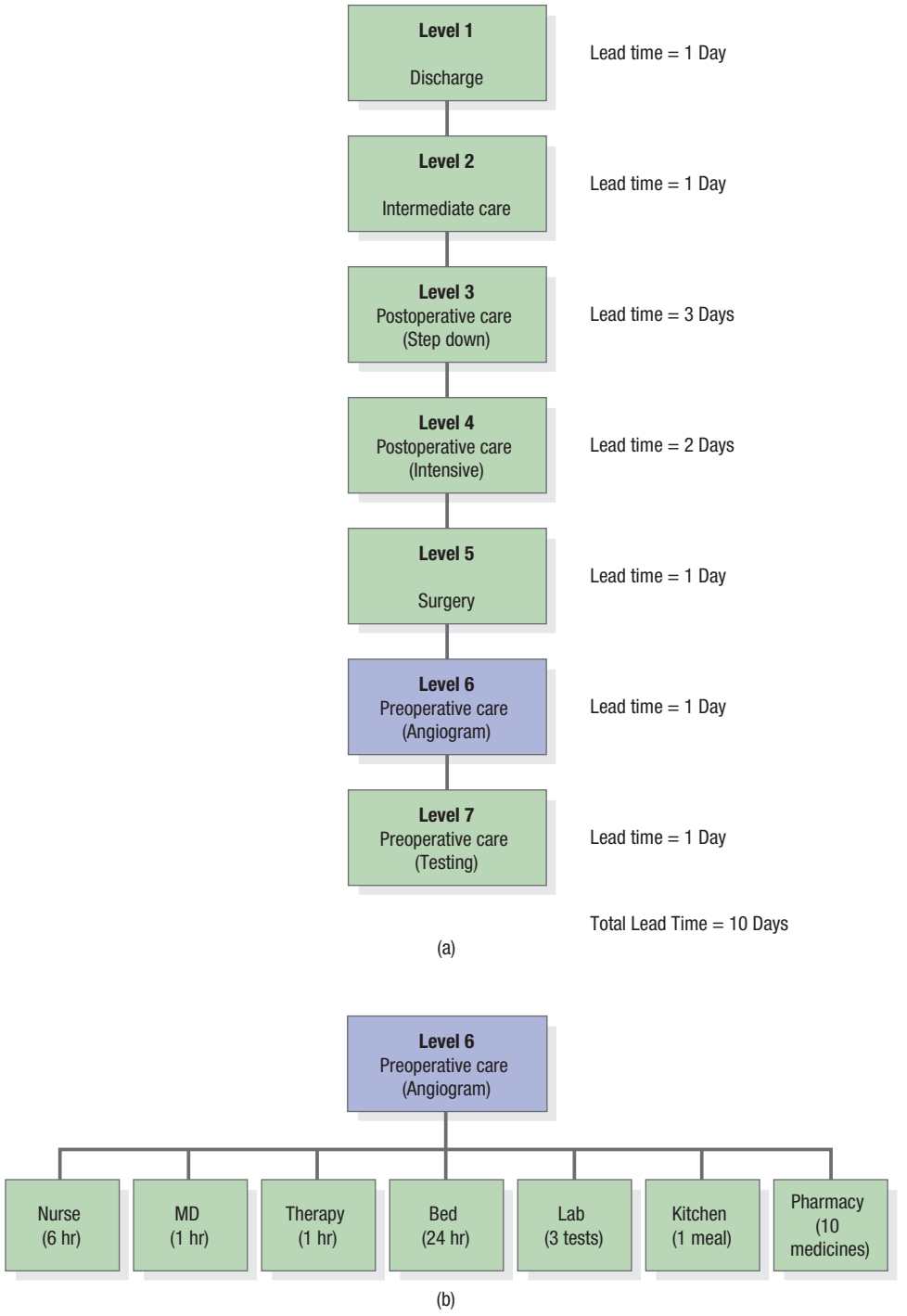


FIGURE 11.21
BOR for Treating an Aneurysm

The hospital is interested in understanding how much of each critical resource of nurses, beds, and lab tests will be needed if the projected patient departures from the aneurysm treatment process over the next 15 days are as shown in Table 11.1. The first 10 days of the projected departures represent actual patients who have started the process (booked orders), while the last 5 days represent patients who were either prescheduled ahead of time to depart after the aneurysm treatment, or patients who, based on historical records, were forecasted to depart after receiving the aneurysm treatment. In effect, Table 11.1 is an MPS for the aneurysm process based on the activity at the discharge level. In addition, resources required for treating each aneurysm patient at each level of the BOR are shown in Table 11.2.

TABLE 11.1 | PROJECTED PATIENT DEPARTURES FROM ANEURYSM TREATMENT

Day of the Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Aneurysm Patients	1	2	1	3	2	3	0	1	2	1	2	2	2	2	2

To use the information in Table 11.2 to calculate the daily resource requirements for treating aneurysm patients (similar to the gross requirements in a MRP record), we begin by calculating the number of patients that will be at each level (or stage) of treatment each day. As shown in Figure 11.22, the aneurysm patient departures become the master schedule for level 1. These departures drive the need for resources at each level of the process. Resource calculations are worked backwards from level 1, while explicitly recognizing lead times. For example, follow the patient who is scheduled to depart on day 10 **(bold)**. That patient would be on level 1 on day 10, level 2 on day 9, spend 3 days on level 3 and 2 days on level 4, spend 1 day each on levels 5 and 6, and be at level 7 on day 1. Following the same process for each patient in the master schedule enables us to determine the patients residing at each level on a given day. Consider level 4, which has a lead time of 2 days. We must accumulate the patients that are spending multiple days at this level, always remembering to offset the lead times. For example, the three patients at level 4 on day 5 represent the patient scheduled to depart on day 10 and the two patients scheduled to depart on day 11 from the hospital.

TABLE 11.2 | RESOURCE REQUIREMENTS FOR TREATING AN ANEURYSM AT EACH LEVEL OF BOR

Resources Required for Each Aneurysm Patient	Nurse Hours Required per Patient per Day	Beds Required per Patient per Day	Lab Tests Required per Patient per Day
Level 1	0	0	0
Level 2	6	0	0
Level 3	16	1	4
Level 4	12	1	6
Level 5	22	1	2
Level 6	6	1	3
Level 7	1	0	0

FIGURE 11.22 ▶
Number of Patients at Each Level of the Aneurysm Treatment

Notes: Aneurysm patient departures are actual patients for days 1–10 and forecasted departures for days 11–15. Transfers to next level or departure from hospital are at the end of the day. The rows represent numbers of patients in process for each level, accounting for Lead Times (LT) shown for each level. The top row of each level shows the number of patients who will advance to the next level at the end of the day.

Day of the Month		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Aneurysm Patient Departures		1	2	1	3	2	3	0	1	2	**1**	2	2	2	2	2
Number of Patients at Level 1 (LT = 1 Day)		1	2	1	3	2	3	0	1	2	**1**	2	2	2	2	2
Number of Patients at Level 2 (LT = 1 Day)		2	1	3	2	3	0	1	2	**1**	2	2	2	2	2	
Number of Patients at Level 3 (LT = 3 Days)	Advancing to Level 2	1	3	2	3	0	1	2	**1**	2	2	2	2	2		
	In Progress Second Day	3	2	3	0	1	2	**1**	2	2	2	2	2			
	In Progress First Day	2	3	0	1	2	**1**	2	2	2	2	2	_	_		
	Total	**6**	**8**	**5**	**4**	**3**	**4**	**5**	**5**	**6**	**6**	**6**	**4**	**2**		
Number of Patients at Level 4 (LT = 2 Days)	Advancing to Level 3	3	0	1	2	**1**	2	2	2	2	2					
	In Progress First Day	0	1	2	**1**	2	2	2	2	2	_					
	Total	**3**	**1**	**3**	**3**	**3**	**4**	**4**	**4**	**4**	**2**					
Number of Patients at Level 5 (LT = 1 Day)		1	2	**1**	2	2	2	2	2							
Number of Patients at Level 6 (LT = 1 Day)		2	**1**	2	2	2	2	2								
Number of Patients at Level 7 (LT = 1 Day)		**1**	2	2	2	2	2									

Once we know how many patients will need each level of treatment on each day, we can multiply this demand by the amount of each resource required to treat them. For example, on day 5, the projected number of lab tests required is calculated by multiplying the patients at each level on day 5 by the number of lab tests each level requires per day. Starting at level 1, which requires 0 tests and has two patients, a total of 40 tests will be required, as shown here:

$$\text{Total Number of Lab Tests Projected for Day 5} = [0(2) + 0(3) + 4(3) + 6(3) + 2(2) + 3(2) + 0(2)] = \mathbf{40}$$

Note in Figure 11.22 that due to the lead times involved, there is diminishing visibility into future resource requirements as we go down the BOR. This problem can be remedied by projecting the master schedule farther into the future.

Table 11.3 shows how much of each critical resource is required in total to treat aneurysm patients for the 15-day master schedule. While the busiest day for the nursing staff will be on day 2, the busiest day for the lab will be on day 7 when 54 tests will be requested. It is also important to note that 13 beds will serve the clinic for aneurysm patients throughout this 15-day planning horizon. Notice that for all the patients departing before day 10, nursing hours, beds, and lab tests resources that were consumed in the past (before day 1) at lower levels in the BOR (levels 5, 6, 7 for instance) are not reflected in Table 11.3. Any delays in patient treatment prior to day 1 will have been reflected in adjustments to the master schedule of departures. Consequently, what we see in Table 11.3 are the resources needed from day 1 to day 15 for the current master schedule.

TABLE 11.3 | TOTAL RESOURCE REQUIREMENTS FOR TREATING ANEURYSM PATIENTS

Day of the Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Nursing Hours Required	179	198	170	170	160	170	190	184	150	132	108	76	44	12	0
Beds Required	12	12	11	11	10	12	13	11	10	8	6	4	2	0	0
Lab Tests Required	50	45	46	44	40	50	54	48	48	36	24	16	8	0	0

Just like projecting the total resource requirements for treating aneurysms, a master schedule of patient admissions and the BORs for each illness can enable the hospital to manage its critical resources. Reports analogous to the MRP II reports we discussed earlier in the chapter can be generated for the people who manage the various functional areas of the hospital.

One resource every service provider needs, however, is cash. Service organizations have to forecast the number of customers they expect to serve so that they have enough cash on hand to purchase materials that support the services—labor and other products. Purchasing these items increases the firm's accounts payable. As services are actually completed for customers, the firm's accounts receivable increases. The firm's master schedule and its accounts receivable and payable help a company predict the amount and timing of its cash flows.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
11.1 Explain how the concept of dependent demand in material requirements planning is fundamental to resource planning.	See the subsection "Dependent Demand," which shows how continuous independent demand can lead to lumpy requirements for dependent demand. Then, a separate system, called material requirements planning (MRP), is needed to manage dependent demand situations.	
11.2 Describe the process of developing a master production schedule (MPS) and compute available-to-promise quantities.	The section "Master Production Scheduling" shows you how firms break down a production plan into more detailed schedules. Understand the key relationships between Figures 11.3, 11.4, and 11.5.	**OM Explorer Solver:** Master Production Scheduling **OM Explorer Tutor:** 11.1: Master Production Scheduling
11.3 Apply the logic of an MRP explosion to identify production and purchase orders needed for dependent demand items.	Using Figure 11.11, understand how an inventory record is created for a given lot-size rule. The subsection "Planning Factors" shows you how the choice of different managerial policies affects material plans. Finally, focus on understanding the MRP explosion process as illustrated in Figure 11.17 and Solved Problem 3.	**Active Model Exercise:** 11.1: Material Requirements Planning **OM Explorer Solver:** Material Requirements Planning Single-Item MRP **OM Explorer Tutor:** 11.2: FOQ, POQ, and L4L Rules
11.4 Explain how enterprise resource planning (ERP) systems can foster better resource planning.	Review the section "Enterprise Resource Planning." Pay attention to Figure 11.20 to understand how different application modules come together to create functionality and value in the ERP systems.	
11.5 Apply resource planning principles to the provision of services and distribution inventories.	The section "Resource Planning for Service Providers" and Solved Problem 4 illustrate how the bill of resources can be used to plan dependent demand for services in settings such as restaurants, airlines, hospitals, and hotels.	

Key Terms

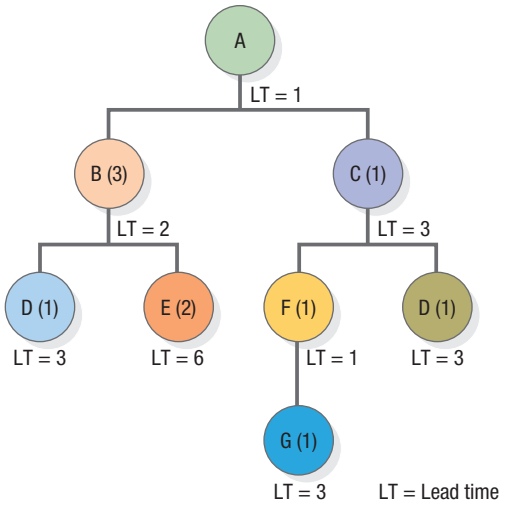
action notice 497
available-to-promise (ATP) inventory 486
bill of materials (BOM) 487
bill of resources (BOR) 502
capacity requirements planning (CRP) 497
component 482
dependent demand 481
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parent 482
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planned order release 491
planned receipts 490
projected on-hand inventory 490
purchased item 488
resource planning 481
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usage quantity 487

Solved Problem 1

Refer to the bill of materials for product A shown in Figure 11.23.

If there is no existing inventory and no scheduled receipts, how many units of items G, E, and D must be purchased to produce five units of end item A?

FIGURE 11.23 ▶
BOM for Product A



SOLUTION

Five units of item G, 30 units of item E, and 20 units of item D must be purchased to make five units of A. The usage quantities shown in Figure 11.23 indicate that two units of E are needed to make one unit of B and that three units of B are needed to make one unit of A; therefore, five units of A require 30 units of E ($2 \times 3 \times 5 = 30$). One unit of D is consumed to make one unit of B, and three units of B per unit of A result in 15 units of D ($1 \times 3 \times 5 = 15$); one unit of D in each unit of C and one unit of C per unit of A result in another five units of D ($1 \times 1 \times 5 = 5$). The total requirements to make five units of A are 20 units of D ($15 + 5$). The calculation of requirements for G is simply $1 \times 1 \times 1 \times 5 = 5$ units.

Solved Problem 2

The order policy is to produce end item A in lots of 50 units. Using the data shown in Figure 11.24 and the FOQ lot-sizing rule, complete the projected on-hand inventory and MPS quantity rows. Then, complete the MPS start row by offsetting the MPS quantities for the final assembly lead time. Compute the available-to-promise inventory for item A. Finally, assess the following customer requests for new orders. Assume that these orders arrive consecutively and their effect on ATP is cumulative. Which of these orders can be satisfied without altering the MPS start quantities?

Item: A **Order Policy:** 50 units
Lead Time: 1 week

Quantity on Hand: 5	Week 1	2	3	4	5	6	7	8	9	10
Forecast	20	10	40	10			30	20	40	20
Customer orders (booked)	30	20	5	8		2				
Projected on-hand inventory	25									
MPS quantity	50									
MPS start										
Available-to-promise (ATP) inventory										

◀ **FIGURE 11.24**
MPS Record for End Item A

a. Customer A requests 30 units in week 1.
b. Customer B requests 30 units in week 4.
c. Customer C requests 10 units in week 3.
d. Customer D requests 50 units in week 5.

SOLUTION

The projected on-hand inventory for the second week is

$$\begin{pmatrix}\text{Projected On-hand inventory at end of week 2}\end{pmatrix} = \begin{pmatrix}\text{On-hand inventory in week 1}\end{pmatrix} + \begin{pmatrix}\text{MPS quantity due in week 2}\end{pmatrix} - \begin{pmatrix}\text{Requirements in week 2}\end{pmatrix}$$

$$= 25 + 0 - 20 = 5 \text{ units}$$

where requirements are the larger of the forecast or actual customer orders booked for shipment during this period. No MPS quantity is required.

Without an MPS quantity in the third period, a shortage of item A will occur: $5 + 0 - 40 = -35$. Therefore, an MPS quantity equal to the lot size of 50 must be scheduled for completion in the third period. Then, the projected on-hand inventory for the third week will be $5 + 50 - 40 = 15$.

Figure 11.25 shows the projected on-hand inventories and MPS quantities that would result from completing the MPS calculations. The MPS start row is completed by simply shifting a copy of the MPS quantity row to the left by one column to account for the 1-week final assembly lead time. Also shown are the available-to-promise quantities. In week 1, the ATP is

$$\begin{pmatrix}\text{Available-to-Promise in week 1}\end{pmatrix} = \begin{pmatrix}\text{On-hand quantity in week 1}\end{pmatrix} + \begin{pmatrix}\text{MPS quantity in week 1}\end{pmatrix} - \begin{pmatrix}\text{Orders booked up to week 3 when the next MPS arrives}\end{pmatrix}$$

$$= 5 + 50 - (30 + 20) = 5 \text{ units}$$

The ATP for the MPS quantity in week 3 is

$$\begin{pmatrix}\text{Available-to-Promise in week 3}\end{pmatrix} = \begin{pmatrix}\text{MPS quantity in week 3}\end{pmatrix} - \begin{pmatrix}\text{Orders booked up to week 7 when the next MPS arrives}\end{pmatrix}$$

$$= 50 - (5 + 8 + 0 + 2) = 35 \text{ units}$$

Lot Size: 50 units
Lead Time: 1 week

Quantity on Hand: 5	Week 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Forecast	20	10	40	10			30	20	40	20					
Customer orders (booked)	30	20	5	8		2									
Projected on-hand inventory	25	5	15	5	5	3	23	3	13	43					
MPS quantity	50		50				50		50	50					
MPS start		50				50		50	50						
Available-to-promise (ATP) inventory	5		35				50		50	50					

FIGURE 11.25 ▲
Completed MPS Record for End Item A

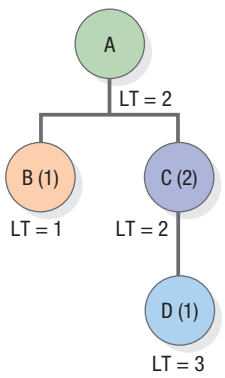
The other ATPs equal their respective MPS quantities because no orders are booked for those weeks. As for the new orders, Customer A's request for 30 units in week 1 cannot be accommodated; the earliest it can be shipped is week 3 because the ATP for week 1 is insufficient. Assuming that Customer A's order is rejected, Customer B's request may be satisfied. The ATP for week 1 will stay at five units and the ATP for week 3 will be reduced to five units. This acceptance allows the firm the flexibility to immediately satisfy an order for five units or less, if one comes in. When the MPS is updated next, the customer orders booked for week 4 will be increased to 38 to reflect the new order's shipping date. Customer C's order for 10 units in week 3 is likewise accepted. The ATP for weeks 1 and 3 will be reduced to 0, and when the MPS is updated, the customer orders booked for week 3 will be increased to 15. Finally, Customer D's order for 50 units in week 5 cannot be satisfied without changing the MPS.

Solved Problem 3

Online Resource
Active Model 11.1 provides additional insight on lot-sizing decisions for this problem.

The MPS start quantities for product A calls for the assembly department to begin final assembly according to the following schedule: 100 units in week 2; 200 units in week 4; 120 units in week 6; 180 units in week 7; and 60 units in week 8. Develop a material requirements plan for the next 8 weeks for items B, C, and D. The BOM for A is shown in Figure 11.26, and data from the inventory records are shown in Table 11.4.

▼ FIGURE 11.26
BOM for Product A



SOLUTION

We begin with items B and C and develop their inventory records, as shown in Figure 11.27. The MPS for product A must be multiplied by 2 to derive the gross requirements for item C

TABLE 11.4 | INVENTORY RECORD DATA

	ITEM		
Data Category	**B**	**C**	**D**
Lot-sizing rule	POQ (P = 3)	L4L	FOQ = 500 units
Lead time (LT)	1 week	2 weeks	3 weeks
Scheduled receipts	None	200 (week 1)	None
Beginning (on-hand) inventory	20	0	425

Item: B
Description:
Lot Size: POQ (P = 3)
Lead Time: 1 week

		Week									
		1	2	3	4	5	6	7	8	9	10
Gross requirements			100		200		120	180	60		
Scheduled receipts											
Projected on-hand inventory	20	20	200	200	0	0	240	60	0	0	0
Planned receipts			280				360				
Planned order releases		280				360					

Item: C
Description:
Lot Size: L4L
Lead Time: 2 weeks

		Week									
		1	2	3	4	5	6	7	8	9	10
Gross requirements			200		400		240	360	120		
Scheduled receipts		200									
Projected on-hand inventory	0	200	0	0	0	0	0	0	0	0	0
Planned receipts					400		240	360	120		
Planned order releases			400		240	360	120				

Item: D
Description:
Lot Size: FOQ = 500 units
Lead Time: 3 weeks

		Week									
		1	2	3	4	5	6	7	8	9	10
Gross requirements			400		240	360	120				
Scheduled receipts											
Projected on-hand inventory	425	425	25	25	285	425	305	305	305	305	305
Planned receipts					500	500					
Planned order releases		500	500								

◀ FIGURE 11.27
Inventory Records for Items B, C, and D

because of the usage quantity. Once the planned order releases for item C are found, the gross requirements for item D can be calculated.

Solved Problem 4

The Pet Training Academy offers a 5-day training program for troubled dogs. As seen in Table 11.5, the training process requires 5 days, beginning with the dog's arrival at 8 A.M. on day 1 and concluding with departure after a shampoo and trim at 5 P.M. on day 5.

TABLE 11.5 | LEAD TIME DATA FOR THE PET TRAINING ACADEMY

Pet Training Academy Process	Lead Time in Days
Level 1: Departure Day	1
Level 2: 3rd Day	1
Level 3: 2nd Day	2
Level 4: Arrival Day	1
Total	5

To adequately train a dog, the Academy requires Training Coaches, Dog Dietitians, Care Assistants, and Boarding Kennels where the dogs rest. The time required per dog by each employee and resource classification by process level is provided in Table 11.6.

TABLE 11.6 | RESOURCE REQUIREMENTS FOR TRAINING DOGS AT THE PET TRAINING ACADEMY

Pet Training Academy Process Resources Required	Training Coach (Hours per Dog)	Dog Dietitian (Hours per Dog)	Care Assistant (Hours per Dog)	Boarding Kennel (Hours per Dog)
Level 1: Departure Day	2	1	1	12
Level 2: 3rd Day	3	1	2	24
Level 3: 2nd Day	3	1	2	24
Level 4: Arrival Day	2	1	1	12

The master schedule for the trained dogs is shown in the following table, noting that departures for trained dogs are actual departures for days 1–5 and forecasted departures for days 6–12.

Day of the Month	1	2	3	4	5	6	7	8	9	10	11	12
Master Schedule of Trained Dogs	5	2	2	8	3	0	1	8	4	3	6	0

a. Use the information from the table to calculate the daily resource requirements in hours for employees in each category, and the hours of boarding room needed to train the dogs.

b. Assuming that each boarding kennel is available for 24 hours in a day, how many kennels will be required each day?

c. Assuming that each employee is able to work only 8 hours per day, how many people in each employee category will be required each day?

SOLUTION

a. Figure 11.28 shows the number of dogs at each level during their stay at the Pet Training Academy. The top row of each level shows the number of dogs who will advance to the next level at the end of the day. For example, the three dogs scheduled to depart on day 5 **(bold)** would be at level 1 on day 5, at level 2 on day 4, at level 3 on days 3 and 2, and at level 4 on day 1 right after their arrival at the Pet Training Academy.

The daily resource requirements for each resource required to train the departing dogs are shown in Table 11.7. For example, on day 2, the projected number of hours required for Care Assistant (CA) is calculated by multiplying the number of dogs at each level on day 2 by the number of CA hours each level requires per day. Starting at level 1, which requires 1 hour and has two dogs, a total of 28 hours will be required as shown here:

Total Number of CA Hours Projected for Day 2 = [1(2) + 2(2) + 2(11) + 1(0)] = **28 hours**

Day of the Month		1	2	3	4	5	6	7	8	9	10	11	12
Trained Dog Departures		5	2	2	8	**3**	0	1	8	4	3	6	0
Number of Dogs at Level 1 (LT = 1 Day)		5	2	2	8	**3**	0	1	8	4	3	6	0
Number of Dogs at Level 2 (LT = 1 Day)		2	2	8	**3**	0	1	8	4	3	6	0	
Number of Dogs at Level 3 (LT = 2 Days)	Advancing to Level 2	2	8	**3**	0	1	8	4	3	6	0		
	In Progress First Day	8	3	0	1	8	4	3	6	0	_		
	Total	**10**	**11**	**3**	**1**	**9**	**12**	**7**	**9**	**6**	**0**		
Number of Dogs at Level 4 (LT = 1 Day)		**3**	0	1	8	4	3	6	0				

FIGURE 11.28
Number of Dogs at Each Level

TABLE 11.7 | TOTAL RESOURCE REQUIREMENTS FOR TRAINING DOGS

Day of the Month	1	2	3	4	5	6	7	8	9	10	11	12
Training Coach hours required	52	43	39	44	41	45	59	55	35	24	12	0
Dog Dietitian hours required	20	15	14	20	16	16	22	21	13	9	6	0
Care Assistant hours required	32	**28**	25	24	25	29	37	34	22	15	6	0
Boarding Kennels hours required	384	336	300	288	300	348	444	408	264	180	72	0
Number of Boarding Kennels required	16	14	13	12	13	15	19	17	11	8	3	0

b. The number of boarding kennels required per day (note that all fractional kennels are rounded to the next higher integer) is obtained by dividing the total numbers of hours needed for boarding kennels by 24, and is shown in the last row in Table 11.7.

c. The number of people required per day in each employee category is obtained by dividing the resource requirements in Table 11.7 by working hours in each day (8), and is shown in Table 11.8. Note that all fractional employees are rounded to the next higher integer.

TABLE 11.8 | NUMBER OF EMPLOYEES REQUIRED PER DAY FOR TRAINING DOGS

Number of Employees Required per Day	1	2	3	4	5	6	7	8	9	10	11	12
Training Coaches	7	6	5	6	6	6	8	7	5	3	2	0
Dog Dietitians	3	2	2	3	2	2	3	3	2	2	1	0
Care Assistants	4	4	4	3	4	4	5	5	3	2	1	0

Discussion Questions

1. Form a group in which each member represents a different functional area of a firm. Provide a priority list of the information that could be generated from an MPS, from the most important to the least important, for each functional area. Rationalize the differences in the lists.
2. Consider the master flight schedule of a major airline, such as Air New Zealand. Discuss the ways in which it is analogous to an MPS for a manufacturer.
3. For an organization of your choice, such as where you previously worked, discuss how an ERP system could be used and whether it would increase effectiveness.
4. Consider a hospital that specializes in treating patients with cardiac problems. The surgery team is facing delays due to missing items before an operation. How can the principles of MRP and BOR be applied to overcome the challenges faced by the surgery team?

Problems

The OM Explorer, POM for Windows, and Active Models software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decision, the software entirely replaces the manual calculations.

Master Production Scheduling

1. Complete the MPS record in Figure 11.29 for a single item.

FIGURE 11.29 ▶
MPS Record for Single Item

Item: A
Order Policy: 60 units
Lead Time: 1 week

Quantity on Hand: 35	**Week** 1	2	3	4	5	6	7	8
Forecast	20	18	28	28	23	30	33	38
Customer orders (booked)	15	17	9	14	9		7	
Projected on-hand inventory								
MPS quantity								
MPS start								

2. Complete the MPS record shown in Figure 11.30 for a single item.

FIGURE 11.30 ▶
MPS Record for Single Item

Item: A
Order Policy: 100 units
Lead Time: 1 week

Quantity on Hand: 75	**January** 1	2	3	4	**February** 5	6	7	8
Forecast	65	65	65	45	50	50	50	50
Customer orders (booked)	40	10	85		35	70		
Projected on-hand inventory								
MPS quantity								
MPS start								

3. An end item's demand forecasts for the next 10 weeks are 30, 20, 35, 50, 25, 25, 0, 40, 0, and 50 units. The current on-hand inventory is 80 units. The order policy is to produce in lots of 100. The booked customer orders for the item, starting with week 1, are 22, 30, 15, 9, 0, 0, 5, 3, 7, and 0 units. At present, no MPS quantities are on-hand for this item. The lead time is 2 weeks. Develop an MPS for this end item.

4. Figure 11.31 shows a partially completed MPS record for ball bearings.
   - **a.** Develop the MPS for ball bearings.
   - **b.** Four customer orders arrived in the following sequence:

Order	Quantity	Week Desired
1	500	4
2	400	5
3	300	1
4	300	7

   Assume that you must commit to the orders in the sequence of arrival and cannot change the desired shipping dates or your MPS. Which orders should you accept?

5. Tabard Industries forecasted the following demand for one of its most profitable products for the next 8 weeks: 120, 120, 120, 100, 100, 100, 80, and 80 units. The booked customer orders for this product, starting in week 1, are 100, 80, 60, 40, 10, 10, 0, and 0 units. The current on-hand inventory is 150 units, the order quantity is 200 units, and the lead time is 1 week.
   - **a.** Develop an MPS for this product.
   - **b.** The marketing department revised its forecast. Starting with week 1, the new forecasts are 120, 120, 120, 150, 150, 150, 100, and 100 units. Assuming that the prospective MPS you developed in part (a) does not change, prepare a revised MPS record. Comment on the situation that Tabard now faces.
   - **c.** Returning to the original forecasted demand level and the MPS record you developed in part (a), assume that marketing accepted a new customer order for 200 units in week 2, and thereby booked orders in week 2 now total 280 units. Assuming that the prospective MPS you developed in part (a) does not change, prepare a revised MPS record. Comment on the situation that Tabard now faces.

Item: Ball bearings — **Order Policy:** 500 units — **Lead Time:** 1 week

Quantity on Hand: 400	Week 1	2	3	4	5	6	7	8	9	10
Forecast	550	300	400	450	300	350	200	300	450	400
Customer orders (booked)	300	350	250	250	200	150	100	100	100	100
Projected on-hand inventory										
MPS quantity	500									
MPS start										
Available-to-promise (ATP) inventory										

◀ **FIGURE 11.31**
MPS Record for Ball Bearings

6. Figure 11.32 shows a partially completed MPS record for 2-inch pneumatic control valves. Suppose that you receive the following orders at right for the valves (shown in the order of their arrival). As they arrive, you must decide whether to accept or reject them. Which orders would you accept for shipment?

Order	Amount (Units)	Week Requested
1	15	2
2	30	5
3	25	3
4	75	7

FIGURE 11.32 ▶
MPS Record for 2'' Pneumatic Control Valve

Item: 2" Pneumatic control valve — **Order Policy:** 75 units — **Lead Time:** 1 week

Quantity on Hand: 10	Week 1	2	3	4	5	6	7	8
Forecast	40	40	40	40	30	30	50	50
Customer orders (booked)	60	45	30	35	10	5	5	
Projected on-hand inventory								
MPS quantity	75	75						
MPS start	75							
Available-to-promise (ATP) inventory								

7. The forecasted requirements for a new variety of bread with a longer shelf-life for the next 6 weeks are 10, 35, 5, 15, 45, and 25 units. The marketing department has booked orders totaling 8, 40, 5, and 15 units for delivery in the first (current), second, third, and fourth weeks. Currently, 25 units are in stock, ready for dispatch. The production department's policy is to produce in lots of 30 units. Lead time is 1 week.

a. Develop the MPS record for the new bread variety.

b. A retailer places an order for 20 units. What is the appropriate date for the baker to fulfill the entire order?

8. A forecast of 240 units in January, 320 units in February, and 240 units in March has been approved for the seismic-sensory product family manufactured at the Rockport facility of Maryland Automated, Inc. Three products, A, B, and C, make up this family. The product mix ratio for products A, B, and C for the past 2 years has been 35 percent, 40 percent, and 25 percent, respectively. Management believes that the monthly forecast requirements are evenly spread over the 4 weeks of each month. Currently, 10 units of product C are on hand. The company produces product C in lots of 40, and the lead time is 2 weeks. A production quantity of 40 units from the previous period is scheduled to arrive in week 1. The company has accepted orders of 25, 12, 8, 10, 2, and 3 units of product C in weeks 1 through 6, respectively. Prepare a prospective MPS for product C and calculate the available-to-promise inventory quantities.

9. Joeblog imports spectrometers for forensic laboratories and educational institutions. The item's demand forecasts for the next 6 weeks are 25 units, followed by forecasts of 20 units for weeks 7 through 10. The current on-hand inventory is 50 units. The order policy is to produce in lots of 75. The booked customer orders for the item, starting with week 1, are 17, 25, 10, 11, 5, 10, and 5 units. The lead time is 3 weeks.

a. Develop an MPS for the spectrometer.

b. The marketing department has received further orders for this item in the following sequence:

Order 1 is for 35 units to be delivered in period 4.

Order 2 is for 55 units to be delivered in period 5.

Order 3 is for 65 units to be delivered in period 6.

Order 4 is for 35 units to be delivered in period 7.

Order 5 is for 20 units to be delivered in period 6.

Order 6 is for 15 units to be delivered in period 9.

Assuming that the prospective MPS you developed in part (a) does not change, which orders would you be able to accept based on the available to promise (ATP)?

10. A brick seller's demand forecasts for the next 10 weeks are 25, 25, 25, 25, 20, 30, 30, 30, 25, and 30 units. The current on-hand inventory is 110 units. The order policy is to produce in lots of 70. The booked customer orders for the item, starting with week 1, are 12, 35, 5, 7, 5, 9, 3, 12, 0, 0, and 0 units. The lead time is 2 weeks.

a. Develop an MPS for the bricks.

b. The marketing department has received five orders for this item in the following sequence:

Order 1 is for 18 units to be delivered in period 1.

Order 2 is for 70 units to be delivered in period 3.

Order 3 is for 85 units to be delivered in period 6.

Order 4 is for 70 units to be delivered in period 7.

Order 5 is for 85 units to be delivered in period 9.

Assuming that the prospective MPS you developed in part (a) does not change, which orders would you be able to accept based on the available to promise (ATP)?

MRP Explosion

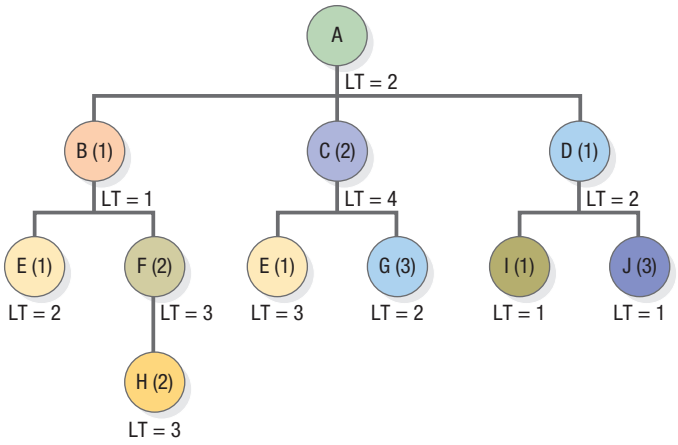
11. Olympic Enterprises plans to assemble a new breed of mountain bikes as per the bill of materials (BOM) in Figure 11.33.

a. Which component has more than one parent?

b. How many unique components does product A have at all levels?

c. How many intermediate items does product A have at all levels?

d. Given the lead times (LT) in weeks noted on Figure 11.33, how far can the business delay the purchase of component C if the outcome is beneficial for the business?

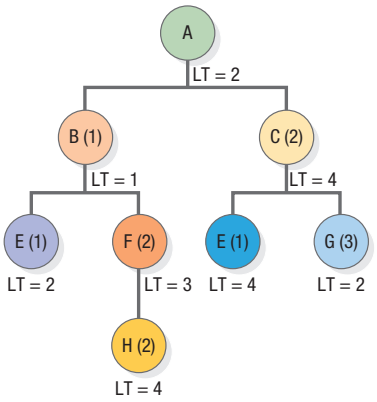


▲ **FIGURE 11.33**
BOM for Product A

12. Draw the BOM for an object that you use daily. For example, the BOM for your laptop.

13. What is the lead time (in weeks) to respond to a customer order for product A, based on the BOM shown in Figure 11.34, assuming no existing inventories or scheduled receipts?

FIGURE 11.34 ▶
BOM for Product A



14. Product A is made from components B and C. Item B, in turn, is made from D and E. Item C also is an intermediate item, made from F and H. Finally, intermediate item E is made from H and G. Note that item H has two parents. The following are item lead times:

Item	A	B	C	D	E	F	G	H
Lead Time (weeks)	1	2	2	6	5	6	4	3

a. What lead time (in weeks) is needed to respond to a customer order for product A, assuming no existing inventories or scheduled receipts?

b. What is the customer response time if all purchased items (i.e., D, F, G, and H) are in inventory?

c. If you are allowed to keep just one purchased item in stock, which one would you choose?

15. Refer to Figure 11.23 and Solved Problem 1. If inventory consists of two units of B, one unit of F, and three units of G, how many units of G, E, and D must be purchased to produce five units of product A?

16. The partially completed inventory record for the tabletop subassembly in Figure 11.35 shows gross requirements, scheduled receipts, lead time, and current on-hand inventory.

a. Complete the last three rows of the record for an FOQ of 110 units.

b. Complete the last three rows of the record by using the L4L lot-sizing rule.

c. Complete the last three rows of the record by using the POQ lot-sizing rule, with $P = 2$.

17. The partially completed inventory record for the rotor subassembly in Figure 11.36 shows gross requirements, scheduled receipts, lead time, and current on-hand inventory.

a. Complete the last three rows of the record for an FOQ of 150 units.

b. Complete the last three rows of the record by using the L4L lot-sizing rule.

c. Complete the last three rows of the record by using the POQ lot-sizing rule, with $P = 2$.

18. The partially completed inventory record for the driveshaft subassembly in Figure 11.37 shows gross requirements, scheduled receipts, lead time, and current on-hand inventory.

a. Complete the last three rows of the record for an FOQ of 50 units.

b. Complete the last three rows of the record by using the L4L lot-sizing rule.

c. Complete the last three rows of the record by using the POQ lot-sizing rule with $P = 4$.

FIGURE 11.35 ▶
Inventory Record for the Tabletop Subassembly

Item: M405—X
Description: Tabletop subassembly
Lot Size:
Lead Time: 2 weeks

		Week									
		1	2	3	4	5	6	7	8	9	10
Gross requirements		90		85		80		45	90		
Scheduled receipts		110									
Projected on-hand inventory	40										
Planned receipts											
Planned order releases											

FIGURE 11.36 ▶
Inventory Record for the Rotor Subassembly

Item: Rotor subassembly
Lot Size:
Lead Time: 2 weeks

		Week							
		1	2	3	4	5	6	7	8
Gross requirements		65	15	45	40	80	80	80	80
Scheduled receipts		150							
Projected on-hand inventory	20								
Planned receipts									
Planned order releases									

FIGURE 11.37 ▶
Inventory Record for the Driveshaft Subassembly

Item: Driveshaft subassembly
Lot Size:
Lead Time: 3 weeks

		Week							
		1	2	3	4	5	6	7	8
Gross requirements		35	25	15	20	40	40	50	50
Scheduled receipts		80							
Projected on-hand inventory	10								
Planned receipts									
Planned order releases									

19. Figure 11.38 shows a partially completed inventory record for the rear wheel subassembly. Gross requirements, scheduled receipts, lead time, and current on-hand inventory are shown.

a. Complete the last three rows of the record for an FOQ of 200 units.

b. Complete the last three rows of the record by using an FOQ of 100 units.

c. Complete the last three rows of the record by using the L4L rule.

Item: MQ–09 **Lot Size:**
Description: Rear wheel subassembly **Lead Time:** 1 week

	Week									
	1	2	3	4	5	6	7	8	9	10
Gross requirements	25	105	110	90		45	110	60		
Scheduled receipts										
Projected on-hand inventory 50										
Planned receipts										
Planned order releases										

◀ **FIGURE 11.38**
Inventory Record for the Rear Wheel Subassembly

20. A partially completed inventory record for the motor subassembly is shown in Figure 11.39.

a. Complete the last three rows of the record by using the L4L rule.

b. Complete the last three rows of the record by using the POQ rule with $P = 2$.

c. Complete the last three rows of the record by using the POQ rule with $P = 2$.

d. If it costs the company \$1 to hold a unit in inventory from one week to the next, and the cost to release an order is \$50, which of the lot-sizing rules used above will provide the lowest inventory holding + order release cost?

Item: GF–4 **Lot Size:**
Description: Motor subassembly **Lead Time:** 2 weeks

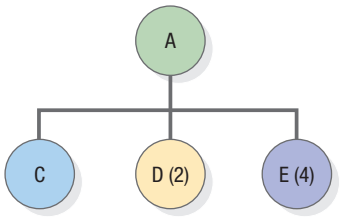
	Week									
	1	2	3	4	5	6	7	8	9	10
Gross requirements		80	50	35	20	55	15	30	25	10
Scheduled receipts	60									
Projected on-hand inventory 20										
Planned receipts										
Planned order releases										

◀ **FIGURE 11.39**
Inventory Record for the Motor Subassembly

21. The BOM for product A is shown in Figure 11.40, and data from the inventory records are shown in Table 11.9. In the MPS for product A, the MPS start row has 100 units in week 3 and 200 in week 6. Develop the material requirements plan for the next 6 weeks for items C, D, and E.

a. Develop the material requirements plan for the next 6 weeks for items C, D, and E.

b. What specific managerial actions are required in week 1?



▲ **FIGURE 11.40**
BOM for Product A

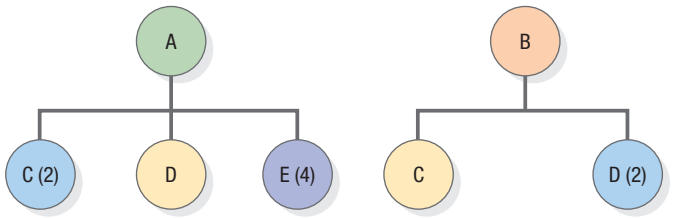
TABLE 11.9 | INVENTORY RECORD DATA

	ITEM		
Data Category	**C**	**D**	**E**
Lot-sizing rule	L4L	FOQ = 200	POQ (P = 2 weeks)
Lead time	2 weeks	1 week	1 week
Scheduled receipts	None	200 (in week 3)	200 (in week 3)
Beginning inventory	50	200	0

22. The BOMs for products A & B and data from the inventory records are shown in Figure 11.41. Data from the inventory records are shown in Table 11.10. In the MPS for product A, the MPS start row has 85 units in week 2 and 200 in week 4 and 50 in week 8. In the MPS for product B, the MPS start row has 65 units in week 3 and 50 in week 4 and 50 in week 5 and 75 in week 8.

a. Develop the material requirements plan for the next 8 weeks for items C, D, and E. Note any difficulties you observe in the inventory records.

b. Can the difficulties noted in part (a) be rectified by expediting any Scheduled Receipts?

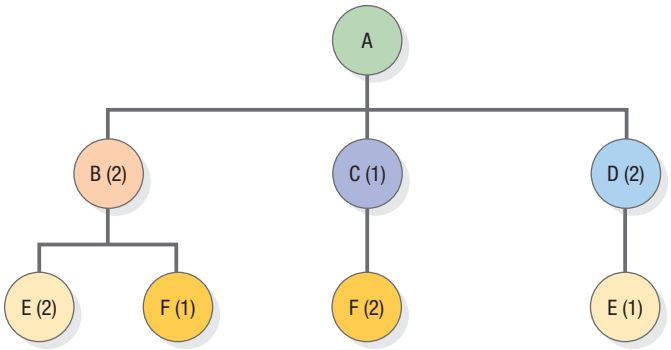


◀ **FIGURE 11.41**
BOMs for Product A and Product B

TABLE 11.10 | INVENTORY RECORD DATA

	ITEM		
Data Category	**C**	**D**	**E**
Lot-sizing rule	L4L	FOQ = 200	POQ (P = 2 weeks)
Lead time	2 weeks	1 week	1 week
Scheduled receipts	200 (in week 3)	0	0
Beginning inventory	0	0	200

23. Figure 11.42 illustrates the BOM for product A. The MPS start row in the MPS for product A calls for 50 units in week 2, 65 units in week 5, and 80 units in week 8. Item C is produced to make A and to meet the forecasted demand for replacement parts. Past replacement part demand has been 20 units per week (add 20 units to C's gross requirements). The lead times for items F and C are 1 week, and for the other items the lead time is 2 weeks. No safety stock is required for items B, C, D, E, and F. The L4L lot-sizing rule is used for items B and F; the POQ lot-sizing rule (P = 2) is used for C. Item E has an FOQ of 600 units, and D has an FOQ of 250 units. On-hand inventories are 50 units of B, 50 units of C, 120 units of D, 70 units of E, and 250 units of F. Item B has a scheduled receipt of 50 units in week 2. Develop a material requirements plan for the next 8 weeks for items B, C, D, E, and F.

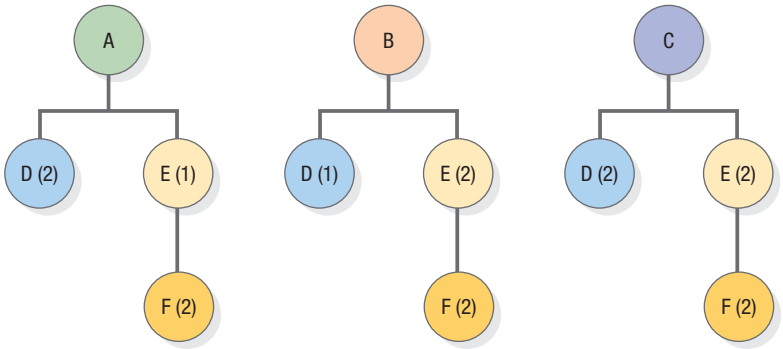


▲ **FIGURE 11.42**
BOM for Product A

24. The following information is available for three MPS items:

Product A	An 80-unit order is to be started in week 3.
	A 55-unit order is to be started in week 6.
Product B	A 125-unit order is to be started in week 5.
Product C	A 60-unit order is to be started in week 4.

Develop the material requirements plan for the next 6 weeks for items D, E, and F. The BOMs are shown in Figure 11.43, and data from the inventory records are shown in Table 11.11. (*Warning:* A safety stock requirement applies to item F. Be sure to plan a receipt for any week in which the projected on-hand inventory becomes less than the safety stock.)



◀ **FIGURE 11.43**
BOMs for Products A, B, and C

TABLE 11.11 | **INVENTORY RECORD DATA**

	ITEM		
Data Category	**D**	**E**	**F**
Lot-sizing rule	FOQ = 150	L4L	POQ (P = 2)
Lead time	3 weeks	1 week	2 weeks
Safety stock	0	0	30
Scheduled receipts	150 (week 3)	120 (week 2)	None
Beginning inventory	150	0	100

25. Figure 11.44 shows the BOMs for two products, A and B. Table 11.12 shows the MPS quantity start date for each one. Table 11.13 contains data from inventory records for items C, D, and E. There are no safety stock requirements for any of the items.

a. Determine the material requirements plan for items C, D, and E for the next 8 weeks.

b. What specific managerial actions are required in week 1?

c. Suppose that a very important customer places an emergency order for a quantity of product A. To satisfy this order, a new MPS of 200 units of product A is now required in week 5. Determine the changes to the material requirements plan if this order is accepted and note any problems that you detect.

▼ **FIGURE 11.44**
BOMs for Products A and B

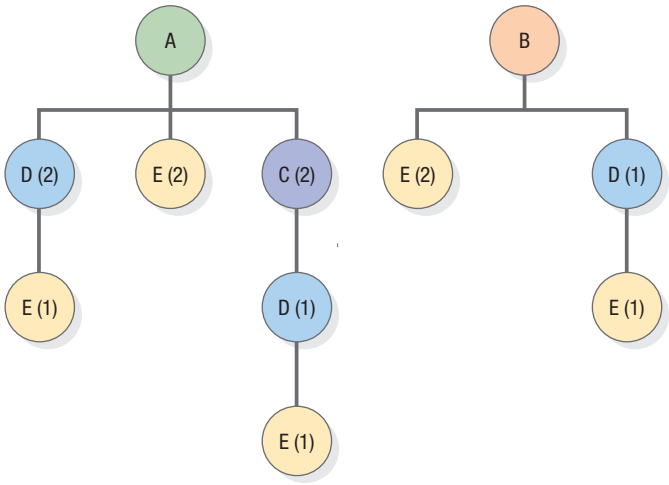


TABLE 11.12 | MPS QUANTITY START DATES

	DATE							
Product	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
A		125		95		150		130
B			80			70		

TABLE 11.13 | INVENTORY RECORD DATA

	ITEM		
Data Category	**C**	**D**	**E**
Lot-sizing rule	L4L	POQ ($P = 3$)	FOQ = 800
Lead time	3 weeks	2 weeks	1 week
Scheduled receipts	200 (week 2)	None	800 (week 1)
Beginning inventory	85	625	350

26. The BOM for product A is shown in Figure 11.45. The MPS for product A calls for 120 units to be started in weeks 2, 4, 5, and 8. Table 11.14 shows data from the inventory records.

a. Develop the material requirements plan for the next 8 weeks for each item.

b. What specific managerial actions are required in week 1? Make sure you address any specific difficulties you encounter in the inventory records.

FIGURE 11.45 ▶
BOM for Product A

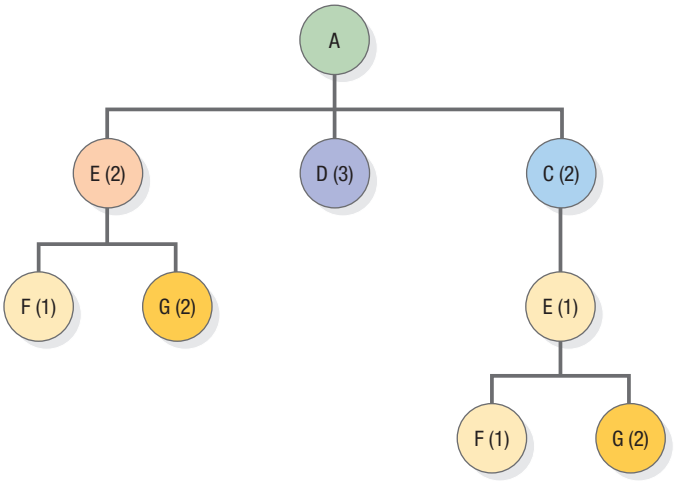


TABLE 11.14 | INVENTORY RECORD DATA

	ITEM				
Data Category	**C**	**D**	**E**	**F**	**G**
Lot-sizing rule	L4L	FOQ = 700	FOQ = 700	L4L	L4L
Lead time	3 weeks	3 weeks	4 weeks	2 weeks	1 week
Safety stock	0	0	0	50	0
Scheduled receipts	150 (week 2)	450 (week 2)	700 (week 1)	None	1,400 (week 1)
Beginning inventory	125	0	235	750	0

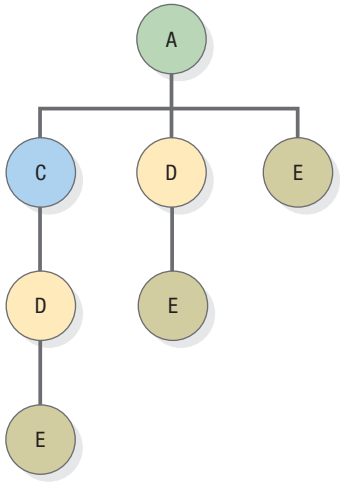
27. Refer to Solved Problem 1 (Figure 11.23) for the bill of materials and Table 11.15 for component inventory record information. Develop the material requirements plan for all components and intermediate items associated with product A for the next 10 weeks. The MPS for product A calls for 50 units to be started in weeks 2, 6, 8, and 9. (*Warning:* Safety stock requirements apply to items B and C.)

TABLE 11.15 | INVENTORY RECORD DATA

	ITEM					
Data Category	**B**	**C**	**D**	**E**	**F**	**G**
Lot-sizing rule	L4L	L4L	POQ (P = 2)	L4L	L4L	FOQ = 100
Lead time	2 weeks	3 weeks	3 weeks	6 weeks	1 week	3 weeks
Safety stock	30	10	0	0	0	0
Scheduled receipts	150 (week 2)	50 (week 2)	None	400 (week 6)	40 (week 3)	None
Beginning inventory	30	20	60	400	0	0

28. The bill of materials and the data from the inventory records for product A are shown in Figure 11.46. Assume that the MPS start quantities for A are 100 units in weeks 1, 2, 3, 4, 7, 8, 9, and 10. Derive an MRP plan for the components going into product A using the data in Table 11.16.

What specific managerial actions are required in week 1? Make sure you address any specific difficulties you encounter in the inventory records.

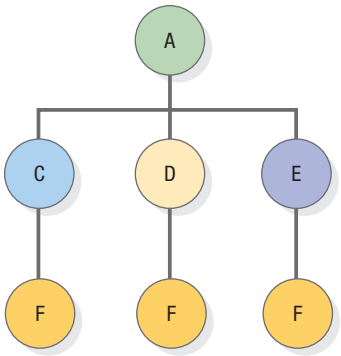


▲ **FIGURE 11.46**
BOM for Product A

TABLE 11.16 | INVENTORY RECORD DATA

	ITEM		
Data Category	**C**	**D**	**E**
Lot-sizing rule	L4L	L4L	FOQ = 300
Lead time	1 week	2 weeks	2 weeks
Scheduled receipts		100 (in week 2)	300 (in week 2)
Beginning inventory	225	350	100

29. The bill of materials and the data from the inventory records for product A are shown in Figure 11.47. Assume that the MPS start quantities for A are 50 units in weeks 1, 2, and 3, and 150 units in weeks 6 and 8. Derive an MRP plan for the components going into product A using the data in Table 11.17.



▲ **FIGURE 11.47**
BOM for Product A

TABLE 11.17 | INVENTORY RECORD DATA

	ITEM			
Data Category	**C**	**D**	**E**	**F**
Lot-sizing rule	POQ (P = 2)	L4L	FOQ = 300	FOQ = 400
Lead time	1 week	1 week	2 weeks	4 weeks
Scheduled receipts		100 (week 2)		400 (week 1)
Beginning inventory	100	0	110	40

Resource Planning for Service Providers

30. All Smiles Dental Clinic would like to develop a hygienist master schedule for the treatment of patients. Five full-time hygienists are scheduled 6 days a week, and each hygienist can treat 10 patients per day. If the number of patients expected is greater than the hygienist capacity scheduled, additional hygienists may be hired on a daily basis from a temporary worker employment agency. The agency requires a 1-day notice. Based on your knowledge of MPS, complete the following prototype schedule shown in Figure 11.48.

FIGURE 11.48 ▶
Hygienist Master Schedule

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Forecasted Patients	50	50	50	50	50	75
Booked Patients	45	60	25	25	50	40
Hygienists Scheduled						
Hygienists Required						
Hygienists Notified						

31. The McDuff Credit Union advertises its ability to quickly process personal loan applications for members. As seen in Table 11.18, the loan process requires four steps and takes approximately 8 working days to complete. To process a loan, the Credit Union requires accounting clerks, financial analysts, and a branch manager. Table 11.19 provides the time required by each employee classification by process level.

TABLE 11.18 | LEAD TIME DATA FOR MCDUFF CREDIT UNION

Personal Loan Approval Process	Lead time in Days
Level 1: Final Approval	1
Level 2: Loan Processing	3
Level 3: Pre-Approval	2
Level 4: Initial Application Screen	2
Total	8

TABLE 11.19 | RESOURCE REQUIREMENT DATA FOR MCDUFF CREDIT UNION

Personal Loan Approval Process – Resources Required	Accounting Clerk Hours per Day	Financial Analyst Hours per Day	Branch Manager Hours per Day
Level 1: Final Approval	2.00	0.00	0.00
Level 2: Loan Processing	0.50	1.50	0.00
Level 3: Pre-Approval	1.00	0.20	0.00
Level 4: Initial Application Screen	0.00	1.00	1.00

Calculate the total hours of each resource that will be required by McDuff's if the following numbers of final loan approval applications are forecasted by the Credit Union for each working day over the next 12 days.

Day of the Month	1	2	3	4	5	6	7	8	9	10	11	12
Final Loan Approval Applications	5	5	7	8	2	2	4	6	2	1	6	3

32. The comprehensive regional hospital discussed in the section "Resource Planning for Service Providers" performs bypass surgery at its state-of-the-art facility. Similar to aneurysm repair, this procedure also requires the patient to proceed through seven levels of treatment, as seen in the bill of resources in Figure 11.21(a). The amount of time it takes for a patient to move from one level of treatment to the next is shown in Table 11.20.

TABLE 11.20 | LEAD TIME DATA

BOR Level	Lead Time in Days
Level 1	1
Level 2	1
Level 3	1
Level 4	2
Level 5	1
Level 6	2
Level 7	1
Total	9

The projected number of completed bypass procedures over the next 15 days is shown in Table 11.21.

TABLE 11.21 | PROJECTED PATIENT DEPARTURES FROM THE BYPASS PROCEDURE

Day of the Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Bypass Patients	2	3	2	2	2	3	0	3	2	3	4	3	2	0	3

Consider three critical resources of nurses, beds, and lab tests that are required at each level of treatment as shown in Table 11.22.

a. Use the above information to calculate the daily resource requirements (similar to gross requirements on a material record) for each resource to treat bypass patients at this regional hospital.

b. What are the 15-day resource requirements to treat both aneurysm patients and bypass patients?

TABLE 11.22 | RESOURCE REQUIREMENT DATA

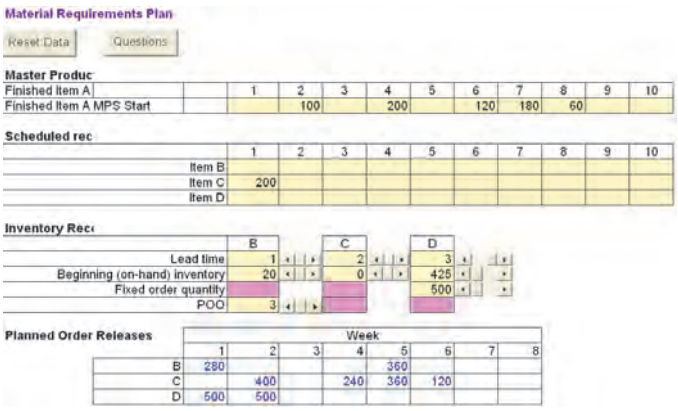
Resources Required for Bypass Patients	Nurse Hours Required per Patient per Day	Beds Required per Patient per Day	Lab Tests Required per Patient per Day
Level 1	0	0	0
Level 2	2	1	0
Level 3	8	1	2
Level 4	12	1	4
Level 5	22	1	1
Level 6	12	1	4
Level 7	1	0	0

Active Model Exercise

This Active Model is available online. It allows you to evaluate the relationship between the inventory record data and the planned order releases.

QUESTIONS

1. Suppose that the POQ for item B is changed from 3 weeks to 2 weeks. How does this change affect the order releases for items B, C, and D?
2. As the on-hand inventory for item C increases from 0 to 200, what happens to the order releases for items B, C, and D?
3. As the fixed order quantity (FOQ) for item D increases from 500 to 750, what happens to the order releases for items B, C, and D?
4. As the lead time for item C changes, what happens to the order releases for items B, C, and D?



▲ **ACTIVE MODEL**
Material Requirements Planning Using Data from Solved Problem 3 and Table 11.4

CASE Wolverine, Inc.

Wolverine, Inc. is a medium-sized firm employing 900 persons and 125 managerial and administrative personnel. The firm produces a line of automotive electrical components. It supplies about 95 auto parts stores and several car dealers in its region. Johnny Bennett, who serves as the president, founded the company by producing cable assemblies in his garage. By working hard, delivering consistent product quality, and by providing good customer service, he expanded his business to produce a variety of electrical components. Bennett's commitment to customer service is so strong that his company motto, "Love Thy Customers as Thyself," is etched on a big cast-iron plaque under his giant oil portrait in the building's front lobby.

The company's two most profitable products are the automotive front sidelamp and the headlamp. With the rising popularity of Eurosport sedans, Wolverine has enjoyed substantial demand for these two lamp items.

Last year, Kathryn Marley, the vice president of operations and supply chain management, approved the installation of a new MRP system. It is a first important step toward the eventual goal of a full-fledged ERP system. Marley worked closely with the task force that was created to bring MRP online. She frequently attended the training sessions for selected employees, emphasizing how MRP should help Wolverine secure a better competitive edge.

A year later, the MRP system is working fairly well. However, Marley believes that there is always a better way and seeks to continually improve the company's processes. To get a better sense for potential improvements, she met with the production and inventory control manager, the shop supervisor, and the purchasing manager. Here are some of their observations.

Production and Inventory Control Manager

Inventory records and BOM files are accurate and well maintained. Inventory transactions are faithfully made when inventory is replenished or removed from the stockroom so that current on-hand balances are credible. There is an MRP explosion each week, which gives the company the new MRP. It provides information that helps identify when new orders need to be launched. Information can also be searched to help identify which scheduled receipts need to be expedited and which ones can be delayed by assigning them a later due date, thereby making room for more urgent jobs.

One planner suggested that the MRP outputs should be extended to provide priority and capacity reports, with pointers as to which items need their attention. The original plan was to get the order-launching capability implemented first. However, there is no formal system of priority planning, other than the initial due date assigned to each scheduled receipt when it is released, transforming it from a planned order release into a scheduled receipt. The due dates do not get updated later even when there are unexpected scrap losses, capacity shortages, short shipments, or last-minute changes in the MPS (responding to requests from favorite customers). Jobs are scheduled on the shop floor and by suppliers according to the EDD rule, based on their due dates. If due dates assigned to scheduled receipts were updated, it might help get open orders done when they are really needed. Furthermore, planned order releases in the action bucket are translated into scheduled receipts (using inventory transactions), after checking that its components are available. The current system does not consider possible capacity problems when releasing new orders.

Shop Supervisor

His primary complaint is that the shop workloads are anything but level. One week, they hardly have any work, and the supervisor overproduces (more than called for by the scheduled receipts) just to keep everyone busy. The next week can be just the opposite—so many new orders with short fuses that almost everyone needed to work overtime or else the scheduled receipt quantities are reduced to cover immediate needs. It is feast or famine, unless they make things work on the shop floor! They do make inventory transactions to report deviations from plan for the scheduled receipts, but these "overrides" make the scheduled receipt information in the MRP records more uncertain for the planners. A particular concern is to make sure that the bottleneck workstations are kept busy.

Purchasing

Buyers are putting out too many fires, leaving little time for creative buying. In such cases, their time is spent following up on orders that are required in the very near future or that are even late. Sometimes, the MRP plan shows planned order releases for purchased items that that are needed almost immediately, not allowing for the planned lead time. In checking the MRP records, the planned lead times are realistic and what the suppliers expect. Last week, things were fine for an item, and this week a rush order needs to be placed. What is the problem?

Marley tried to assimilate all this information. She decided to collect all the required information about the sidelamps and headlamps (shown in Tables 11.23 through 11.26 and in Figure 11.49) to gain further insight into possible problems and identify areas for improvement.

TABLE 11.23 | PART NUMBERS AND DESCRIPTIONS

Part Number	Description
C206P	Screws
C310P	Back rubber gasket
HL200E	Headlamp
HL211A	Head frame subassembly
HL212P	Head lens
HL222P	Headlamp module
HL223F	Head frame
SL100E	Sidelamp
SL111P	Side lens
SL112A	Side frame subassembly
SL113P	Side lens rubber gasket
SL121F	Side frame
SL122A	Side bulb subassembly
SL123A	Flasher bulb subassembly
SL131F	Side cable grommet and receptacle
SL132P	Side bulb
SL133F	Flasher cable grommet and receptacle
SL134P	Flasher bulb

Your Assignment

Put yourself in Marley's place and prepare a report on your findings. Specifically, you are required to do a manual MRP explosion for the sidelamps and headlamps for the next 6 weeks (beginning with the current week). Assume that it is now the start of week 1. Fill in the planned order releases form provided in Table 11.27. It should show the planned order releases for all items for the next 6 weeks. Include it in your report.

Supplement your report with worksheets on the manual MRP explosion, and list the actions that planners should consider this week to (1) release new orders, (2) expedite scheduled receipts, and (3) delay a scheduled receipt's due date.

Finally, identify the good and bad points of MRP implementation at Wolverine. Conclude by making suggestions on ways to improve its resource planning process.

TABLE 11.24 | MASTER PRODUCTION SCHEDULE

Item Description and Part Number	Quantity	MPS Start Date
Headlamp (HL200E)	120	Week 4
	90	Week 5
	75	Week 6
Sidelamp (SL100E)	100	Week 3
	80	Week 5
	110	Week 6

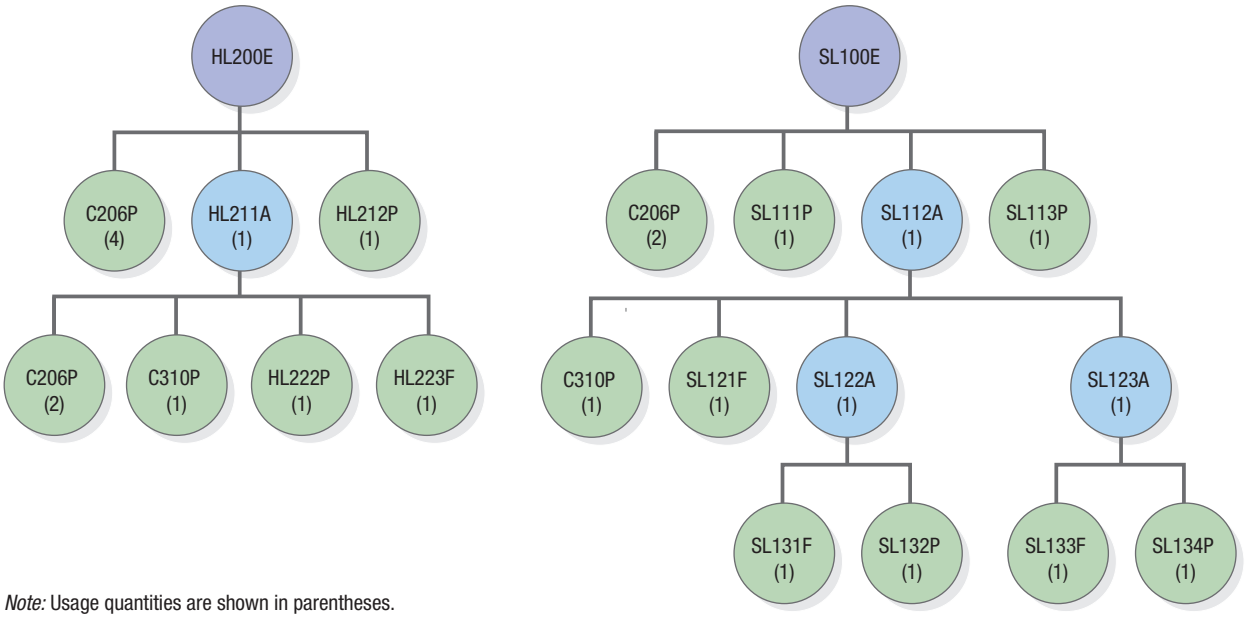
TABLE 11.25 | REPLACEMENT PART DEMAND

Item Description and Part Number	Quantity	Date
Side lens (SL111P)	40	Week 3
	35	Week 6

TABLE 11.26 | SELECTED DATA FROM INVENTORY RECORDS

Part Number	Lead Time (Weeks)	Safety Stock (Units)	Lot-Sizing Rule	On-Hand (Units)	Scheduled Receipt (Units and Due Dates)
C206P	1	30	FOQ = 2,500	270	—
C310P	1	20	FOQ = 180	40	180 (week 1)
HL211A	3	0	L4L	0	
HL212P	2	15	FOQ = 350	15	—
HL222P	3	10	POQ(P = 4 weeks)	10	285 (week 1)
HL223F	1	0	POQ(P = 4 weeks)	0	120 (week 1)
SL111P	2	0	FOQ = 350	15	—
SL112A	3	0	L4L	20	80 (week 2)
SL113P	1	20	FOQ = 100	20	—
SL121F	2	0	L4L	0	80 (week 2)
SL122A	2	0	L4L	0	80 (week 2)
SL123A	2	0	FOQ = 200	0	—
SL131F	2	0	POQ(P = 2 weeks)	0	110 (week 1)
SL132P	1	25	FOQ = 100	35	100 (week 1)
SL133F	2	0	FOQ = 250		—
SL134P	1	0	FOQ = 400	100	—

Source: This case was originally prepared by Professor Soumen Ghosh, Georgia Institute of Technology, for the purpose of classroom discussion only. Copyright © Soumen Ghosh. Used with permission.



Note: Usage quantities are shown in parentheses.

▲ **FIGURE 11.49**
BOMs for Headlamps and Sidelamps

TABLE 11.27 | PLANNED ORDER RELEASE FORM

FILL IN THE PLANNED ORDER RELEASES FOR ALL COMPONENTS.

	Week					
Item Description and Part Number	**1**	**2**	**3**	**4**	**5**	**6**
Side lens (SL111P)						
Side lens rubber gasket (SL113P)						
Side frame subassembly (SL112A)						
Side frame (SL121F)						
Side bulb subassembly (SL122A)						
Flasher bulb subassembly (SL123A)						
Side cable grommet and receptacle (SL131F)						
Flasher cable grommet and receptacle (SL133F)						
Side bulb (SL132P)						
Flasher bulb (SL134P)						
Head frame subassembly (HL211A)						
Head lens (HL212P)						
Headlamp module (HL222P)						
Head frame (HL223F)						
Back rubber gasket (C310P)						
Screws (C206P)						

VIDEO CASE Resource Planning at Cleveland Clinic

Founded in 1921 by four physicians with a mission to provide better care for the sick, investigate patient problems, and further educate those who serve, Cleveland Clinic is one of the world's most respected healthcare organizations, offering patients access to its world-renowned healthcare specialists at multiple locations globally. At Cleveland Clinic, the focus is on putting "Patients First." This means a patient experience that includes safe care, high value care, high quality care, and patient satisfaction. The effort has not gone unnoticed. For 26 consecutive years, *U.S. News and World Report* has recognized Cleveland Clinic as #1 in cardiology and heart surgery, with an additional 13 specialties ranked in the Top Ten.

According to its website, to deliver on this "patient-centric" promise requires more than world-class clinical care—it requires "care that addresses every aspect of a patient's encounter with Cleveland Clinic, including the patient's physical comfort, as well as their educational, emotional, and spiritual needs." Cleveland Clinic was the first major academic medical center to make patient experience a strategic goal, appoint a Chief Experience Officer, and establish an Office of Patient Experience.[6]

Each patient at the Clinic generates a demand for activities and supplies used in the hospital, which we term *dependent demand*. To support its patient centric approach, Cleveland Clinic's Supply Chain and Patient Support Services team has been on a journey of establishing a foundation of strategic sourcing that places emphasis on understanding this dependent demand and how to fulfill it to maximize patient outcomes. This journey is supported by an innovative program that seeks to align supply chain support across all levels of care, from pre-operative through to patient discharge.

The Cleveland Clinic performs a large number of complicated surgeries and procedures on a daily basis. Each of them has its own set of required resources that are much too voluminous to mention here, but include assorted material supplies, operating rooms, recovery rooms, nurses, doctors, and support personnel among others. The timing and quantity needed of a given resource is aggregated across each patient's specific type of surgery or procedure and their associated schedules. Cleveland Clinic thus manages dependent demand by focusing on the specific needs of each patient and then working backward through each level of care similar to the bill of resources depicted in Figure 11.21. Resource planning at Cleveland Clinic ensures that all services, supplies, and staff necessary for the proper care of a given patient at different stages of care are available at the time needed.

A simplified example of this resource planning approach can be seen in the workflow for how the nursing staff handles flushing intravenous tubing lines (IVs) with medicine to keep them from becoming blocked. The daily demand for IV usage is driven by the aggregated number of surgeries and procedures scheduled each day. Following Cleveland Clinic's Clinical Care protocols for patient care, a nurse is required to flush an IV line with the drug Heparin to prevent the tubing from being blocked. To physically complete this protocol, the nurse retrieves a pre-filled Heparin flush syringe from a supply cart, usually inside or close to the patient room. This action is performed multiple times a day for every patient on the nursing floor that has an intravenous line or port. At some point in the day, the nurses need to replenish that drawer with the pre-filled Heparin flush syringes. These supplies are stocked in a nearby supply location managed by the Supply Chain organization, which requires notification



Photo courtesy of Cleveland Clinic/Russell Lee

Eric Roselli, MD, adult cardiac surgeon, performs a procedure in Cleveland Clinic's hybrid cardiac catheterization lab. Complicated surgeries, such as the one shown here, generate required supplies, operating rooms, recovery rooms, nurses, doctors, and support personnel, all of which must be planned using resource planning information systems.

when the Heparin runs low to assure there are no stockouts at a critical time in the patient care process.

As the nursing staff remove Heparin flushes from the supply carts, the on-hand inventory is reduced or even depleted. If a floor has multiple patients on IV and port catheters, the demand for the Heparin flush will increase. If the medical floor has very few patients on IVs, the Heparin flush usage is reduced. The future estimates of patients requiring IVs is important in keeping enough Heparin in stock.

This process is repeated for hundreds of items that are required to deliver daily therapies for a patient. Each of the supplies has its own pattern of usage. The Supply Chain organization has to understand all the dependent demand patterns from the patient that drive the need for supplies at the internal supply locations and then to the external vendors and manufacturers. This "Patient-Centric Supply Chain" is responsive to the demand pull of a nurse retrieving items required to administer a prescribed therapy. The goal of "patient first" drives the physical flow of items to come through the supply chain process, starting at the receiving dock (operations) and moving through the hospital's various supply locations to the supply carts, and eventually to the nurses and patients.

Historically, point-of-care supply locations in hospitals were always managed by nurses. Surgical and procedural areas limited access to those areas and a physical "Red Line" was often painted on the floor designating it as a "Staff Only" area. Supplies used behind the Red Line were always considered too unique and complex to be managed by a logistics organization that was mostly focused on lower cost, high velocity common items such as bedpans, gloves, sponges, gauze, needles, syringes, bandages, and Heparin flushes. The Supply Chain organization would previously service the needs of Surgical and Procedural areas by processing the departmental supply requests and delivering requested items to drop off locations, largely staying outside of the patient care work streams behind the red lines. But all that changed with the

[6]https://my.clevelandclinic.org/departments/patient-experience/depts/office-patient-experience/about

Patient-Centric Supply Chain. Now, the supply chain organization is able to cross the Red Line to replenish needed items as they are pulled by the clinical staff so there is never a risk of outage on the carts.

QUESTIONS

1. Explain how the concepts of dependent demand and bills of resources are being used at the Cleveland Clinic. Using Heparin IV flushes as an example, how do these concepts support Cleveland Clinic's "Patient First" focus?
2. Why is Cleveland Clinic's Patient-Centric Supply Chain so vital to the organization's strategic vision and future plans?
3. What might be risked if the supply chain organization is not fully aligned with the entire spectrum of managing dependent demand for a patient from pre-operative care to discharge?

12

SUPPLY CHAIN DESIGN

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

12.1 Explain the competitive pressures to consider when creating an effective supply chain.

12.2 Calculate the critical supply chain performance measures.

12.3 Describe the strategic options for supply chain design and how autonomous supply chains can play a role.

12.4 Explain the strategy of mass customization and its implications for supply chain design.

12.5 Understand the considerations firms make when deciding which processes to outsource.

Amazon.com



dpa picture alliance/Alamy Stock Photo

State-of-the-art robot arms lift containers with products in an Amazon distribution center in Dortmund, Germany. In Europe's first distribution center with conveyor technology, products are received and distributed to other Amazon distribution centers in Europe.

Amazon.com is a $281 billion company specializing in the online retail business. Worldwide, it has 1,248 facilities in its distribution infrastructure and 840,000 employees to deliver enormous volumes of packages of diverse products to an international clientele. On one of its busiest days in 2019, Prime Day, customers ordered more than $7 billion in products. And, on an average day, Amazon sells 4000 items per minute. Seasonality in demand patterns, customers demanding variety in product selection, and many brick-and-mortar stores offering stiff competition: If there is ever a situation in which supply chain design is important, this is it.

Competing against the likes of Walmart, Target, and Best Buy is a challenging task. All have retail stores as well as an online presence. At brick-and-mortar retail stores customers can see the products they are interested in and experience instant gratification in obtaining the item the second it is bought. Also, Best Buy and Walmart, for example, use their store locations as distribution hubs for online orders, cutting their delivery times to 2 days or less, which is quicker than having them shipped from warehouses located across the country.

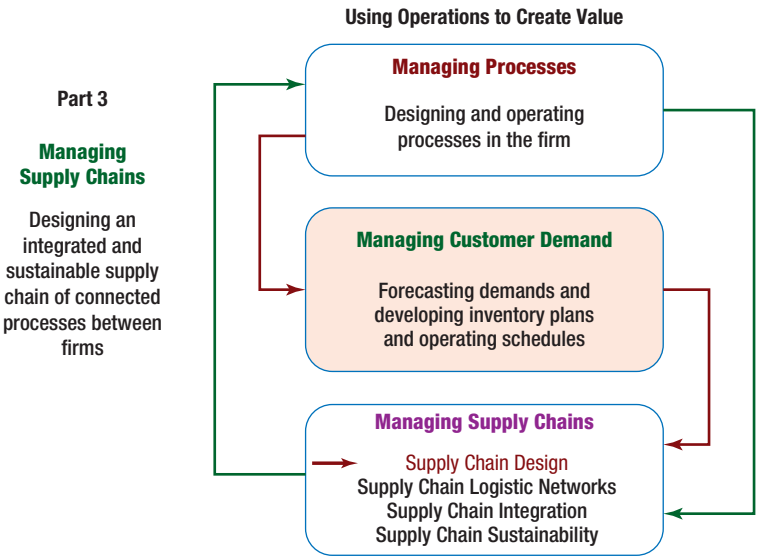
How can Amazon compete? There are four key competitive priorities for its supply chain: delivery speed, variety, customization, and low-cost operations. Amazon has achieved delivery speed by strategically locating its distribution facilities and adding more capacity, using more than 200,000 robots to help get packages out the door faster, increasing the items held in stock to support delivery speed while not overinvesting in slow-moving items, and working with manufacturers and distributors to ship products directly to customers for those items not in stock, a practice known as *drop shipping*. To further reduce the time between a customer's order and delivery of the products, Amazon has initiated a program to use the U.S. Postal Service to make Sunday home deliveries.

As for variety, customers shopping on Amazon.com have access to literally hundreds of millions of products. For example, Amazon Marketplace, the online shopping network where other retailers can sell their products on the Amazon site, gives the shopper access to over 350 million products. In addition, 12 million items are stocked in Amazon's warehouses, all of which put a high priority on coordination with manufacturers and distributors. Customization is the ability to provide the specific, unique order each customer wants. The distribution process is initiated by a customer ordering from the Amazon.com website or an affiliate website. The system determines which distribution center to ship the item from or whether to use a drop shipper, who uses Amazon packaging and delivers the item directly to the customer. The decision is determined by product availability and transportation costs. Several items for an order may come from different sources, in which case they are amalgamated at transportation hubs before final delivery. Amazon is practicing *mass customization* and is using an *assemble-to-order* supply chain design. Finally, price is a major order winner for Amazon. Low prices are supported by low-cost operations in the supply chain. High volumes put a downward pressure on per-unit prices from manufacturers and distributors. Further, Amazon's revenues do not have to support operations at retail outlets, thereby saving the overhead associated with them. The high cost of transportation and shipping has forced Amazon to carefully design their supply chains with logistics in mind, such as the use of its own fleet in some of its major markets.

Supporting the four competitive priorities requires Amazon to design a supply chain that is agile and able to produce unique customer orders on a timely basis.[1]

[1] *Sources:* David Edwards, "Amazon Now Has 200,000 Robots Working in Its Warehouses," *Robotics and Automation News* (January 21, 2020); Jay Greene, "Amazon.com Cuts Deal with USPS," Associated Press, *Naples Daily News* (Tuesday, November 12, 2013), pp. 5A–5B; Mark Solomon, "Amazon Plans Revamp of U.S. Shipping with Mix of Private Fleet, Regional Carriers, and USPS," *DC Velocity* (March 6, 2014), pp. 1–3; "How Many Products Does Amazon Carry?" *Retail TouchPoint*, (May, 2016); Amazon.com 2019 Annual Report, www.annualreports.com (2020); MWPVL International, www.mwpvl.com/html/amazon_com.html (2020); https://www.statista.com/statistics/266282/annual-net-revenue-of-amazoncom/.

Thus far in this text we have discussed how successful firms design and operate their internal processes and manage the demands for their products and services. The missing link is the critical aspect of getting the needed supplies of materials and services that an individual firm cannot produce itself. In Part 3 we address the design and integration of sustainable supply chains of connected processes between firms. A *supply chain* is the interrelated series of processes within a firm and across different firms that produces a service or product to the satisfaction of customers. More specifically, it is a network of service, material, monetary, and information flows that link a firm's customer relationship, order fulfillment, and supplier relationship processes to those of its suppliers and customers. Amazon.com is an excellent example of how a supply chain can be successfully tailored to customer needs in a highly competitive market. It is important to note, however, that a firm such as Amazon may have multiple supply chains, depending on the mix of products it buys and sells. A supplier in one supply chain may not be a supplier in another supply chain because the product may be different or the supplier may simply be unable to negotiate a successful contract.



Creating an Effective Supply Chain

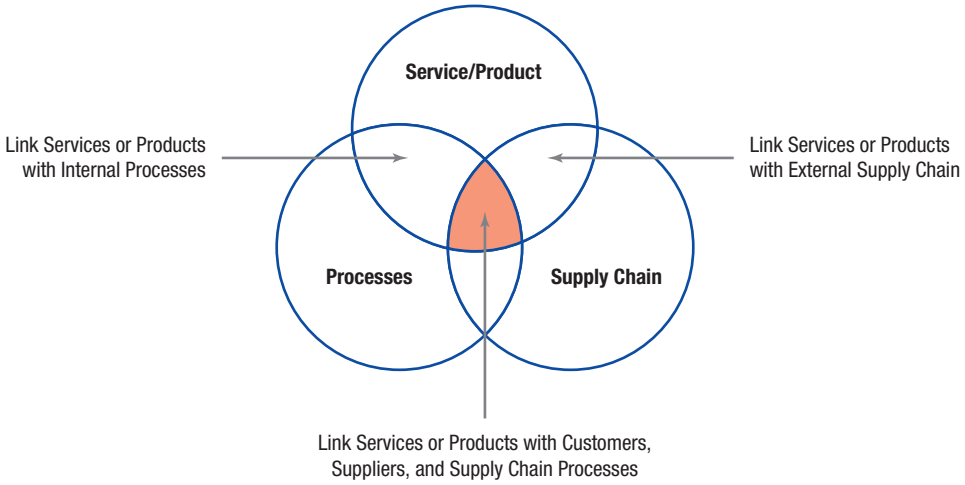
Creating an effective supply chain involves the recognition of external competitive pressures as well as internal organizational pressures from groups such as sales, marketing, and product development. These pressures are (1) dynamic sales volumes, (2) customer service and quality expectations, (3) service/product proliferation, and (4) emerging markets.

Dynamic Sales Volumes One of the costliest operating aspects of supply chains is trying to meet the needs of volatile sales volumes. Often this involves excessive inventories, underutilized personnel, or more expensive delivery options to meet customer demands on time. While sometimes these volatile demands are caused by external sources such as the customers themselves, they are often caused internally by end-of-month sales promotions. Supply chain design should involve close collaboration between top-level managers across the organization so that unnecessary costly supply chain options are avoided. We will discuss the implications of supply chain dynamics in more depth in Chapter 14, "Supply Chain Integration."

Customer Service and Quality Expectations We have discussed customer service levels as they relate to an organization's internal inventories in Chapter 9, "Inventory Management." Here we focus on the organizational pressures emanating from the sales and marketing groups for superior service levels for the organization's customers. Questions such as "What service level should be guaranteed?" or "How speedy must our deliveries be?" need collaborative discussion from the sales, marketing, and finance groups. Customers are also demanding stricter conformance to service or product specifications and higher levels of quality. "What levels of quality are achievable and at what cost?" The answers to these questions impinge on the design of the supply chain, particularly its points of supply and the choice of suppliers.

Service/Product Proliferation The sales and marketing groups provide the momentum to create new services or products because they are closely in touch with customers and their needs. The survival of any organization depends on the development of new markets. However, adding more services or products often adds complexity to the supply chain. It is not an unusual circumstance to find that a relatively large proportion of SKUs contribute only a small percentage of the revenues. Generally, these niche services or products have low volumes and therefore cost more to produce, market, and deliver. A thoughtful balance needs to be struck between the cost of operating the supply chain and the need to market new services and products.

Emerging Markets The increasing importance of emerging markets and the roles they play in the global market emphasizes the pressure on critical resources such as iron ore, agricultural commodities, and labor. For example, differing growth rates or internal strife across various emerging markets means that rising labor costs can quickly change the attractiveness of manufacturing facilities. Emerging markets also represent pools of new customers who demand products with lower price points. Such was the case with Gillette, which produced a low-cost razor as an entry to the Indian market. The health of the global economy often determines the need to examine the design of an organization's supply chains.



▲ **FIGURE 12.1**
Creating an Effective Supply Chain

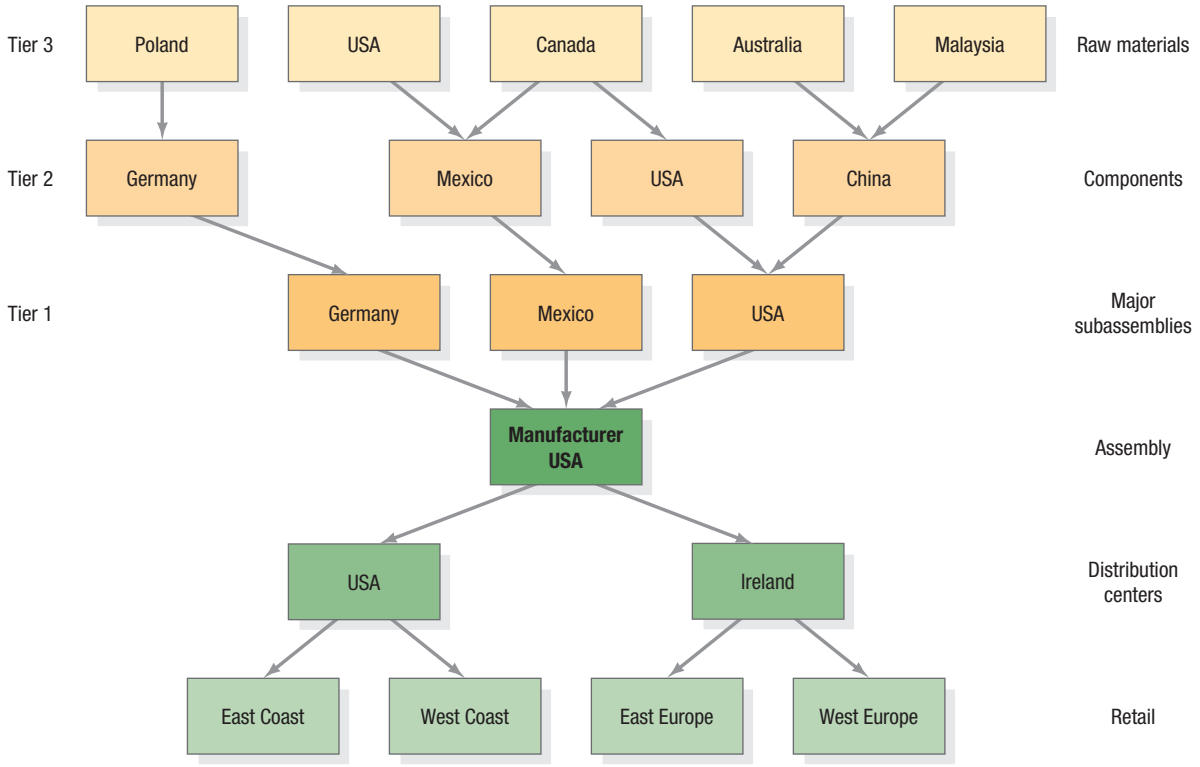
The design of an effective supply chain must be a collaborative effort from the CEO down if it is to meet the four pressures. All functional areas have a stake in an organization's supply chains. The firm's operations strategy and competitive priorities guide its supply chain choices. Figure 12.1 shows the three major areas of focus in creating an effective supply chain.

1. **Link Services or Products with Internal Processes.** Parts 1 and 2 of this text have shown how firms coordinate internal process decisions with the competitive priorities of the services or products covered in the operations strategy.
2. **Link Services or Products with the External Supply Chain.** The competitive priorities assigned to the firm's services or products must be reflected in the design of the network of suppliers.
3. **Link Services or Products with Customers, Suppliers, and Supply Chain Processes.** The firm's processes that enable it to develop what customers want, interact with suppliers, deliver services or products, interact with customers, address environmental and ethical issues, and provide the information and planning tools needed to execute the operations strategy are the glue that binds the effective supply chain.

supply chain design
Designing a firm's supply chain to meet the competitive priorities of the firm's operations strategy.

Supply chain management, the synchronization of a firm's processes with those of its suppliers and customers to match the flow of materials, services, and information with demand, is a critical skill in most organizations. A key part of supply chain management is **supply chain design**, which seeks to design a firm's supply chain to meet the competitive priorities of the firm's operations strategy. Supply chains, however, can be very complicated, as Figure 12.2 illustrates. The supply chain depicted is an oversimplification because many companies have hundreds, if not thousands, of suppliers. In this example, the firm is a manufacturer in the United States and deals with an

▼ **FIGURE 12.2**
Supply Chain for a Manufacturing Firm



international supply chain. Suppliers are often identified by their position in the supply chain. Here, tier 1 suppliers provide major subassemblies that are assembled by the manufacturing firm, tier 2 suppliers provide tier 1 suppliers with components, and so on. Not all companies have the same number of levels in their supply chains. For example, companies that engineer products to customer specifications normally do not have distribution centers as part of their supply chains. Such companies often ship products directly to their customers.

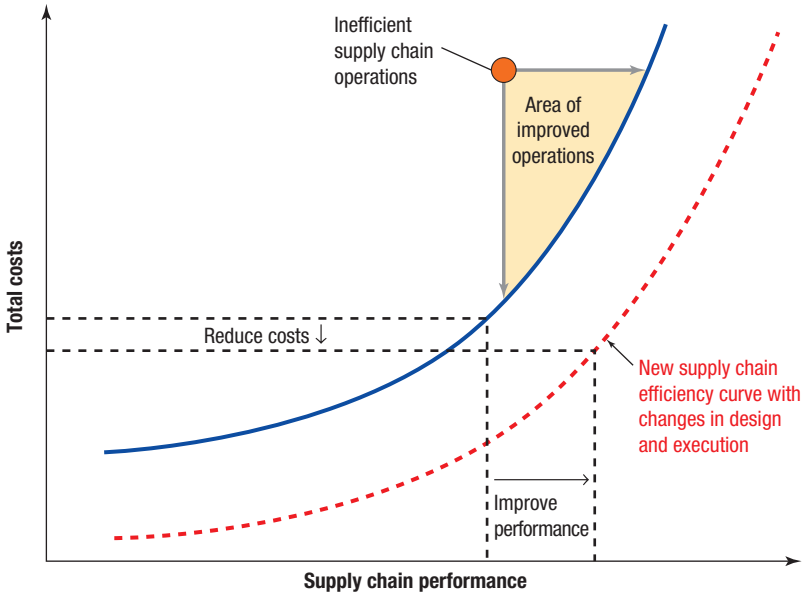
To get a better understanding of the importance of supply chain design, consider Figure 12.3, which conceptually shows the challenges facing supply chain managers. The solid line in the graph is an *efficiency curve*, which shows the trade-off between costs and performance for the current supply chain design if the supply chain is operated as efficiently as it can be. Now, suppose that your firm plots its actual costs and performance, as indicated by the solid circle labeled "Inefficient supply chain operations." It is far off of the efficiency curve, which is not an uncommon occurrence. Perhaps the performance is due to the four pressures mentioned above, which have been left unchecked for a period of time. The challenge is to move operations into the tinted area, as close to the solid line as possible, which can be accomplished by better forecasting, inventory management, operations planning and scheduling, and resource planning, all of which we have already discussed in previous chapters. However, quantum steps in improvement can be obtained by improving the design of the supply chain in accordance with a sound operations strategy and employing the latest in new technology, which moves the curve as shown by the dashed line. The goal is to reduce costs as well as increase performance.

What options are available to design a supply chain that best meets an organization's needs? Supply chain design options can be placed into four categories:

1. Strategic options, which include linking supply chain designs to competitive priorities, mass customization, outsourcing decisions, and incorporating new digital technologies. These topics are discussed in this chapter.
2. Logistical network options, which include facility locations, inventory placement, and the level of automation in the network of material flows. See Chapter 13, "Supply Chain Logistic Networks," for details.
3. Integration options, which include designs to mitigate supply chain dynamics and risk, supply chain collaboration to link major processes, and supplier selection. Chapter 14, "Supply Chain Integration," discusses this important set of issues.
4. Sustainability options, which include designs for environmental concerns and disaster relief. See Chapter 15, "Supply Chain Sustainability," for insights into the considerations managers must make in this important area.

Fixing an inefficient supply chain involves a number of major decisions that affect all functional areas of a firm, as demonstrated in the following Managerial Challenge.

▼ **FIGURE 12.3**
Supply Chain Efficiency Curve



MANAGERIAL CHALLENGE Operations

Timing is everything in the fashion industry. Adorn, a manufacturer of a leading fashion brand in women's clothing, is facing intense competition—it is losing the race to market. A recent study of the competitive landscape concluded that Adorn's competitors are getting new products from design to market in 6 to 8 weeks, and some have the capability to rush seasonal products to market in 3 weeks to stay within the season. The finance department complained that revenues are down, putting a strain on working capital. The marketing department is tired of hearing from buyers for the retail outlets who are upset with tardy performance.

Wendy Chen, supply chain manager, has been hired to get Adorn back on track. She is responsible for the entire process that begins with procuring the raw material, such as yarn and fabric, and ends with the finished product available for sale in a retail outlet. Throughout the process, she oversees production planning; sourcing of supplies, raw materials, and factories; and logistics. Complicating her job is the fact that the fashion world is very demanding. For example, sales can be extremely dynamic, related not only

to the seasons of the year but also to the timing of fashion shows in Paris, which drive world demand for the latest in European fashion. Customers (buyers for the major retail outlets) demand top quality and speedy development of new clothing and accessories.

Wendy knew from prior experience that the design of the supply chain is the foundation of successful performance. Does the current supply chain support competitive priorities such as top quality, development speed, and volume flexibility? Are the production processes aligned with the degree of responsiveness needed in the supply chain? What performance measures are currently being used and are they adequate for identifying trouble spots? Of major importance is the sourcing strategy, given the need for speed and flexibility. Should she recommend sourcing overseas, to take advantage of labor rates, or locally, to take advantage of logistics? Should she recommend becoming more vertically integrated? The remainder of this chapter has important insights into these questions.

Before we get into the discussion of strategic issues and the digital technologies that can move firms toward the dashed line in Figure 12.3, we first discuss the major inventory and financial measures firms use to monitor the performance of their supply chains.

Measuring Supply Chain Performance

Regardless of the firm, whether services or manufacturing, management needs measures to assess the performance of its supply chains. Before discussing the major supply chain design decisions, we define the typical inventory measures and financial measures used to monitor supply chain performance and evaluate alternative supply chain designs.

Inventory Measures

All methods of measuring inventory begin with a physical count of units, volume, or weight. However, measures of inventories are reported in three basic ways: (1) average aggregate inventory value, (2) weeks of supply, and (3) inventory turnover.

average aggregate inventory value

The total average value of all items held in inventory for a firm.

weeks of supply

An inventory measure obtained by dividing the average aggregate inventory value by sales per week at cost.

The **average aggregate inventory value** is the total average value of all items held in inventory by a firm. We express the dollar values in this inventory measure at cost because we can then sum the values of individual items in raw materials, work-in-process, and finished goods. Final sales dollars have meaning only for final services or products and cannot be used for all inventory items. It is an average because it usually represents the inventory investment over some period of time. Suppose a retailer holds items A and B in stock. One unit of item A may be worth only a few dollars, whereas one unit of item B may be valued in the hundreds of dollars because of the labor, technology, and other value-added operations performed in manufacturing the product. This measure for an inventory consisting of only items A and B is

$$\text{Average aggregate inventory value} = \begin{pmatrix}\text{Number of units of item A}\\ \text{typically on hand}\end{pmatrix}\begin{pmatrix}\text{Value of each}\\ \text{unit of item A}\end{pmatrix} + \begin{pmatrix}\text{Number of units of item B}\\ \text{typically on hand}\end{pmatrix}\begin{pmatrix}\text{Value of each}\\ \text{unit of item B}\end{pmatrix}$$



Alistair Berg/Getty Images

Just looking at the size of an inventory does not reveal if it is a problem or an important element of a firm's strategy. Measures such as weeks of inventory or inventory turnover, relative to the industry, are needed. Here a distribution center is storing boxes of clothing, which have an industry average of about five turns per year.

Summed over all items in an inventory, this total value tells managers how much of a firm's assets are tied up in inventory. Manufacturing firms typically have about 25 percent of their total assets in inventory, whereas wholesalers and retailers average about 75 percent.

To some extent, managers can decide whether the aggregate inventory value is too low or too high by historical or industry comparisons or by managerial judgment. However, a better performance measure would take demand into account because it would show how long the inventory resides in the firm. **Weeks of supply** is an inventory measure obtained by dividing the average aggregate inventory value by sales per week at cost. (In some low-inventory operations, days or even hours are a better unit of time for measuring inventory.) The formula (expressed in weeks) is

$$\text{Weeks of supply} = \frac{\text{Average aggregate inventory value}}{\text{Weekly sales (at cost)}}$$

Although the numerator includes the value of all items a firm holds in inventory (raw materials, WIP, and finished

goods), the denominator represents only the finished goods sold—at cost rather than the sale price after markups or discounts. This cost is referred to as the *cost of goods sold*.

Inventory turnover (or *turns*) is an inventory measure obtained by dividing annual sales at cost by the average aggregate inventory value maintained during the year, or

inventory turnover
An inventory measure obtained by dividing annual sales at cost by the average aggregate inventory value maintained during the year.

$$\text{Inventory turnover} = \frac{\text{Annual sales (at cost)}}{\text{Average aggregate inventory value}}$$

The "best" inventory level, even when expressed as turnover, cannot be determined easily. A good starting point is to benchmark the leading firms in an industry.

Example 12.1 shows how to calculate the two most commonly used inventory measures.

EXAMPLE 12.1 Calculating Inventory Measures

The Eagle Machine Company averaged $2 million in inventory last year, and the cost of goods sold was $10 million. Figure 12.4 shows the breakout of raw materials, work-in-process, and finished goods inventories. The best inventory turnover in the company's industry is six turns per year. If the company has 52 business weeks per year, how many weeks of supply were held in inventory? What was the inventory turnover? What should the company do?

Online Resource
Tutor 12.1 in OM Explorer provides a new example to practice the calculation of inventory measures.

SOLUTION

The average aggregate inventory value of $2 million translates into 10.4 weeks of supply and five turns per year, calculated as follows:

$$\text{Weeks of supply} = \frac{\$2 \text{ million}}{(\$10 \text{ million})/(52 \text{ weeks})} = 10.4 \text{ weeks}$$

$$\text{Inventory turns} = \frac{\$10 \text{ million}}{\$2 \text{ million}} = 5 \text{ turns/year}$$

DECISION POINT

The analysis indicates that management must improve the inventory turns by 20 percent. Management should improve its order fulfillment process to reduce finished goods inventory. Supply chain operations can also be improved to reduce the need to have so much raw materials and work-in-process inventory

Cost of Goods Sold	$10,000,000
Weeks of Operation	52

	Item Number	Average Level	Unit Value	Total Value
Raw Materials	1	1,400	$50.00	$70,000
	2	1,000	$32.00	$32,000
	3	400	$60.00	$24,000
	4	2,400	$10.00	$24,000
	5	800	$15.00	$12,000
Work in Process	6	320	$700.00	$224,000
	7	160	$900.00	$144,000
	8	280	$750.00	$210,000
	9	240	$800.00	$192,000
	10	400	$1,000.00	$400,000
Finished Goods	11	60	$2,000.00	$120,000
	12	40	$3,500.00	$140,000
	13	50	$2,800.00	$140,000
	14	20	$5,000.00	$100,000
	15	40	$4,200.00	$168,000
Total				$2,000,000

Average Weekly Sales at Cost	$192,308
Weeks of Supply	10.4
Inventory Turnover	5.0

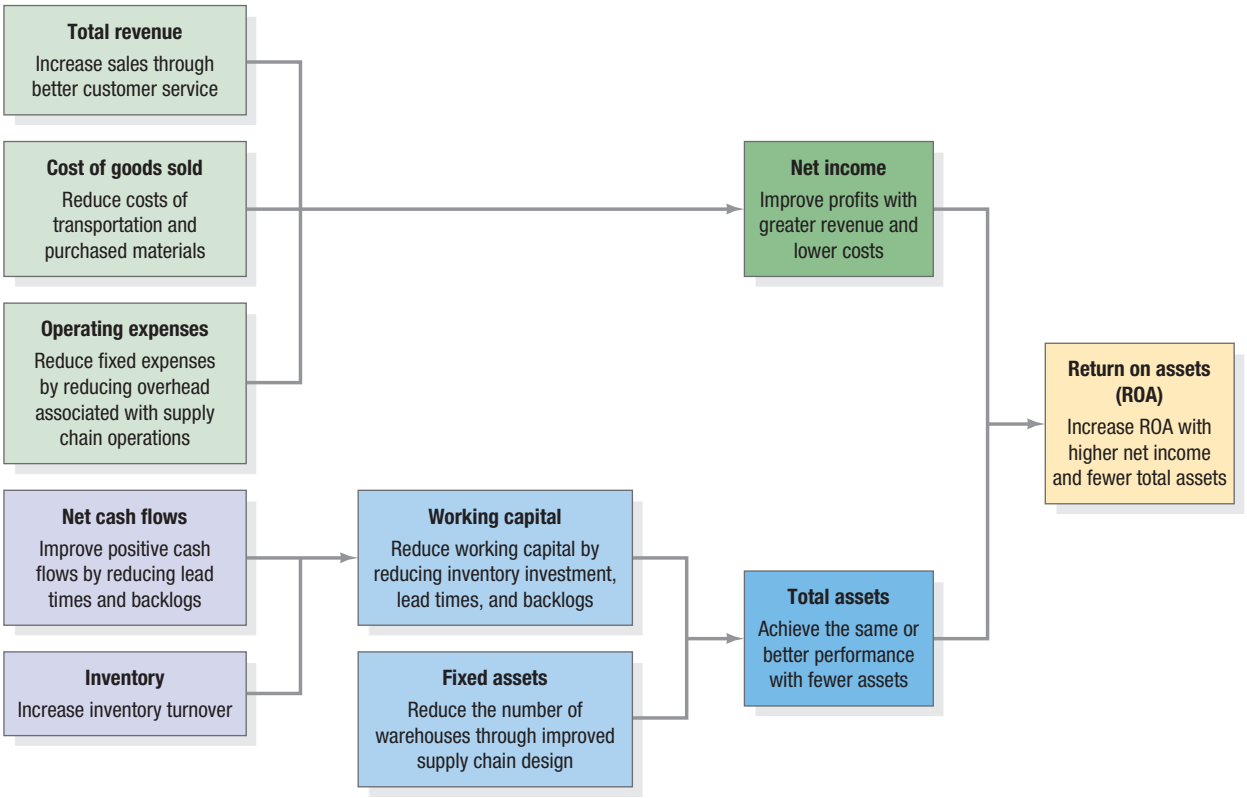
◀ **FIGURE 12.4**
Calculating Inventory Measures Using *Inventory Estimator* Solver

stock. It will take an inventory reduction of about 16 percent to achieve the target of six turns per year. However, inventories would not have to be reduced as much if sales increased. If the sales department targets an increase in sales of 8 percent ($10.8 million), inventories need only be reduced by 10 percent ($1.8 million) to get six turns a year. Management can now do sensitivity analyses to see what effect reductions in the inventory of specific items or increases in the annual sales have on weeks of supply or inventory turns.

Financial Measures

How the supply chain is designed and managed has a huge financial impact on the firm. Inventory is an investment because it is needed for future use. However, inventory ties up funds that might be used more profitably in other operations. Figure 12.5 shows how supply chain decisions can affect financial measures.

▼ **FIGURE 12.5**
How Supply Chain Decisions Can Affect ROA



Total Revenue Supply chain performance measures related to time, which is a critical dimension of supply chain operations, have financial implications. Many service providers and manufacturers measure the percent of on-time deliveries of their services or products to their customers, as well as services and materials from their suppliers. Increasing the percent of on-time deliveries to customers, for example, will increase *total revenue* because satisfied customers will buy more services and products from the firm.

Cost of Goods Sold Being able to buy materials or services at a better price and transform them more efficiently into services or products will improve a firm's *cost of goods sold* measure and ultimately its *net income*. These improvements will also have an effect on *contribution margin*, which is the difference between price and the variable costs to produce a service or good. Reducing production, material, transportation, and poor-quality costs increases the contribution margin, allowing for greater profits. Contribution margins are often used as inputs to decisions regarding the portfolio of services or products the firm offers.

Operating Expenses Selling expenses, fixed expenses, and depreciation are considered operating expenses. Designing a supply chain with minimal capital investment can reduce depreciation charges. Changes to the supply chain infrastructure can have an effect on overhead, which is considered a fixed expense.

Cash Flow The supply chain design can improve positive net cash flows by focusing on reducing lead times and backlogs of orders. The Internet brings another financial measure related to cash flows to the forefront: *Cash-to-cash* is the time lag between paying for the services and materials needed to produce a service or product and receiving payment for it. The shorter the time lag, the better the *cash flow* position of the firm because it needs less working capital. The firm can then use the freed-up funds for other projects or investments. Redesigning the order placement process, so that payment for the service or product by the customer is made at the time the order is placed, can reduce the time lag. By contrast, billing the customer after the service is performed or the order is shipped increases the need for working capital. The goal is to have a negative cash-to-cash situation, which is possible when the customer pays for the service or product before the firm has to pay for the resources and materials needed to produce it. In such a case, the firm must have supplier inventories on consignment, which allows it to pay for materials as it uses them.

Working Capital Weeks of inventory and inventory turns are reflected in another financial measure, *working capital*, which is money used to finance ongoing operations. Decreasing weeks of supply or increasing inventory turns reduces the working capital needed to finance inventories. Reductions in working capital can be accomplished by improving the customer relationship, order fulfillment, or supplier relationship processes. For example, reducing supplier lead times has the effect of reducing weeks of supply and increasing inventory turns. Matching the input and output flows of materials is easier because shorter range, more reliable forecasts of demand can be used.

Return on Assets Designing and managing the supply chain so as to reduce the aggregate inventory investment or fixed investments such as warehouses will reduce the *total assets* portion of the firm's balance sheet. An important financial measure is *return on assets* (*ROA*), which is net income divided by total assets. Consequently, reducing aggregate inventory investment and fixed investments, or increasing net income by better cost management, will increase ROA.

We now turn to a discussion of several strategic options for supply chain design and their implications for a firm's performance.

Strategic Options for Supply Chain Design

A supply chain is, of course, a network of firms. Thus, each firm in the chain should design its own supply chains to support the competitive priorities of its services or products. Even though extensive technologies such as the Internet, machine learning, computer-assisted design, flexible manufacturing, and automated warehousing have been applied to all stages of the supply chain, the performance of many supply chains remains dismal. One possible cause for failures is that managers do not understand the nature of the demand for their services or products and, therefore, cannot design supply chains to satisfy those demands. Two distinct designs used to competitive advantage are *efficient supply chains* and *responsive supply chains*. Table 12.1 shows the environments that best suit each design.

TABLE 12.1 | ENVIRONMENTS BEST SUITED FOR EFFICIENT AND RESPONSIVE SUPPLY CHAINS

Factor	Efficient Supply Chains	Responsive Supply Chains
Demand	Predictable, low forecast errors	Unpredictable, high forecast errors
Competitive priorities	Low cost, consistent quality, on-time delivery	Development speed, fast delivery times, customization, volume flexibility, variety, top quality
New-service/product introduction	Infrequent	Frequent
Contribution margins	Low	High
Product variety	Low	High

Efficient Supply Chains

The nature of demand for the firm's services or products is a key factor in the best choice of supply chain strategy. Efficient supply chains work best in environments where demand is highly predictable, such as demand for staple items purchased at grocery stores or demand for a package delivery service.



domonabikeSingapore/Alamy Stock Photo

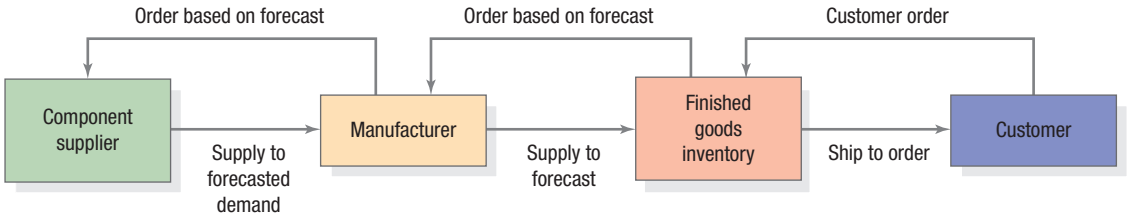
Efficient supply chains need to keep logistical costs to a minimum. Here ships wait in queue in the harbor to load shipping containers at Singapore's Keppel Port, one of the world's most efficient, and busiest, sea ports.

Common Designs There is one popular design for efficient supply chains.

- *Make-to-stock* (MTS): The product is built to a sales forecast and sold to the customer from a finished goods stock. The end customer has no individual inputs into the configuration of the product and typically purchases the product from a retailer. Examples include groceries, books, appliances, and housewares. Figure 12.6 shows that these designs rely heavily on forecasts to move materials down the chain to the customer.

The focus of the MTS supply chain is on efficient service, material, monetary, and information flows; and keeping inventories to a minimum. Because of the markets the firms serve, service or product designs last a long time, new introductions are infrequent, and variety is small. Such firms typically produce for markets in which price is crucial to winning an order. Contribution margins are low and efficiency is important. Consequently, efficient supply chains have competitive priorities of low-cost operations, consistent quality, and on-time delivery.

FIGURE 12.6 ▶
Supply Chain Design for Make-to-Stock Strategy



Responsive Supply Chains

Responsive supply chains are designed to react quickly to hedge against uncertainties in demand. They work best when firms offer a great variety of services or products and demand predictability is low.

Common Designs There are three popular designs for responsive supply chains.

- *Assemble-to-order* (ATO): The product is built to customer specifications from a stock of existing components. Customers can choose among various standard components in arriving at their own products; however, they have no control over the design of the components. Assembly is delayed until the order is received. Examples include Dell's approach to customizing desktops and laptops and automobile manufacturers who offer a selection of options with each model. Figure 12.7 shows how an ATO supply chain is designed. Notice that much of the material flows are on an "as needed" basis, as opposed to the MTS design. We will return to this design when we address mass customization as a strategy.

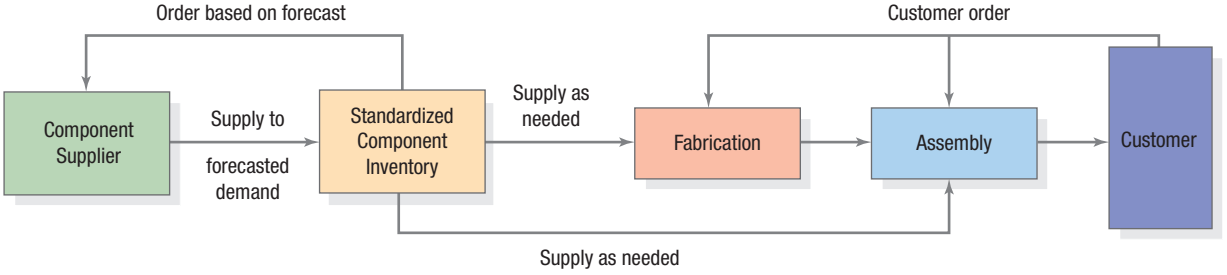


FIGURE 12.7 ▲
Supply Chain Design for Assemble-to-Order Strategy

- *Make-to-order* (MTO): The product is based on a standard design; however, component production and manufacture of the final product is linked to the customer's specifications. Examples include custom-made clothing, such as that offered by Land's End and Tommy Hilfiger, predesigned houses, and commercial aircraft, as in the case of the Boeing 787 Dreamliner.

- *Design-to-order* (DTO): The product is designed and built entirely to the customer's specifications. This supply chain allows customers to design the product to fit their specific needs. Examples include large construction projects, women's designer dresses, custom-made men's suits, and original architecture house construction.

To stay competitive, firms in a responsive supply chain frequently introduce new services or products. Nonetheless, because of the innovativeness of their services or products, they enjoy high contribution margins. Typical competitive priorities for responsive supply chains are development speed, fast delivery times, customization, variety, volume flexibility, and top quality. The firms may not even know what services or products they need to provide until customers place orders. In addition, demand may be short lived, as in the case of fashion goods. The focus of responsive supply chains is reaction time, which helps avoid keeping costly inventories that ultimately must be sold at deep discounts.



Feature China/Barcroft Media/Getty Images

The Intercontinental Wonderland Hotel, shown in the construction phase, is on the east side of an 89-meter deep former quarry pit in Shanghai, China. The hotel, which opened in November, 2019, has 2 floors above ground, 14 floors under ground level, and two floors under water in a 33-foot-deep aquarium. The hotel is an example of a design-to-order product requiring a responsive supply chain.

A firm may need to utilize both types of supply chains, especially when it focuses its operations on specific market segments or it can segment the supply chain to achieve two different requirements. For example, the supply chain for a standard product, such as an oil tanker, has different requirements than that for a customized product, such as a luxury liner, even though both are ocean-going vessels and both may be manufactured by the same company. You might also see elements of efficiency and responsiveness in the same supply chain. For example, Gillette uses an efficient supply chain to manufacture its products so that it can utilize a capital-intensive manufacturing process, and then it uses a responsive supply chain for the packaging and delivery processes to be responsive to retailers. The packaging operation involves customization in the form of printing in different languages. Just as processes can be broken into parts, with different process structures for each, supply chain processes can be segmented to achieve optimal performance.

Designs for Efficient and Responsive Supply Chains

Table 12.2 contains the basic design features for efficient and responsive supply chains. The more downstream (closer to the final customer) in an efficient supply chain that a firm is, the more likely it is to have a line-flow strategy that supports high volumes of standardized services or products. Consequently, suppliers in efficient supply chains should have low capacity cushions because high utilization keeps the cost per unit low. High inventory turns are desired because inventory investment must be kept low to achieve low costs. Firms should work with their suppliers to shorten lead times, but care must be taken to use tactics that do not appreciably increase costs. For example, lead times for a supplier could be shortened by switching from rail to air transportation; however, the added cost may offset the savings or competitive advantages obtained from the shorter lead times. Suppliers should be selected with emphasis on low prices, consistent quality, and on-time delivery. Because of low capacity cushions, disruptions in an efficient supply chain can be costly and must be avoided. Figure 12.8 shows that firms with large batch, line, or continuous flow processes are more likely to be part of an efficient supply chain.

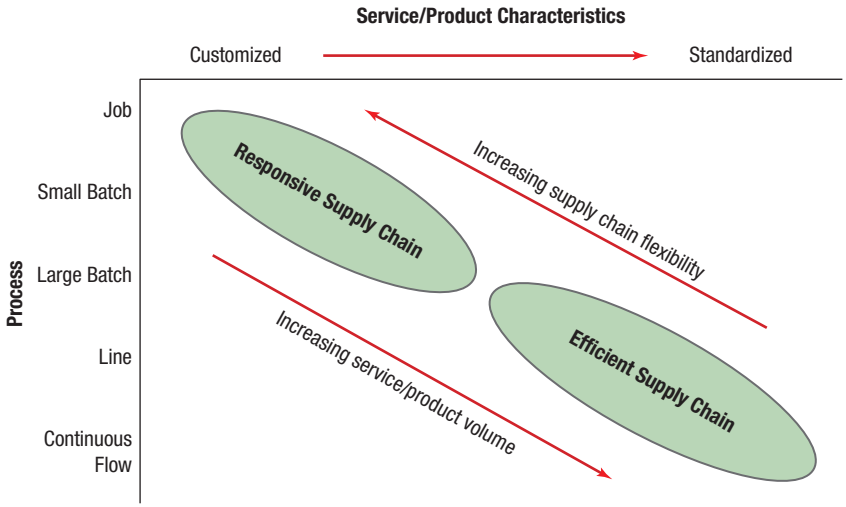
By contrast, firms in a responsive supply chain should be flexible and have high capacity cushions. WIP inventories should be positioned in the chain to support delivery speed, but

TABLE 12.2 | DESIGN FEATURES FOR EFFICIENT AND RESPONSIVE SUPPLY CHAINS

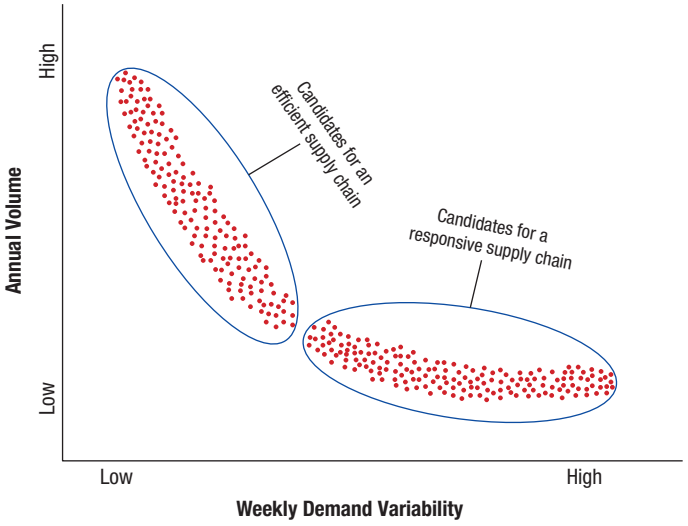
Factor	Efficient Supply Chains	Responsive Supply Chains
Operation strategy	Make-to-stock standardized services or products; emphasize high volumes	Assemble-to-order, make-to-order, or design-to-order customized services or products; emphasize variety
Capacity cushion	Low	High
Inventory investment	Low; enable high inventory turns	As needed to enable fast delivery time
Lead time	Shorten, but do not increase costs	Shorten aggressively
Supplier selection	Emphasize low prices, consistent quality, on-time delivery	Emphasize fast delivery time, customization, variety, volume flexibility, top quality

inventories of expensive finished goods should be avoided. Firms should aggressively work with their suppliers to shorten lead times because it allows them to wait longer before committing to a customer order—in other words, it gives them greater flexibility. Firms should select suppliers to support the competitive priorities of the services or products provided, which in this case would include the ability to provide quick deliveries, customize services or components, adjust volumes quickly to match demand cycles, offer variety, and provide top quality. Figure 12.8 shows that firms with job or small batch processes are more likely to be a part of a responsive supply chain.

FIGURE 12.8 ▶
Linking Supply Chain Design to Processes and Service/Product Characteristics



Poor supply chain performance often is the result of using the wrong supply chain design for the services or products provided. A common mistake is to use an efficient supply chain in an environment that calls for a responsive supply chain. Over time, a firm may add options to its basic service or product, or introduce variations, so that the variety of its offerings increases dramatically and demand for any given service or product predictability drops. Yet the firm continues to measure the performance of its supply chain as it always has, emphasizing efficiency, even when contribution margins would allow a responsive supply chain design. Consider Figure 12.9, which shows a generalized relationship between the annual volumes of a firm's stock-keeping units (SKUs) and their weekly demand variability. For this firm, some SKUs have high volume and low variability while some SKUs have low volume and high variability. To the extent that the volatility in demands is outside the control of the firm, hanging on to the firm's legacy supply chain may be too costly because of supply chain dynamics. Mapping the portfolio of products along the dimensions of annual volume and weekly demand variability may reveal better configurations of the supply chain. A firm may therefore have two distinctly different supply chain designs serving two different product groups. For example, SKUs with lower volumes and higher weekly variability may be best served with a responsive supply chain design, such as ATO or MTO. Doing so reduces the need for finished goods inventories in which customer demands are very unpredictable. Alternatively, serving the high volume, low weekly demand variability SKUs with an efficient supply chain design such as build-to-stock would be better. Forecasts are more accurate, and using a finished goods inventory is an effective strategy. Redesigning a supply chain is a costly endeavor and should only be contemplated when the dynamics cannot be sufficiently reduced by other means.



▲ FIGURE 12.9
Annual Volume Versus Variability in Weekly Demands for a Firm's SKUs

Autonomous Supply Chains

We have discussed the basic tenets of designing an effective supply chain from a strategic perspective: measuring performance to assess the supply chain's current state and selecting the appropriate competitive design to improve performance. In reference to Figure 12.3, the goal in

designing supply chains is to put the correct infrastructure in place to move the firm closer to the dashed **red** line. However, a mistake many managers make is to change operations without including complementary changes to technology. In contrast, forward-looking firms are evolving toward *autonomous supply chains*, a *digital transformation* whereby the latest in digital technology is used to facilitate and automate decision making up and down the supply chain and thereby transform the way supply chains operate. Technologies such as advanced analytics, artificial intelligence (AI) and machine learning, robotics, and the Internet of Things (IoT) can be used to collect and transmit data automatically to assist decision-making activities or even automate them entirely.

What motivates firms to aspire to achieve an autonomous supply chain? As organizations grow, traditional supply chains also grow and become more complex, increasing the difficulty of coordinating with external entities. Technology systems tend to be designed for small organizational units, repeated across the organization, giving birth to redundant and complex processes and legacy systems. This leads to considerable difficulty in getting the right data in a timely fashion. Further, challenges arise when making informed decisions because combining various streams of data from different sources may be required. Manual intervention is required for exceptions, and data are often stored in templates that are not standard in format. All of this incompatibility degrades performance.

What is an autonomous supply chain? For example, an autonomous supply chain has the capability to identify the need for a component at an assembly plant, order it from the supplier who produces it, pick it from the supplier's warehouse, and have it delivered to the assembly plant without human intervention. Of course, life is more complicated than this, with thousands of requests to multiple locations taking place all the time. The achievement of a totally autonomous supply chain is a journey that can be traveled one step at a time. For example, short-term time-series demand forecasts for base stock-keeping units (SKUs) can be done completely automatically and used for inventory decisions. Independent demand inventory systems, which decide when to order an item and in what quantity, can be automated. The order-to-ship process (from order receipt through transportation to the outbound shipping hub or customer) can also be automated. The ultimate step toward an autonomous supply chain is automated execution, whereby a computer-generated plan can be passed along to the next level without reviews from managers. Today, in most cases, once a plan is generated by the planning tool, planners are responsible for approving, rejecting, or adjusting it based on experiential knowledge. Automatic execution, which makes use of artificial intelligence tools, intends to not only mimic the planner's behavior but also improve on it.

Supply chain planning is often a highly manual process. However, many of the tasks can be automated. A digital transformation of the supply chain can increase the speed and quality of supply chain decisions, thereby reducing costs and taking pressure off the decision-making team. We will have more examples of digital transformations in the chapters to come.[2]

Mass Customization

A firm's supply chain must be capable of addressing certain competitive priorities that will win orders from customers. Often customers want more than a wide selection of standard services or products; they want a personalized service or product and they want it fast. For example, suppose you want to paint your living room a new color. You need to complement all of the existing furnishings, wall decorations, and carpet. You go to your local retail paint store and select a color from a stack of books that spans every color of the rainbow. The store can give you all the paint you need in your selected color while you wait. How can the store provide that service economically? Certainly, the store cannot stock thousands of colors in sufficient quantities for any job. The store stocks the base colors and pigments separately and mixes them as needed, thereby supplying an unlimited variety of colors without maintaining the inventory required to match each customer's particular color needs. The paint retailer is practicing a strategy known as *mass customization*, whereby a firm's highly divergent processes generate a wide variety of customized services or products at reasonably low costs. Essentially, the firm allows customers to select from a variety of standard options to create the service or product of their choice.

[2]See the following references for additional information: Shreyas Shukla, Guarav Goel, and Ajai Vasudevan, "Building a Digital Supply Chain the Right Way," *SCM Now Magazine*, Association for Supply Chain Management (2018); Ignacio Felix, Christoph Kuntz, Ildefonzo Silva, and Eduardo Tobias Benoliel, " The Route to No-Touch Planning: Taking the Human Error Out of Supply Chain Planning," McKinsey & Company, Operations (August, 2018); Enis Gezgin, Xin Huang, Prakash Samal, and Ildefonzo Silva, "Digital Transformation: Raising Supply-Chain Performance to New Levels," McKinsey & Company, Operations (November, 2017).

Competitive Advantages

A mass customization strategy has three important competitive advantages.

- *Managing Customer Relationships.* Mass customization requires detailed inputs from customers so that the ideal service or product can be produced. The firm can learn a lot about its customers from the data it receives. Once customers are in the database, the firm can keep track of them over time. A significant competitive advantage is realized through these close customer relationships based on a strategy of mass customization.
- *Eliminating Finished Goods Inventory.* Producing to a customer's order is more efficient than producing to a forecast because forecasts are not perfect. The trick is to have everything you need to produce the order quickly. A technology some firms use for their order placement process is a software system called a *configurator*, which gives firms and customers easy access to data relevant to the options available for the service or product. Dell uses a configurator that allows customers to design their own computer from a set of standard components that are in stock. Once the order is placed, the product is assembled and then delivered. Using sales promotions, the firm can exercise some control over the requirements for the inventory of components by steering customers away from options that are out of stock in favor of options that are in stock. This capability takes pressure off the supply chain while keeping the customer satisfied.

  Service providers also take advantage of mass customization to reduce the level of inventory. British Airways is trying to personalize the service of customers once they are on board. It has a software system that tracks the preferences of its most favored customers down to the magazines they read. This information allows the airline to more accurately plan what to pack on each flight. This information saves the airline a significant amount of money because it does not pack amenities passengers do not want.
- *Increasing Perceived Value of Services or Products.* With mass customization, customers can have it their way. In general, mass customization often has a higher value in the mind of the customer than it actually costs to produce. This perception allows firms to charge prices that provide a nice margin.

Supply Chain Design for Mass Customization

How does mass customization affect the design of supply chains? We address three major considerations.

Assemble-to-Order Strategy The underlying process design is an assemble-to-order strategy. This strategy involves two stages in the provision of the service or product. Initially, standardized components are produced or purchased and held in stock. This stage is important because it enables the firm to produce or purchase these standard items in large volumes to keep the costs low. In the second stage, the firm assembles these standard components to a specific customer order. In mass customization, this stage must be flexible to handle a large number of potential combinations and be capable of producing the order quickly and accurately. For example, Custom Doll Baby, Inc., has 500 vinyl doll kits sculpted by world-renowned doll artists. Customers submit a photograph of their baby, an artist selects a doll kit, and then hand-paints the baby's complexion and features to match the photograph. As shown in Figure 12.7 when we introduced the ATO design, the doll kits are held in a standardized component inventory. Once the customer order is received, the fabrication and assembly operations are performed by the artist, and standardized purchased components are taken to the point of fabrication or assembly as needed for the order. Notice that there is no finished goods inventory.

Modular Design The service or product must have a modular design that enables the "customization" the customer desires. This approach requires careful attention to service or product designs so that the final service or product can be assembled from a set of standardized modules economically and quickly in response to a customer order.

Postponement Finally, successful mass customizers postpone the task of differentiating a service or product for a specific customer until the last possible moment. *Postponement* is a concept whereby some of the final activities in the provision of a service or product are delayed until the orders are received. Doing so allows the greatest application of standard modules before specific customization is done. Postponement is a key decision because it specifies where in the supply chain volume-oriented, standardized operations are separated from custom-oriented, assembly operations. Sometimes the final customization occurs in the last step.

channel assembly

The process of using members of the distribution channel as if they were assembly stations in the factory.

The assemble-to-order strategy and postponement can be extended to supply chains. The costs of inventory and transportation often determine the extent to which a manufacturer uses postponement in the supply chain. With postponement, manufacturers can avoid inventory buildup. Some firms take advantage of a process called **channel assembly**, whereby members of

the distribution channel act as if they were assembly stations in the factory. Distribution centers or warehouses can perform the last-minute customizing operations after specific orders have been received. Channel assembly is particularly useful when the required customizing has some geographical rationale, such as language differences or technical requirements. In general, beyond the inventory advantages, the advantage of postponement in the distribution channel is that the firm's plants can focus on the standardized aspects of the product, while the distributor can focus on customizing a product that may require additional components from local suppliers.

Outsourcing Processes

All businesses buy at least some inputs to their processes (such as professional services, raw materials, or manufactured parts) from other producers. Most businesses also purchase services to get their products to their customers. How many of the processes that produce those purchased items and services should a firm own and operate instead? The answer to that question determines the extent of the firm's vertical integration. The more processes in the supply chain that the organization performs itself, the more vertically integrated it is. If it does not perform some processes itself, it must rely on **outsourcing**, or paying suppliers and distributors to perform those processes and provide needed services and materials. Some firms outsource important processes such as accounting, marketing, manufacturing, or distribution. Many firms outsource payroll, security, cleaning, and other types of services rather than employ personnel to provide these services. Outsourcing is a particularly attractive option to those firms that have low volumes. What prompts a firm to outsource? An outsourcing firm realizes that another firm can perform the outsourced process more efficiently and with better quality than it can. They opt to add external suppliers to their supply chains rather than to keep internal suppliers. However, the outsourcing decision is a serious one because the firm can lose the skills and knowledge needed to conduct the process. All learning about process advancements is left to the outsourcing partner, which makes it difficult to ever bring that process back into the firm. Managerial Practice 12.1 shows that many restaurants are outsourcing their home delivery processes so they can focus on their key expertise, the preparation of meals.

outsourcing

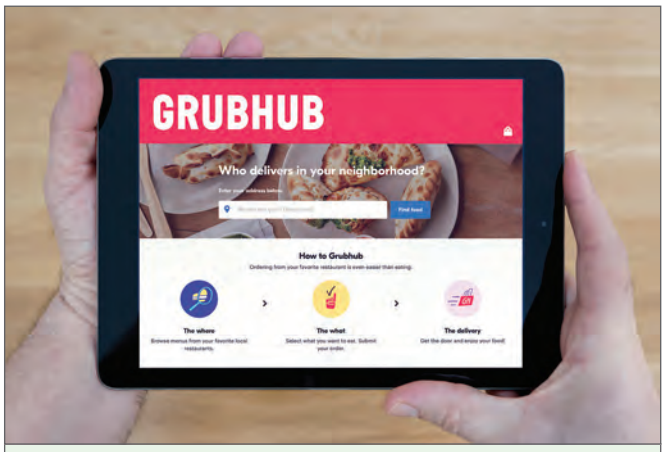
Paying suppliers and distributors to perform processes and provide needed services and materials.

MANAGERIAL PRACTICE 12.1 Outsourcing in the Food Delivery Business

After a long day's work you get home feeling hungry, open the refrigerator door, and there's nothing to eat. No problem, you reach for the phone, dial the number for your local eatery, Roman Pizzeria, and order your standard disk, complete with pepperoni, onions, and extra cheese. You give the associate your name, number, and address, and get the target time for delivery. Now, sit back, grab your favorite beverage, and be comforted in the fact that you participated in the most common form of home food delivery. It is called the "traditional" model, which represents the typical way food delivery orders are placed.

While you are waiting for your meal, have you wondered what is going on behind the scenes at Roman Pizzeria? Of course there is the cooking of your order; however, Roman Pizzeria is vertically integrated in that it has its own delivery vehicles and drivers. Those drivers must be routed to customers such that deliveries are made on time with the correct order. Drivers must be paid, vehicles must be maintained, and someone must be in charge of the routing and scheduling. All of this is a major expense, and opens the door to a new approach to the home delivery of prepared food.

With the rise of digital technology, consumers have grown accustomed to shopping online through apps or websites, and expect the same convenience when ordering dinner. This trend has provided an opportunity for companies such as DoorDash, Uber Eats, Postmates, Delivery.com, and GrubHub to become major players in the food delivery business. GrubHub, a $5.87 billion company, offers 22.62 million customers access to 140,000 restaurants through a single online portal where they can compare menus, prices, and reviews from peers. That service alone offers restaurants already vertically integrated in the home delivery market an aggregated source of new orders; however, the potential market for home delivery, including restaurants that presently do not have the logistical capability in their supply chains, is estimated to reach more than $21 billion worldwide by 2025. Consequently, GrubHub acquired several smaller home food delivery services, such as LAbite, to add a logistical capability to their restaurant services. It uses state-of-the-art technology in operating its delivery processes. For example, GrubHub knows how long a particular meal will stay fresh. They use a concept called isochrones that delimit on a map the boundaries of freshness for that meal, which change by the time of day



M4OS Photos/Alamy Stock Photo

The GrubHub app allows customers access to many local restaurants. Here a customer uses his iPad to select a restaurant and meal.

because of traffic congestion. They know that delivery outside that boundary may cause a problem of freshness. Also, understanding how long it takes a restaurant to prepare their food and how often they hold true to their projections helps their algorithm to schedule drivers and deliveries. High-end restaurants have been reluctant to enter the home delivery market for fear that the quality of their food would deteriorate and cause bad reviews. Now they can focus on making their specialty menu items and still enter the home delivery market without the need to vertically integrate the delivery logistics processes. Instead, they can outsource the delivery service to companies such as GrubHub and be confident that the food will retain its high quality when the customer receives it.[3]

Still waiting on your disk from Roman Pizzeria?

Outsourcing and Globalization

offshoring
A supply chain strategy that involves moving processes to another country.

next-shoring
A supply chain strategy that involves locating processes in close proximity to customer demand or product R&D.

The strategy of globalizing a firm adds a new dimension to the development of supply chains and the use of outsourcing. Several strategies have emerged. **Offshoring** is a supply chain strategy that involves moving processes to another country. As such, offshoring is more encompassing than outsourcing because it also includes ownership of facilities and internal processes in other countries. Firms are motivated to initiate operations offshore by the market potential and the cost advantages it provides. The firm may be able to create new markets because of its presence in other countries and its ability to offer competitive prices due to its cost efficiencies. Competitive priorities other than low costs, such as delivery speed to distant customers, can drive the decision, too. However, the term "offshoring" was popular when labor costs and other factors were very favorable in Asia and many companies were conducting operations there. Over time, costs and business conditions have changed, which has spawned sourcing strategies that focus on key operational advantages. For example, **next-shoring** is a supply chain strategy that involves locating processes in close proximity to customer demand or product R&D. These processes may be outsourced or owned by the firm and may be in-country or offshore. This strategy is useful in situations in which evolving demand from new markets places a premium on the ability to adapt products to different regions or to reduce logistics costs to the new market. Other strategies, such as *near-shoring* and *on-shoring*, are largely a reaction to the increasing costs of operations and logistics in Asia and focus on moving processes closer to the home operation.

Decision Factors The strategy to pursue is, of course, situational and depends on a number of factors.

- *Comparative Labor Costs.* Some countries such as China and India have traditionally held a huge edge when it comes to labor costs. In India, the salary for a computer programmer is much less than that of a programmer in the United States with comparable skills. In China, the average monthly wages are much less than those in Japan. However, the advantage of doing business in these and other low-wage countries is eroding as wages in those countries rise due to increased demands. In some cases, the labor-cost advantage may only be a short-term one because of local economic conditions abroad and at home.
- *Rework and Product Returns.* While labor wage rates may be low in a particular location, the quality of workmanship must also be considered. Internal rework costs and the cost of product returns may offset the advantage in wage rates.
- *Logistics Costs.* Even if labor costs are not favorable, it may still be less costly to outsource or move final assembly processes to other countries to reduce the logistical costs of delivering products to international customers. Moving processes closer to the customer and using more local suppliers reduces the cost of transporting the final product to its ultimate destination. Using shipping or air transportation can be costly because of their dependence on oil. The savings in logistical costs can offset the higher labor costs in those countries.
- *Tariffs and Taxes.* Some countries offer tax incentives to firms that do business within their borders. Tariffs can also be a stumbling block for firms looking to do business in a country. Sometimes they are high enough that the firm decides to assemble the products in that country rather than export the products in.

[3] *Sources*: Alison DeNisco Rayome, "Best Food Delivery Service: Doordash, Grubhub, Uber Eats and More Compared," CNET, https://www.cnet.com/news/best-food-delivery-service-doordash-grubhub-uber-eats-andmore-compared/ (January 20, 2020); Carsten Hirschberg, Alexander Rajko, Thomas Schumacher, and Martin Wrulich, "The Changing Market for Food Delivery," McKinsey & Company, Telecommunications (November, 2016); Addie Broyles, "How One Austin Company Revolutionized How We Get Food Delivered," Associated Press (May 17, 2016); Jacob Hall, "AT SXSW: GrubHub—Great Delivery Takes Data, Tech and a Love for Food," SXSW 2106, https:/www.entrepreneur.com/article/272742.

- *Market Effects.* Not to be overlooked is the potential advantage of next-shoring a process in a location where the presence of the firm can have a positive effect on local sales.
- *Labor Laws and Unions.* Some countries have fewer unions or restrictions on the flexible use of labor. The ability to have workers perform a number of different tasks without restrictions can be important to firms trying to achieve flexibility in operations and reduce costs. Nonetheless, firms must be cognizant of local labor laws and customs and strive to achieve a high level of ethical behavior when doing business in other countries.
- *Internet.* The Internet reduces the transaction costs of managing distant partners or operations.
- *Energy Costs.* As technology advances and carbon-based energy sources deplete, comparative energy costs can be a major cost consideration.
- *Access to Low-Cost Capital.* It is often easier and cheaper to buy equipment, buildings, and land at home than it is abroad.
- *Supply Chain Complexity.* Producing goods or services in another country requires the operation of two supply chains—one at home and one in the other country. With two supply chains to manage, issues of quality, meeting customer schedule commitments, and theft of intellectual property, among other things, become real concerns.

Potential Pitfalls Even though outsourcing may appear to offer some big advantages, it also has some pitfalls that should be carefully explored before using this strategy.

- *Pulling the Plug Too Quickly.* A major mistake is to decide to outsource a process before making a good-faith effort to fix the existing one. We discussed many ways to improve processes in Parts 1 and 2 of this text; these methods should be explored first. It is not always the case that outsourcing is the answer, even if local labor wages far exceed those of other countries. Make sure you really need to outsource to accomplish your operations strategy.
- *Technology Transfer.* Often an outsourcing strategy involves creating a *joint venture* with a company in another country. With a joint venture, two firms agree to jointly produce a service or product together. Typically, a transfer of technology takes place to bring one partner up to speed regarding the service or product. The danger is that the firm with the technology advantage will essentially be setting up the other firm to be a future competitor.
- *Process Integration.* Despite the power of the Internet, it is difficult to fully integrate outsourced processes with the firm's other processes. Time, distance, and communication can be formidable hurdles, especially if the supplier is on the other side of the world. Managing offshore processes will not be the same as managing processes located next door. Often considerable managerial time must be expended to coordinate offshore processes.



Dan Lamont/Alamy Stock Photo

The Boeing 787 Dreamliner, shown here under construction at Boeing's Paine Field plant near Everette, Washington, utilized a modular design with 43 top-tier suppliers on three continents. Outsourcing so much responsibility required a lot of managerial attention and caused major glitches in the early stages of the program.

Vertical Integration

Outsourcing is one means to acquire processes a firm lacks or is unwilling to perform. Another approach is vertical integration whereby the firm purchases the processes it needs. Vertical integration can be in two directions. **Backward integration** represents a firm's movement upstream in the supply chain toward the sources of raw materials, parts, and services through acquisitions, such as a major grocery chain investing in its own plants to produce house brands of ice cream, frozen pizza dough, and peanut butter. Backward integration has the effect of reducing the risk of supply. **Forward integration** means that the firm acquires more channels of distribution, such as its own distribution centers (warehouses) and retail stores. It can also mean that the firm goes even farther by acquiring its business customers. A firm chooses vertical integration when it has the skills, volume, and resources to hit the competitive priorities better than outsiders can. Doing the work within its organizational structure may mean better control over quality and more timely

backward integration

A firm's movement upstream toward the sources of raw materials, parts, and services through acquisitions.

forward integration

Acquiring more channels of distribution, such as distribution centers (warehouses) and retail stores, or even business customers.

delivery, as well as taking better advantage of the firm's human resources, equipment, and space. Extensive vertical integration is generally attractive when input volumes are high because high volumes allow task specialization and greater efficiency. It is also attractive if the firm has the relevant skills and views the processes that it is integrating as particularly important to its future success. However, care must be exercised that excessive vertical integration does not lead to a loss of focus for the firm in delivering value in its core business.

Management must identify, cultivate, and exploit its core competencies to prevail in global competition. Recall that core competencies reflect the collective learning of the organization, especially its ability for coordinating diverse processes and integrating multiple technologies. (See Chapter 1, "Using Operations to Create Value.") They define the firm and provide its reason for existence. Management must be constantly attentive to bolstering core competencies, perhaps by looking upstream toward its suppliers and downstream toward its customers and acquiring those processes that support its core competencies—those that allow the firm to organize work and deliver value better than its competitors. To do otherwise poses a risk that the firm will lose control over critical areas of its business.

Make-or-Buy Decisions

make-or-buy decision
A managerial choice between whether to outsource a process or do it in-house.

When managers opt for more vertical integration, by definition less outsourcing occurs. These decisions are sometimes called **make-or-buy decisions**, with a *make* decision meaning more vertical integration and a *buy* decision meaning more outsourcing. After deciding what to outsource and what to do in-house, management must find ways to coordinate and integrate the various processes and suppliers involved. Example 12.2 shows how break-even analysis, which can be found in Supplement A, "Decision Making," can be used for the make-or-buy decision.

EXAMPLE 12.2 Using Break-Even Analysis for the Make-or-Buy Decision

Online Resources
Active Model A.2 provides additional insight on the make-or-buy decision and its extensions.

Tutor A.2 in OM Explorer provides a new example to practice break-even analysis on make-or-buy decisions.

Thompson Manufacturing produces industrial scales for the electronics industry. Management is considering outsourcing the shipping operation to a logistics provider experienced in the electronics industry. Thompson's annual fixed costs of the shipping operation are $1,500,000, which includes costs of the equipment and infrastructure for the operation. The estimated variable cost of shipping the scales with the in-house operation is $4.50 per ton-mile. If Thompson outsourced the operation to Carter Trucking, the annual fixed costs of the infrastructure and management time needed to manage the contract would be $250,000. Carter would charge $8.50 per ton-mile. How many ton-miles per year would Thompson need to break even on these two options?

SOLUTION

From Supplement A, "Decision Making," the formula for the break-even quantity yields

$$Q = \frac{F_m - F_b}{c_b - c_m}$$

$$= \frac{1{,}500{,}000 - 250{,}000}{8.50 - 4.50} = 312{,}500 \text{ ton-miles}$$

DECISION POINT

Thompson management must assess how many ton-miles of product will likely be shipped now and in the future. If that estimate is less than 312,500 ton-miles, the best option is to outsource the operation to Carter Trucking.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
12.1 Explain the competitive pressures to consider when creating an effective supply chain.	Review Figures 12.1 and 12.2 for the big picture of supply chain strategy and design. The section "Creating an Effective Supply Chain" reveals the nature of designing supply chains that support competitive priorities and the pressures that impinge on supply chain design.	
12.2 Calculate the critical supply chain measures.	"Measuring Supply Chain Performance" explains the important inventory and financial measures. Be sure to understand Example 12.1 and the Solved Problem. Use OM Explorer Solver: Financial Measures Analyzer for the Brunswick Distribution, Inc., case.	**Active Model:** A.2 **OM Explorer Solvers:** Inventory Estimator, Financial Measures Analyzer **OM Explorer Tutors:** A.1: Break-Even, Evaluating Products and Services; A.2: Break-Even Evaluating Processes; 12.1: Calculating Inventory Measures; F.4: NPV, IRR, Payback **POM for Windows:** Break-Even Analysis, Financial Analysis **Tutor Exercise:** 12.1: Calculating Inventory Measures Under Different Scenarios
12.3 Describe the strategic options for supply chain design and how autonomous supply chains can play a role.	Review the section "Strategic Options for Supply Chain Design." Be sure to understand Tables 12.1 and 12.2.	
12.4 Explain the strategy of mass customization and its implications for supply chain design.	The section "Mass Customization" describes the competitive advantages and the implications for supply chain design. Be sure to understand the ATO responsive supply chain design, which is the basis for the mass customization strategy.	
12.5 Understand the considerations firms make when deciding which processes to outsource.	Outsourcing, offshoring, and next-shoring are discussed in detail in the section "Outsourcing Processes." Be sure to review Example 12.2, which uses break-even analysis for the make-or-buy decision. Managerial Practice 12.1 shows how complex the outsourcing decision can become.	

Key Equations

Measuring Supply Chain Performance

1. Average aggregate inventory value = average inventory of each SKU multiplied by its value, summed over all SKUs held in stock.
2. $$\text{Weeks of supply} = \frac{\text{Average aggregate inventory value}}{\text{Weekly sales (at cost)}}$$
3. $$\text{Inventory turnover} = \frac{\text{Annual sales (at cost)}}{\text{Average aggregate inventory value}}$$

Outsourcing Processes

4. Make-or-buy break-even quantity: $Q = \dfrac{F_m - F_b}{c_b - c_m}$

Key Terms

average aggregate inventory value 534
backward integration 545
channel assembly 542
forward integration 545
inventory turnover 535
make-or-buy decision 546
next-shoring 544
offshoring 544
outsourcing 543
supply chain design 532
weeks of supply 534

Solved Problem

A firm's cost of goods sold last year was $3,410,000, and the firm operates 52 weeks per year. It carries seven items in inventory: three raw materials, two work-in-process items, and two finished goods. The following table contains last year's average inventory level for each item, along with its value.

a. What is the average aggregate inventory value?

b. How many weeks of supply does the firm maintain?

c. What was the inventory turnover last year?

Category	Part Number	Average Level	Unit Value
Raw materials	1	15,000	$3.00
	2	2,500	$5.00
	3	3,000	$1.00
Work-in-process	4	5,000	$14.00
	5	4,000	$18.00
Finished goods	6	2,000	$48.00
	7	1,000	$62.00

SOLUTION

a.

Part Number	Average Level		Unit Value		Total Value
1	15,000	×	$3.00	=	$ 45,000
2	2,500	×	$5.00	=	$12,500
3	3,000	×	$1.00	=	$3,000
4	5,000	×	$14.00	=	$70,000
5	4,000	×	$18.00	=	$72,000
6	2,000	×	$48.00	=	$96,000
7	1,000	×	$62.00	=	$62,000
	Average aggregate inventory value =				$360,500

b. Average weekly sales at cost = $3,410,000/52 weeks = $65,577/week

$$\text{Weeks of supply} = \frac{\text{Average aggregate inventory value}}{\text{Weekly sales (at cost)}} = \frac{\$360{,}500}{\$65{,}577} = 5.5 \text{ weeks}$$

c. $$\text{Inventory turnover} = \frac{\text{Annual sales (at cost)}}{\text{Average aggregate inventory value}} = \frac{\$3{,}410{,}000}{\$360{,}500} = 9.5 \text{ turns}$$

Discussion Questions

1. "Organizations don't compete but supply chains do." Explain how taking a supply chain approach can make a firm cost effective and improve performance at the same time.
2. The Walmart retail chain sells standardized items and enjoys great purchasing clout with its suppliers, none of which it owns. The Limited retail chain sells fashion goods and owns Mast Industries, which is responsible for producing many of the items sold in The Limited stores. The Limited boasts that it can go from the concept for a new garment to the store shelf in 1,000 hours. Compare and contrast the implications for supply chain design for these two retail systems.
3. Canon, a Japanese manufacturer of photographic equipment, decided against offshoring and kept its manufacturing and new product development processes in Japan, which has relatively high labor costs. In contrast, GM, headquartered in the United States, has a joint venture with Shanghai Auto Industry Corporation (SAIC) to produce cars in China. Given our discussion of outsourcing, offshoring, next-shoring, and supply chain design, discuss how these two seemingly diverse decisions could be supportive of each company's operations strategy.

Problems

The OM Explorer, POM for Windows, and Active Models software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software replaces entirely the manual calculations.

Measuring Supply Chain Performance

1. EBI Solar uses a high-tech process to turn silicon wafers into tiny solar panels. These efficient and inexpensive panels are used to power low-energy, handheld electronic devices. Last year, EBI Solar turned its inventory 4.5 times and had a cost of goods sold of $2.5 million. Assuming 52 business weeks per year:
   a. Express last year's average inventory in weeks of supply.
   b. After several supply chain improvement initiatives, inventory investment has dropped across all inventory categories. While EBI's cost of goods sold is not expected to change from last year's level, the value of raw materials has dropped to $100,500; work-in-process to $25,800; and finished goods to $16,200. Assuming 52 business weeks per year, express EBI's current total inventory level in weeks of supply and inventory turns.
2. Busy Bee Limited, an e-commerce retailer specializing in household decorative items, ended the year with annual sales (at cost) of £3 million. During the year, the inventory of decorative items turned over seven times. For the next year, Busy Bee plans to increase annual sales (at cost) by 30 percent.
   a. What is the increase in the average aggregate inventory value required if Busy Bee maintains the same inventory turnover during the next year?
   b. What change in inventory turns must Busy Bee achieve if, through better supply chain management, it wants to support next year's sales with no increase in the average aggregate inventory value?
3. Jack Jones, the materials manager at Precision Enterprises, is beginning to look for ways to reduce inventories. A recent accounting statement shows the following inventory investment by category: raw materials, $3,129,500; work-in-process, $6,237,000; and finished goods, $2,686,500. This year's cost of goods sold will be about $32.5 million. Assuming 52 business weeks per year, express total inventory as
   a. Weeks of supply
   b. Inventory turns
4. One product line at Spearman Fishing Industries has 10 turns per year and an annual sales volume (at cost) of $985,000. How much inventory is being held, on average?
5. The Bawl Corporation supplies alloy ball bearings to auto manufacturers in Detroit. Because of its specialized manufacturing process, considerable work-in-process and raw materials are needed. The current inventory levels are $2,470,000 and $1,566,000, respectively. In addition, finished goods inventory is $1,200,000 and sales (at cost) for the current year are expected to be about $48 million. Express total inventory as
   a. Weeks of supply
   b. Inventory turns

6. The following data were collected for a retailer:

Cost of goods sold	$3,500,000
Gross profit	$700,000
Operating costs	$500,000
Operating profit	$200,000
Total inventory	$1,200,000
Fixed assets	$750,000
Long-term debt	$300,000

Assuming 52 business weeks per year, express total inventory as

a. Weeks of supply

b. Inventory turns

7. **[D]** Raj Cycles Limited is a leading bespoke cycle retailer and it operates throughout the year. The cost of goods sold last year was £835,000. The firm modifies eight items to customize cycles as per requests made by customers. Table 12.3 shows last year's average inventory levels for these items, along with their unit values.

a. What is the average aggregate inventory value?

b. The firm is expecting a disruption in its supply due to various reasons. How many weeks can it manage without a supply?

c. What was the inventory turnover last year? What conclusions can you draw from this analysis?

TABLE 12.3 | RAJ CYCLES INVENTORY ITEMS

Category	Part Number	Average Inventory Units	Value per Unit
Frame	Diamond	200	£250
	Stepthrough	500	£260
	Cantilever	300	£175
	Cross	100	£100
Tire			
	Clincher	600	£40
	Tubular	800	£50
Seats			
	Performance	350	£10
	Cushioning	750	£15

8. **[D]** Dogs-R-Us and K-9, Inc., are two retail stores that cater to the needs of dog owners in the greater Charleston area. There is healthy competition between these two establishments. Both operate 52 weeks a year and both sell approximately the same type and dollar value of items. Table 12.4 provides the cost of goods sold, the average inventory level, and unit value of each item sold in the two stores.

a. Compare the two retail stores in terms of average aggregate inventory value.

b. Compare the two retail stores in terms of weeks of supply.

c. Compare the two retail stores in terms of inventory turnover.

TABLE 12.4 | INVENTORY DATA FOR DOGS-R-US AND K-9, INC. STORES

	DOGS-R-US		K-9, INC.	
Cost of Goods Sold	**$560,000.00**		**$640,000.00**	
Category	**Average Inventory in Units**	**Value per Unit**	**Average Inventory in Units**	**Value per Unit**
Dog Beds	200	$55.00	140	$55.00
Dog Bones & Treats	1,200	$2.50	250	$2.50
Pet Feeders	50	$12.50	20	$12.50
Flea & Tick	350	$7.50	75	$7.50
Dog Kennels	10	$65.00	2	$65.00
Dog Pens	10	$220.00	3	$220.00
Patio Pet Doors	5	$120.00	2	$120.00
Dog Ramps	5	$150.00	2	$150.00
Pet Strollers	10	$40.00	2	$40.00
Pet Supplements	1,400	$4.50	150	$4.50
Dog Toys	250	$2.20	100	$2.20

Outsourcing Processes

9. **[D]** A large global automobile manufacturer is considering outsourcing the manufacturing of a solenoid used in the transmission of its SUVs. The company estimates that annual fixed costs of manufacturing the part in-house, which include equipment, maintenance, and management, amounts to $6 million. The variable costs of labor and material are $5.00 per unit. The company has an offer from a major subcontractor to produce the part for $8.00 per unit. However, the subcontractor wants the company to share in the costs of the equipment. The automobile company estimates that the total cost would be $4 million, which also includes management oversight for the new supply contact.

a. How many solenoids would the automobile company need per year to make the in-house option least costly?

b. What other factors, besides costs, should the automobile company consider before revising its supply chain for SUVs?

10. **[D]** Rain Shower is an international supplier of umbrellas. Currently, the company uses a logistical provider to provide warehouse services and handle packages destined for ground delivery. The contract costs $850,000 in annual fixed charges, which covers the provider's overhead and warehouse costs, and variable costs of £10 per package shipped. Recently, Rain Shower found a warehouse it could lease at a cost of £1.2 million per year, which includes lease costs, labor, and management oversight. Furthermore, the company found another provider who would deliver packages from the warehouse for £4.00 per package. Considering only costs, how many packages must Rain Shower ship to make the vertical integration into warehouse operations beneficial?

11. **[D]** At the Pinnacle Enterprise, a UK-based consulting firm, management was discussing the potential of outsourcing the process of handling customer calls and complaints to Relax, an international provider of call center services. Having a team of call center agents was an expensive activity especially due to an increase in employee wages. Based upon initial study and negotiations, Relax will charge £0.20 per call, and Relax will want £500,000 per year to cover equipment and overhead costs associated with the contract. Currently, Pinnacle is spending £0.15 for handling a call. It is yet to develop an estimate for the annual overhead and fixed costs associated with handling the calls. These costs include supervision, administrative support, maintenance, equipment depreciation, and overhead. If Pinnacle must handle 125,000 calls per year, how high must those fixed costs be before it would pay to use Relax?

12. **[D]** A food processing firm makes chocolates by growing its own cocoa. The firm is considering contract farming to outsource the production of cocoa to a dedicated farming company. Currently, the annual fixed cost for the firm amounts to £750,000, which includes investments in land, agricultural machinery, storage facilities, and transportation infrastructure. The variable cost of labor and materials is £2,000 per ton of cocoa. A major contract farmer has quoted a price of £3,300 for per ton of cocoa to be delivered to the site.

a. What amount of cocoa should the firm consume to make the contract farming option feasible?

b. Assume the contract farmer invites the firm to share 50 percent of the costs. The contract farmer incurs £600,000 per year, which includes overheads and other fixed costs. For this concession, the contract farmer will drop the per ton price to £2,500. Under this assumption, how many tons of cocoa should the food processing firm purchase to make this feasible?

c. If the food processing firm is expecting to consume 500 tons of cocoa, which option (make in-house, use contract farming without sharing in the costs incurred, use contract farming with sharing in the costs incurred) is the least costly?

EXPERIENTIAL LEARNING 12.1 Sonic Distributors

Scenario

Sonic Distributors produces and sells music CDs. The CDs are pressed at a single facility (factory), issued through the company's distribution center, and sold to the public from various retail stores. The goal is to operate the distribution chain at the lowest total cost.

Materials (available from instructor)

- Retail and distributor purchase order forms
- Factory work order forms
- Factory and distributor materials delivery forms
- Inventory position worksheets
- A means of generating random demand (typically a pair of dice)

Setup

Each team is in the business of manufacturing music CDs and distributing them to retail stores where they are sold. Two or more people play the role of retail outlet buyers. Their task is to determine the demand for the CDs and order replenishment stock from the distributor. The distributor carries forward-placed stock obtained from the factory. The factory produces in lot sizes either to customer order or to stock.

Tasks

- Divide into teams of four or five.
- Two or three people operate the retail stores.
- One person operates the distribution center.
- One person schedules production at the factory.

Every day, as play progresses, the participants at each level of the supply chain estimate demand, fill customer orders, record inventory levels, and decide how much to order or produce and when to place orders with their supplier.

Costs and Conditions

Unless your instructor indicates otherwise, the following costs and conditions hold.

Costs	
Holding cost per unit per day	Retail outlets: $1.00/CD/day
	Distribution Center: $0.50/CD/day
	Factory: $0.25/CD/day
Pipeline inventory cost	Assume that pipeline cost can be ignored for this exercise (consider it zero).
Ordering cost (retailers and distributors)	$20/order
Factory setup cost (to run an order)	$50 (*Note:* Cost is per order, not per day, because even though successive orders from distributors are for the same item, the factory is busy fabricating other items between orders.)
Stockout (lost margin) cost	Retail Store: $8 per CD sale lost in a period
	$0 for backorders for shortages from the factory or shipping new orders
Shipping cost	Because other products are already being distributed through this chain and because CDs are light and take up little volume, consider the cost to be zero.
Conditions	
Starting inventory	Retail stores each have 15 CDs.
	Distribution center has 25 CDs.
	Factory has 100 CDs.
Lot-sizing restrictions	Retail outlets and distribution centers—no minimum order. Any amount may be stored. Factory production lot sizes and capacity—produce in minimum lots of 20. Maximum capacity: 200/day.
Outstanding orders	None

Delays

Ordering Delay. One day to send an order from a retail store to the distributor or from the distributor to the factory (i.e., 1 day is lost between placing an order and the recipient acting on it).

No delay occurs in starting up production once an order has been received (but 1 day is needed for delivery of an order from the distributor to the factory).

Delivery Delay. One-day shipping time between the distributor and a retail store or between the factory and the distributor (i.e., 1 day is lost between shipping an order and receiving it).

Run the Exercise

For simplicity's sake, assume all transactions take place simultaneously at the middle of the day. For every simulated day, the sequence of play goes as follows.

Retailers

a. Each retailer receives any shipment due in from its distributor (1 day after shipment) and places it in sales inventory (adds the quantity indicated on any incoming Material Delivery Form from the distributor—after its 1-day delay—to the previous day's ending inventory level on the Retailer's Inventory Position Worksheet). (*Note:* For the first day of the exercise, no order will come in.)

b. The retailers each determine the day's retail demand (the quantity of CDs requested) by rolling a pair of dice. The roll determines the number demanded.

c. Retailers fill demand from available stock, if possible. Demand is filled by subtracting it from the current inventory level to develop the ending inventory level, which is recorded. If demand exceeds supply, sales are lost. Record all lost sales on the worksheet.

d. Retailers determine whether an order should be placed. If an order is required, the desired quantity of CDs is written on a Retail Store Purchase Order, which is forwarded to the distributor (who receives it after a 1-day delay). If an order is made, it should be noted on the worksheet. Retailers may also desire to keep track of outstanding orders separately.

Distributor

a. The distributor receives any shipment due in from the factory and places the CDs in available inventory (adds the quantity indicated on any incoming Material Delivery Form from the factory—after its 1-day delay—to the previous day's ending inventory level on the distributor's inventory position worksheet).

b. All outstanding backorders are filled (the quantity is subtracted from the current inventory level indicated on the worksheet) and prepared for shipment. CDs are shipped by filling out a Distribution Center Material Delivery Form indicating the quantity of CDs to be delivered.

c. The distributor uses the purchase orders received from the retail stores (after the designated 1-day delay) to prepare shipments for delivery from available inventory. Quantities shipped are subtracted from the current level to develop the ending inventory level, which is recorded. If insufficient supply exists, backorders are generated.

d. The distributor determines whether a replenishment order should be placed. If an order is required, the quantity of CDs is written on a Distribution Center Purchase Order, which is forwarded to the factory (after a 1-day delay). If an order is made, it should be noted on the worksheet. The distributor may also desire to keep track of outstanding orders separately.

Factory

a. The factory places any available new production into inventory (adds the items produced the previous day to the previous day's ending inventory level on the Factory Inventory Position Worksheet).

b. All outstanding backorders are filled (the quantity is subtracted from the current inventory level indicated on the worksheet) and prepared for shipment. CDs are shipped by filling out a Factory Material Delivery Form, indicating the quantity of CDs to be delivered.

c. The factory obtains the incoming distributor's purchase orders (after the designated 1-day delay) and ships them from stock, if it can. These amounts are subtracted from the current values on the inventory worksheet. Any unfilled orders become backorders for the next day.

d. The factory decides whether to issue a work order to produce CDs either to stock or to order. If production is required, a Factory Work Order is issued, and the order is noted on the inventory worksheet. Remember that a setup cost applies to each *production* order. It is important to keep careful track of all production in process.

Remember, once an order has been placed, it cannot be changed and no partial shipments can be made. For each day, record your ending inventory position, backorder or lost sales amount, and whether an order was made (or a production run initiated). After everyone completes the transactions for the day, the sequence repeats, beginning at retailer step (a). Your instructor will tell you how many simulated days to run the exercise.

When the play is stopped, find the cumulative amount of inventory and other costs. You can do so by summing up the numbers in each column and then multiplying these totals by the costs previously listed. Use the total of these costs to assess how well your team operated the distribution chain.[4]

CASE Brunswick Distribution, Inc.

Alex Brunswick, CEO of Brunswick Distribution, Inc. (BDI), looked out his office window at another sweltering day and wondered what could have gone wrong at his company. He had just finished reviewing his company's recent financial performance and noticed something that worried him. BDI had experienced a period of robust growth over the past 4 years. "What could be going wrong?" he thought to himself. "Our sales have been growing at an average rate of 8 percent over the past 4 years but we still appear to be worse off than before." He sat back in his chair with a heavy sigh and continued reviewing the report on his desk.

Sales had risen consistently over the past 4 years but the future was uncertain. Alex Brunswick was aware that part of the past growth had largely been the result of a few competitors in the region going out of business, a situation that was unlikely to continue. Net earnings, however, had been declining for the past 3 years and were expected to decline next year.

Brunswick was determined to turn his company around within the next 3 years. He sat back from his desk and buzzed his personal assistant: "Gabrielle, could you ask Marianna and Bradley to come up?"

Background

The distribution business, in its simplest form, involves the purchase of inventory from a variety of manufacturers and its resale to retailers. Over the past 3 to 5 years, demands on inventory changed considerably; neither manufacturers nor retailers want to handle inventory, leaving distributors to pick up the slack. In addition, an increased tendency of retailers to order directly from manufacturers placed further strain on the profitability of distributorships in general.

After humble beginnings in a shed behind the house of Brunswick's grandmother, the company moved to a 10,000-square-foot leased facility. Ten years ago, BDI began distributing high-end appliance products to supplement its low-margin products. BDI entered into an agreement with KitchenHelper Corp., a large manufacturer of high-end kitchen appliances, located 35 miles from Moline, Illinois, to distribute KitchenHelper appliances to customers in the region. Over the years BDI enjoyed steady growth and expanded its area of coverage. Currently, Brunswick was covering an area with a radius of 200 miles from the company's main facility. Given the rapid

[4] *Source*: This exercise was developed by Larry Meile, Carroll School of Management, Boston College. Reprinted by permission.

growth, BDI purchased the leased facility and made additions to bring its capacity to 30,000 square feet.

The demise of several of its competitors resulted in the acquisition of new retailer customers and some new product lines. Traditional ordering in the retailer-distributor-manufacturer chain took place via fax or telephone. Brunswick considered implementing an Internet-based ordering system but was unsure of the potential operational and marketing benefits that it could provide.

Concerns

Market

Direct competition from distributors increased over the past 5 years. As a result, the most successful distributors adopted a value-added strategy to remain competitive. Retailers want dependable delivery to support sales promotions and promises to customers. They also want the freedom to hold sales promotions at any time as competitive conditions dictate and with only short notice to distributors. They also want the opportunity to choose from a wide variety of appliances. Nonetheless, many orders are won on the basis of price and lost on the basis of delivery problems.

Financial

Manufacturers commonly demand payment in 30 to 45 days and provide no financing considerations. Retailers, in contrast, pay in 50 to 60 days. This difference often leaves BDI in a cash-poor situation that puts an unnecessary strain on its current operating loan. The company's borrowing capacity has almost been exhausted. Any additional financing will have to be sought from alternative sources. Given BDI's financial situation, any additional financing will be issued at a higher charge than the company's existing debt.

Operations

Inventory turnover also presented a problem for the past 5 years. In the past 2 years, however, a significant downturn in turnover occurred. This trend seems likely to continue.

Orders from retailers come in as their customers near completion of construction or renovations. Even though historical information provided a good benchmark of future sales, the changing market lessened the reliability of the information. The changes also affect BDI's ordering. Manufacturers require projections 60, 90, and 120 days out to budget their production. Sometimes penalties are assessed when BDI changes an order after it is placed with a manufacturer.

Strategic Issues

As Marianna and Bradley walked into Brunswick's office, he was still pondering the report. "Grab a seat," he grunted. They knew they were going to have a long day. Brunswick quickly briefed them on why he had summoned them, and they all immediately dove into a spirited discussion. Brunswick pointed out that BDI would need to be properly structured to deal with the recession and the reality of today's market. "We need to be well positioned for growth as the market stabilizes," he said. To meet this challenge, BDI must evaluate a number of alternative options. Some of the possible options might include expanding current systems and, when necessary, developing new systems that interface with suppliers, customers, and commercial transportation resources to gain total asset visibility.

Before making any investment decision, Brunswick reminded them that BDI would have to evaluate any new capital requirements, as well as the expected contribution to the company's bottom line and market share, that any option might provide. Exhibit 1 shows the income statement for the current year.

EXHIBIT 1 ▼

Company Income Statement ($000's)		
Revenue		33,074
Cost of Goods Sold		
Shipping costs	8,931	
Direct materials	5,963	
Direct labor and other	6,726	
Total	21,620	
Gross Profit		11,454
Operating Expenses		
Selling expenses	2,232	
Fixed expenses	2,641	
Depreciation	1,794	
Total	6,667	
Earnings before Interest and Taxes		4,787
	Interest expense	838
Earnings before Taxes		3,949
	Taxes @ 35%	1,382
Net Income		2,567

Investing in New Infrastructure

Bradley Pulaski, vice president of operations, said, "Since Associated Business Distribution Corp. ceased operations 4 years ago, we have been inundated with phone calls and emails from potential customers across the Midwest looking for an alternative to ABD's services. These requests come not only from former ABD customers, but also from potential customers that have not dealt with either ABD or us in the past. We cannot adequately service this market from our current warehouse because the customers do not want to wait for lengthy deliveries. We are currently servicing some customers in that region; however, I do not think we can keep them much longer because of delayed deliveries. To take advantage of this opportunity, we would have to construct a new storage facility to complement our already strained resources and 'forward position' inventory to shorten our delivery times to customers on short notice. We are challenged by an inadequate infrastructure far too small for our requirements. We only have the Moline warehouse at this time." The addition of new facilities would provide BDI with an opportunity for increased penetration in key industrial markets in the upper Midwest, where the company has had a limited presence.

The financing resources for this option would be a challenge, given that BDI was approaching its credit limit with its principal bank. Additional financing from larger banks in Chicago, however, was not ruled out. It would be expensive (with current interest rates for long-term loans starting at 11 percent). According to Bradley, this option would cost $2 million for property and $10 million for plant and equipment. The new warehouse facilities would be depreciated over 20 years. The 20-year loan would be repaid with a single balloon payment at the end of the loan. With the additional infrastructure,

BDI would be able to increase its annual sales by $4,426,000. In addition, delivery lead times to customers in the region would be reduced from 5 days to 2 days, which would be very competitive. Because of the added warehouse capacity, BDI could also increase the number of brands and models of appliances to better serve the retailers' needs for more variety. However, certain categories in the costs of goods sold would also increase. Total annual shipping costs, which include supplier deliveries to the warehouse as well as deliveries to the customer, would increase by $955,000. Annual materials costs (for the sold appliances) and labor costs would each increase by 6 percent. Total assets would increase from $30,170,000 to $43,551,000. This increase takes into account changes to inventory investment, which would become $7,200,000, accounts receivable, property, and plant and equipment.

Streamlining the Distribution System

Marianna Jackson, the vice president of logistics, stated, "I believe there is an opportunity to capitalize on the void left by our fallen rivals by utilizing a cost-efficient distribution system. We do not need a new facility; we can continue to serve the customers in the Midwest as best we can. However, what we do need is an efficient distribution system. We are holding a considerable amount of stock that has not moved simply because of our inefficient inventory systems. One of our top priorities is working diligently with the inventory control department to keep what we need and dispose of what we do not need. This approach will allow us to use the space recovered from the unneeded items for automated warehouse equipment that will enable us to become more efficient. Everything we do and every dollar we spend affects our customers. We need to keep our prices competitive. Our cost of operations is our customers' cost. Our goal is to enable customers to spend their resources on readiness and the tools of their trade, not logistics. This option will not help us much with product variety or delivery speed; however, it will increase our on-time delivery performance and improve our flexibility to respond to changes in retailer orders to support their sales programs."

The option of having an integrated center, comprising sophisticated automation systems, advanced materials handling equipment, and specially developed information technology, would provide BDI with both the versatility and capacity to offer improved products and services to Brunswick's customers. The system would support real-time ordering, logistics planning and scheduling, and after-sales service. When an order is received through a call center at Brunswick's offices in Moline, it will be forwarded to a logistics center for processing. The customer is given a delivery date based on truck availability. Orders would be grouped by destination so that trucks could be efficiently loaded to maximize the truck capacity. The order would then be scheduled for delivery and the customer notified of the estimated arrival. This new information technology would improve BDI's reliability in delivering the products when promised. The system also includes an automatic storage and retrieval system (AS/RS). The AS/RS selects a customer order and moves it to a dock for loading on a truck headed for the customer's location. The capital costs for this system would be $7 million, which would be depreciated over a 10-year period. The operating costs, including training, would run at $0.5 million each year. These costs would be considered fixed expenses by Brunswick. The improved system, however, would have tremendous cost savings. Marianna estimated that the system would save up to 16 percent in shipping expenses and 16 percent in labor expenses annually. Total assets would increase from $30,170,000 to $35,932,000 to account for changes in accounts receivables and equipment. Aggregate inventories would be only $4,500,000 because of the reduced need for safety stock inventories. BDI could finance this option using a 10-year loan at a 10 percent rate of interest. The loan would be repaid with a balloon payment at the end of the loan.

These savings would come from more efficient handling of customers' orders by the call center, better planning and scheduling of shipments, and improved communication with the warehouse and the customer, resulting in a dramatic reduction in the shipping costs in the supply chain. Additional savings would result from the reduction in personnel costs; fewer operators would be required. Marianna Jackson thought that BDI could maintain its current level of service with her option while becoming much more efficient.

The Decision

Alex Brunswick pondered the two options posed by Bradley Pulaski and Marianna Jackson. Bradley's option enabled the firm to increase its revenues by serving more customers. The capital outlay was sizable, however. Marianna's option focused on serving the firm's existing customers more efficiently. The value of that option was its dramatic reduction in costs; however, it was uncertain whether BDI could hold onto its current upper Midwest customers. Brunswick realized that he could not undertake both options, given the company's current financial position. Brunswick uses a 12 percent cost of capital as the discount rate when making financial decisions. How will each option affect the firm's operational and financial performance measures, which investors watch closely? Which supply chain design option would be better for the company? Use the Solver "Financial Measures Analyzer" for your analysis.

VIDEO CASE Supply Chain Design at Crayola

Crayola, LLC, is a profitable, wholly owned subsidiary of Hallmark Cards of Kansas City, Missouri. The company's world headquarters are located in Easton, Pennsylvania; departments there include house marketing, sales, operations and manufacturing, finance, R&D, Internet services, customer care consumer affairs, and corporate communications. Sales offices in Easton, Bentonville (Arkansas), and Minneapolis manage domestic accounts, while offices in Canada, Mexico, France, Italy, Japan, and Hong Kong handle international business. The Global Operations Division in Easton is responsible for the sourcing, quality, manufacturing, and logistics of Crayola products worldwide.

Two-thirds of what Crayola sells globally is produced in its three Pennsylvania facilities in the Lehigh Valley. The "Forks I" plant is devoted to manufacturing crayons and markers, the "Forks II" plant handles plastic molding, and the Lehigh Valley Industrial Park (LVIP) plant creates paints, modeling compounds, activity kits, and Silly Putty®. A single 800,000-square-foot distribution center in nearby Bethlehem,

Pennsylvania, handles finished goods for logistics to U.S. and international customers, and to global business units.

Each plant and its products have a unique supply chain because the raw materials, suppliers, and requirements all differ. For example, paraffin wax for crayons comes from sources in Louisiana and Pennsylvania via rail tanker cars twice a week, so proximity to the railroad is essential for the Forks I plant making crayons. All raw materials for each supply chain are first evaluated by independent board-certified toxicologists so Crayola can ensure its products are not only of the highest quality but also safe and nontoxic. Then, design hazard and risk assessments are done for all products during development to ensure production meets the stringent standards set by the Art and Creative Materials Institute (ACMI).

Pete Ruggiero, executive vice president—global operations, and his team have responsibility for designing supply chains that are innovative, resilient, responsive, and sustainable while ensuring quality, ethics, and cost considerations are met. Whenever the company's marketing division develops a new product kit that might contain paints, clays, crayons, markers, or other products, the supply chain sourcing of the raw materials as well as the downstream production processes must be addressed to be sure the forecasted demand can be accommodated within the existing facilities. Not long ago, the company introduced an innovative product called Color Wonder® that consists of pens that only write on the special paper they are packed with for sale. This required examining whether the existing supply chain could support the addition of producing the specialized ink markers, where to source the coated paper, and how to best create the kits containing both markers and paper.

Now in production, Color Wonder® is a bestseller worldwide, with nearly 40 percent of Japanese sales coming from this product alone. Managers received feedback from the market that the pens in the kits were lasting longer than the paper, so the supply chain responded by creating separate paper packets so consumers may purchase just the paper after the initial pages in the kit are used. The result of this action has had a ripple effect on the demand for markers, which is now lower, since consumers are buying fewer full kits but more Color Wonder® books, so the supply chain and production had to adjust once again.

Another major challenge is the assembly of kits whose components are derived from diverse supply chains and assembled into finished products in the company's LVIP plant. An example is the popular Washable Deluxe Painting Kit®. The kit consists of paints and watercolors, paintbrushes, smocks for the artist, and sponges for special effects. The company wants to expand sales into the growing Asian market. The kit's paints and watercolors are made by Crayola in the United States, but the paintbrushes and sponges come from China and the smocks come from Vietnam. Labor costs for assembling the kits in the United States is a significant component, so if Crayola wants to sell the kits internationally, it needs to explore whether it makes sense to keep the existing supply chain design in place, or make a change to begin producing the kits closer to the growth in its international customer base. The lynchpin of this decision is that all components (including paint and watercolor trays historically manufactured in the United States) need to be made in Asia to make production efficient, and minimize duties and lead times. By producing the entire product—including its components and packaging—in Asia, Crayola is able to optimize its delivered cost to the markets. Producing this product in the United States and shipping it to Asia would be an impediment because of cost and lead time challenges.



Pearson Education

The Washable Deluxe Painting Kit®, assembled at Crayola's Lehigh Valley Industrial Park plant, contains paints and watercolors produced in the United States and paint brushes, a smock, and a sponge produced in Asia. Demand for the kit has grown substantially in international markets, prompting a redesign of the supply chain so that Asian demand can be satisfied by Asian production facilities capable of producing and assembling the entire kit.

QUESTIONS

1. Describe the text's four external and internal pressures on supply chain design as they relate to Crayola's supply chains for Color Wonder® and the Washable Deluxe Painting Kit®.
2. Review the strategic implications of supply chains as described in the text. Does Crayola have efficient or responsive supply chains, or both? Explain your position.
3. Regarding the design of the Washable Deluxe Painting Kit® supply chain, Crayola must evaluate the strategy of next-shoring in Asia or retaining an existing network that involves the assembly of the kits in the United States. Compare and contrast these two supply chain designs from the perspective of the decision factors and pitfalls for outsourcing discussed in the text.

13

SUPPLY CHAIN LOGISTICS NETWORKS

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

13.1 Identify the factors affecting location choices within a supply chain logistics network.

13.2 Find the center of gravity using the load–distance method.

13.3 Use financial data with break-even analysis to identify the location of a facility.

13.4 Determine the location of a facility in a network using the transportation method.

13.5 Understand the role of geographical information systems in making location decisions.

13.6 Explain the implications of warehouse strategy as it relates to inventory placement and autonomous warehouse operations.

13.7 Use a preference matrix to evaluate proposed locations as part of a systematic location selection process.

Airbus SAS



NICHOLAS KAMM/AFP/Getty Images

Airbus CEO and President Fabrice Bregiere and an employee put up a sticker on the tail of the first Airbus A321 to be assembled during the inauguration of Airbus' first U.S. manufacturing facility in Mobile, Alabama. European jetmaker Airbus inaugurated its first U.S. plant in a move to wrest a chunk of Boeing's domination of the domestic aircraft market including lucrative Pentagon contracts. Airbus expects to eventually assemble 40–50 of its single-aisle A320 family every year from its new plant, built on the site of a World War II bomber support base.

In 2012 Airbus SAS, a division of Airbus Group SE, a $71B manufacturer of civilian aircraft, had final assembly plants in Toulouse, France; Hamburg, Germany; Seville, Spain; and Tianjin, China. The location of final assembly plants in the aerospace industry is a strategic decision because major components such as engines, fuselages, cockpits, wings, and vertical tails must be transported to the site, and then the final product must be delivered to the customers. Airbus has a huge backlog of orders for the fuel-saving A320 aircraft,

a versatile twin-engine plane that is used by hundreds of airlines for both short-haul and intercontinental routes. An A320 takes off and lands in the world every 1.6 seconds. More than 75 airlines have purchased more than 4,300 new-version A320s, and yet there is a backlog of 1,200 conventional A320s. So Airbus SAS decided to expand capacity and build its first U.S.-based aircraft manufacturing center in Mobile, Alabama, at a cost of $600 million. The center consists of a final assembly line (FAL), a logistics building, and a service building totaling 425,000 square feet. The FAL, originally designed to build the A320 family (A318, A319, A320, and A321) of single-aisle aircraft, has now added the A220 family until the production facilities for the A220 are completed. The facility has state-of-the-art technology, and is designed to ultimately achieve Rate 8, or eight planes a month.

Why choose the United States, and specifically Mobile, Alabama, for the new manufacturing center? Several considerations prompted the decision to locate the new facility in this location. First, it reinforces and regenerates Airbus's sales in the United Sates. For example, Airbus estimates that the U.S. market will need 4,730 new single-aisle aircrafts over the next 20 years, and Airbus expects to get orders for 40 percent of that market. The market boost in the United States, however, is that Airbus is not just using U.S. suppliers; it can now claim that its best-selling products are "Made in America." Second, there are also supply chain advantages in locating closer to its U.S. customers. The logistics costs of delivery of the final product from a FAL to the customer are obviously lower. At the same time, logistics costs are further reduced by the fact that smaller aerospace companies that supply parts and components tend to locate near the manufacturing center. For example, the Irish aircraft painting company, MAAS Aviation, has embedded itself within the Airbus Mobile paint shop, and other subcontractors are expected to follow soon. Finally, the presence of a large civil aerospace factory on U.S. soil increases Airbus's credentials and clout for future defense contracts from Washington. A flight-test center also opens the possibility of cooperation with NASA on aeronautical research.

There were also several other key considerations for choosing Mobile, Alabama, for the new facility. First, beyond the $158 million offered as incentives by the state of Alabama, Mobile is the home of the Mobile Aeroplex at Brookley, which has been redeveloped from a former military base. It has a 10,000-foot-long runway, and is located just 4 miles from the city. It is also about the same distance from the Port of Mobile, a large deep-water seaport. Airbus can transport major assemblies such as fuselage sections from Hamburg, cockpits from France, wings from England, and vertical tail sections from Spain and truck them in less than an hour to the assembly line. Second, Mobile offers a nonunionized workforce that allows Airbus a degree of flexibility to adjust production rates and work assignments that would not be possible with strong labor unions. The plant complex currently employs more than 1,000 workers, 30 percent of them being U.S. veterans with excellent skills for the aerospace industry. As part of the Alabama incentive package, Airbus has a $52 million

onsite training facility where workers are trained at state expense. Finally, Airbus and Mobile have a good relationship that was developed from past dealings. Airbus's proposal to build air tankers for the U.S. Air Force was lost to Boeing after a long battle, and Mobile, which was chosen by Airbus for the location of the proposed manufacturing site, played a major role in developing the proposal. So when it came time to find a good U.S. location, Mobile was at the top of the list. As one executive noted at the inauguration of the plant: "If they wanted low-cost labor, they would have just set up in Mexico."

The plant began assembly of its first plane, an A321, in July 2015 and delivered it to JetBlue in April 2016. By the end of 2019 it delivered more than 130 A320 aircraft and plans to deliver its first A220-300 in the third quarter of 2020.[1]

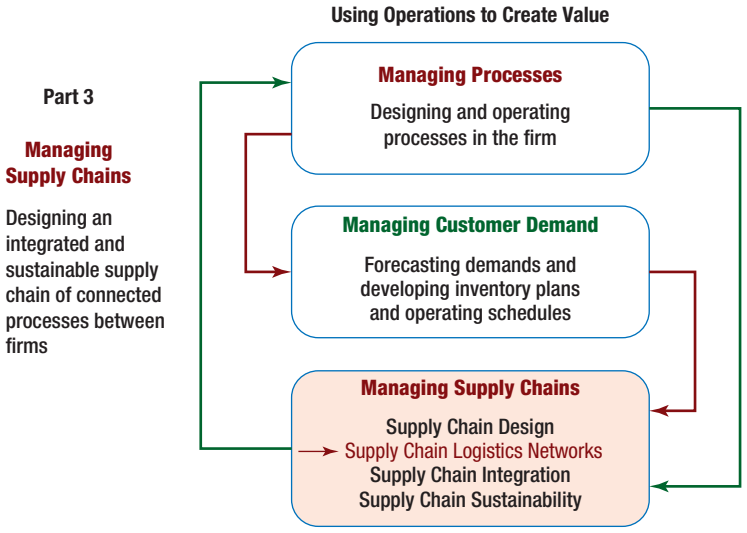
facility location

The process of determining geographical sites for a firm's operations.

distribution center (DC)

A warehouse or stocking point where goods are stored for subsequent distribution to manufacturers, wholesalers, retailers, and customers.

Firms like Airbus SAS evaluate their supply chain network in its entirety when deciding where to locate a new facility. **Facility location** is the process of determining geographical sites for a firm's operations, which could include a manufacturing plant, a distribution center, and a customer service center. A **distribution center (DC)** is a warehouse or a stocking point where goods are stored for subsequent distribution to manufacturers, wholesalers, retailers, and customers. Once there is a decision on a supply chain design that reflects the competitive priorities of a firm, the location of the facilities in the supply network becomes critically important. Location choices can therefore have a profound impact on the strategic design of its supply chains. For example, they can affect the supplier relationship process. The expanding global economy gives firms greater access to suppliers around the world, many of which can offer lower input costs or better-quality services and products. Nonetheless, when manufacturing facilities are offshored, locating far from one's suppliers can lead to higher transportation costs and coordination difficulties. The customer relationship process can also be affected by the firm's location decisions. If, on the one hand, the customer must be physically present at the process, for example, a dental office, it is unlikely that a location will be acceptable if the time or distance between the service provider and a viable customer population is great. If, on the other hand, customer contact is more passive and impersonal or if information or materials are processed rather than people, for example, a call center for AT&T, then location may be less of an issue. Information technology and the Internet can sometimes help overcome the disadvantages related to a company's location. Still, one thing is clear: The location of a business's facilities has a significant impact on the company's operating costs, the prices it charges for services and goods, and its ability to compete in the marketplace and penetrate new customer segments.



Location decisions affect processes and departments throughout the organization. When locating

[1] *Sources*: Jerry Underwood, "Milestone: Airbus Launches A220 Production at Alabama Facility," https://www.madeinalabama.com/2019/08/milestone-airbus-launches-a220-production-at-alabama-facility/ (August 05, 2019); Tim Robinson, "Sweet FAL Alabama," Royal Aeronautical Society (September 16, 2015); Austin Weber,"Airbus Assembly Plant Lands in Alabama," Assembly (January 5, 2016); Chris Kjelgaar, "Airbus Has a Sweet Home for U.S. A320 Production," http://www.ainonline.com/aviation-news (February 12, 2016); Alwyn Scott and Tim Hepher, "Aiming for U.S. Market, Airbus Delivers First U.S.-Made Jetliner," http://www.reuters.com/aricle/us-airbus-usa-idSKCN0XM1SO (April 26, 2016); Lawrence Specker, "Mobile's Airbus Plant Delivers 10th U.S.-Built Jetliner," http:/www.al.com (September 19, 2016).

new facilities, marketing must carefully assess how the location will appeal to customers and possibly open up new markets. Location also has implications for a firm's human resources department because relocating all or part of an organization can significantly affect the attitudes of the firm's workforce and the organization's ability to operate effectively across departmental lines. It can also affect the firm's hiring and training needs. Further, locating new facilities or relocating existing facilities is usually costly; therefore, these decisions must be carefully evaluated by the organization's accounting and finance departments. For instance, when Airbus located its final assembly line complex in Alabama, the economic environment of the state, the proximity of suppliers and customers, and the monetary incentives offered by its legislators played a role in the financial payoff associated with the proposed new plant. Finally, operations and logistics also have an important stake in location decisions because the location needs to be able to efficiently and reliably meet current and future customer demand while respecting the environment and culture of the surrounding area. International operations, like those of McDonald's, Starbucks, Ford, Toyota, and Walmart, introduce a formidable set of challenges because setting up and managing facilities and employees in foreign countries can be extremely time consuming and difficult. Yet it is an important part of a firm's growth.

Analyzing location patterns to discover a firm's underlying strategy is fascinating. Recognizing the strategic impact location decisions have on implementing a firm's strategy and supply chain design, we first consider the qualitative factors that influence location choices and their implications across the organization. Subsequently, we examine quantitative methods for assisting in location decisions, including the use of geographical information systems (GIS) to identify market segments and how serving each segment can profitably affect the firm's location decisions. We follow these analytic techniques with a discussion of warehousing strategy as embodied in the positioning of inventories in a logistics network and the addition of new technologies to make warehouses a competitive weapon. We end by presenting a systematic process for making location decisions, taking into account both quantitative and qualitative factors.

Factors Affecting Location Decisions

Managers of both service and manufacturing organizations must weigh many factors when assessing the desirability of particular locations, including their proximity to customers and suppliers, labor costs, and transportation costs. Managers generally can disregard factors that fail to meet at least one of the following two conditions:

1. **The Factor Must Be Sensitive to Location.** In other words, managers should not consider a factor unaffected by the location decision. For example, if community attitudes are uniformly good at all the locations under consideration, community attitudes should not be considered as a factor.
2. **The Factor Must Have a High Impact on the Company's Ability to Meet Its Goals.** For example, although alternative new facility locations in a supply chain network will have different distances from suppliers, if the shipments from the suppliers can take place overnight and the orders automatically placed online, the distance from suppliers is not likely to have a large impact on the firm's ability to meet its goals. It should therefore not be considered as a factor.

Managers can divide location factors into dominant and secondary factors. Dominant factors are derived from competitive priorities (cost, quality, time, and flexibility) and have a particularly strong impact on sales or costs. For example, a favorable labor climate, the existing infrastructure, and monetary incentives were dominant factors affecting the decision to locate the Airbus plant in Mobile, Alabama. Secondary factors also are important, but management may downplay or even ignore some of these secondary factors if other factors are more important.

Dominant Factors in Manufacturing

The following seven groups of factors dominate the decisions firms, including Airbus SAS, make about the location of new manufacturing plants or distribution centers. Often there is a trade-off among factors. Locating facilities in, say, a location with high labor costs might make sense if other factors such as logistics, taxes, and proximity to customers are favorable. Lowering the total costs of designing, developing, manufacturing, and distributing a product to its market becomes especially important in developing international supply chains and finding locations for plants, distribution centers, software design studios, and the like.

Favorable Labor Climate A favorable labor climate may well be the most important factor for labor-intensive firms in industries such as textiles, furniture, and consumer electronics. Labor climate is a function of wage rates, training requirements, attitudes toward work, worker productivity, and union strength. Many executives perceive weak unions or a low probability of union organizing efforts as a distinct advantage. Having a favorable climate applies not only

to the workforce already onsite but also to the employees that a firm hopes will transfer to or be attracted to the new site. Boeing made a decision in 2009 to locate its assembly lines for the Dreamliner planes in Charleston, South Carolina, because of the favorable labor climate, as well as the presence of other Boeing facilities and suppliers in the area. It was a very carefully thought-out and crafted decision because there are only three sites worldwide at which commercial wide-body jets are assembled—Everett, Washington; Charleston, South Carolina; and Toulouse, France (Airbus plants). The 1.2-million-square-foot plant was formally inaugurated in June 2011 despite a complaint filed by the National Labor Relations Board on behalf of the labor unions in the state of Washington. Boeing would maintain assembly of the Dreamliner planes in both locations and added a new 256,000-square-foot paint facility in 2016. In 2020, 6,900 employees worked at the South Carolina plant.

Proximity to Markets After determining where the demand for services and goods is greatest, management must select a location for the facility that will supply that demand. Often, locating operations offshore near the market is less expensive than manufacturing the product at home and shipping it. Locating near markets is particularly important when the final goods are bulky or heavy and *outbound* transportation rates are high. For example, manufacturers of products such as plastic pipe and heavy metals require proximity to their markets.

Impact on Environment As the focus on sustainability has increased, firms are looking to recognize the impact of the location decisions on the environment. Along with minimizing the carbon footprint of the new facility and its accompanying facilities in the supply chain, consideration must also be given to reducing overall energy costs. These and related issues are covered in greater detail in Chapter 15, "Supply Chain Sustainability."



IKEA installed over one million solar panels in its stores and warehouses at a cost of $2.8 billion in 2019 to reduce its carbon footprint at all of its locations. Here contractors work on the construction of a new store in Miami, Florida, a prime location for the use of solar panels.

Christina Mendenhall/Bloomberg/Getty Images

Quality of Life Good schools, recreational facilities, cultural events, and an attractive lifestyle contribute to **quality of life**. This factor can make the difference in location decisions. Over time there have been population shifts between urban and rural locations. Reasons for this movement include the cost of living, crime rate, opportunity to socialize, and the quality of healthcare.

quality of life

A factor that considers the availability of good schools, recreational facilities, cultural events, and an attractive lifestyle.

Proximity to Suppliers and Resources Firms dependent on inputs of bulky, perishable, or heavy raw materials emphasize proximity to their suppliers and resources. In such cases, *inbound* transportation costs become a dominant factor, encouraging such firms to locate facilities near suppliers. For example, locating paper mills near forests is practical. Another advantage of locating near suppliers is the ability to maintain lower inventories (see Chapter 14, "Supply Chain Integration" and the section "Inventory Placement" in this chapter).

Proximity to the Parent Company's Facilities In many companies, plants supply parts to other facilities or rely on other facilities for management and staff support. These ties require frequent communication and coordination, which can become more difficult as distance increases.

Utilities, Taxes, and Real Estate Costs Other location decision factors include utility costs (telephone, energy, and water), local and state taxes, financing incentives offered by local or state governments, relocation costs, and land costs. For example, the location of the Daimler plant in Alabama for manufacturing its "M series" vehicles, the Airbus plant in Alabama in the opening vignette, and a Toyota plant in Georgetown, Kentucky, were all attractive to these companies in part due to the incentives from local governments.

Other Factors Still other secondary factors may need to be considered, including room for expansion, construction costs, accessibility to multiple modes of transportation, the cost of shuffling people and materials between plants, insurance costs, competition from other firms for the workforce, local ordinances (such as pollution or noise control regulations), community attitudes, and many others. For global operations, firms need a good local infrastructure and local employees who are educated and have good skills. Many firms are concluding that large, centralized manufacturing facilities in low-cost countries with poorly trained workers are not sustainable. Smaller, flexible facilities located in the countries that the firm serves allow it to avoid problems related to trade barriers like tariffs and quotas and the risk that changing exchange rates will adversely affect its sales and profits.

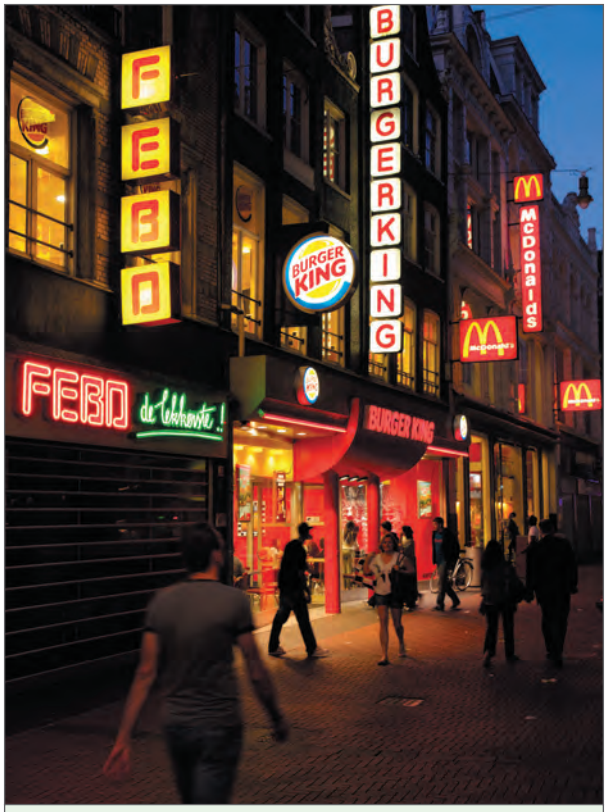
Dominant Factors in Services

The factors mentioned for manufacturers also apply to service providers, especially those with low customer contact. For those service providers with considerable customer contact, there is another important consideration: the impact of location on sales and customer satisfaction.

critical mass

A situation whereby several competing firms clustered in one location attract more customers than the total number who would shop at the same stores at scattered locations.

Proximity to Customers Location is a key factor in determining how conveniently customers can carry on business with a firm. For example, few people will patronize a remotely located dry cleaner or supermarket if another is more convenient. Thus, the influence of location on revenues tends to be a dominant factor for many service providers. In addition, customer proximity by itself is not enough—the key is proximity to customers who will patronize the facility and seek its services. Being close to customers who match a firm's target market and service offerings is thus important for profitability.



Lourens Smak/Alamy Stock Photo

The fast-food industry has long practiced the strategy of critical mass. Here, fast-food restaurants are clustered on the Nieuwendijk in the city center of Amsterdam, the Netherlands.

Transportation Costs and Proximity to Markets For warehousing and distribution operations, transportation costs and proximity to markets are extremely important. With a warehouse nearby, many firms can hold inventory closer to the customer, thus reducing delivery time and promoting sales. For example, Invacare Corporation of Elyria, Ohio, gained a competitive edge in the distribution of home health care products by decentralizing inventory into 30 warehouses across the country. Invacare sells wheelchairs, hospital beds, and other patient aids—some of which it produces and some of which it buys from other firms—to small dealers who sell to consumers. Previously the dealers, often small businesses, had to wait 3 weeks for deliveries, which meant their cash was tied up in excess inventory. With Invacare's new distribution network, the dealers get daily deliveries of products from one source. Invacare's location strategy shows how timely delivery can be a competitive advantage.

Location of Competitors One complication related to estimating the sales potential of different locations is the impact of competitors. Management must not only consider the current location of competitors but also try to anticipate their reaction to the firm's new location. Avoiding areas where competitors are already well established often pays off. However, in some industries, such as new-car sales showrooms and fast-food chains, locating near competitors is actually advantageous. The strategy is to create a **critical mass**, whereby several competing firms clustered in one location attract more customers than the total number who would shop at the same stores at scattered locations. Recognizing this effect, some firms use a follow-the-leader strategy when selecting new sites.

Site-Specific Factors Retailers also must consider the level of retail activity, residential density, traffic flow, and site visibility. Retail activity in the area is important because shoppers often

decide on impulse to go shopping or to eat in a restaurant. Traffic flows and visibility are important because customers arrive in cars. Management considers possible traffic tie-ups, traffic volume and direction by time of day, traffic signals, intersections, and the position of traffic medians. Visibility involves distance from the street and the size of nearby buildings and signs. A high residential density increases nighttime and weekend business if the population in the area fits the firm's competitive priorities and target market segment.

One of the most important parts of the site selection process is creating a site selection committee and identifying the critical factors to consider in the decision. The following Managerial Challenge shows that this committee is multi-functional and generates many factors that are quantitative as well as qualitative.

MANAGERIAL CHALLENGE Human Resources

EuroTran AG is a producer of transmissions, steering and axel systems, and driver assistance features for the automobile industry, with headquarters in Frankfurt, Germany. The company prides itself on being a leader in the industry, recently introducing its new 8-speed and 9-speed automatic transmissions. Recently, as economic conditions continued to improve after the recession caused by the COVID-19 virus pandemic, many original equipment manufacturers (OEM)—including BMW, Mercedes, and VW, who are customers of EuroTran—indicated that they intended to increase production at their facilities in the United States, either by building new plants or by expanding existing ones. While the increase in demand was welcome to EuroTran, it did pose a problem with production capacity. It was time to consider a new assembly plant overseas.

EuroTran's customers are located in the central and eastern sectors of the United States. For example, VW is in Chattanooga, Tennessee; Mercedes in Vance, Alabama; and BMW in Spartanburg, South Carolina. Where should the new assembly plant be located? A site selection committee was assembled to answer that question. The committee consisted of representatives from various functions, including operations, engineering, environmental, legal, human resources, finance, logistics, marketing, purchasing, government relations, and public relations. Emma Rothkopf, director of human resources, was assigned to the committee. The first step was for the committee to identify key location factors from each function's perspective. Engineering was concerned with the construction aspects and soil conditions at the sites. Operations and logistics were focused on the distances to customer assembly plants. Finance was concerned with the tax incentives and energy costs. Purchasing wanted to be in proximal location to EuroTran's suppliers.

Emma will have to argue for key factors associated with labor climate and quality of life at the potential sites. EuroTran produces a highly engineered, high-margin product. Consequently, the skill level of the workforce and the availability of the training resources in the local community will be important. In which states and communities will the initial list of potential sites reside? This list will probably be motivated by logistics considerations involving distance and shipment sizes. Will any of the potential sites be close to other high-tech factories? If so, the labor pool for employees may be affected. Also affecting the labor pool is how automated the new EuroTran facility will be. Finally, how will the committee arrive at a decision, given there will be both quantitative and qualitative factors to consider, and how will Emma make sure that her considerations are adequately reflected in the decision? The remainder of this chapter will help with these questions.

Having examined trends and important factors in location, we now consider four methods useful for making location decisions based on quantitative factors. These methods are the load–distance method, break-even analysis, transportation method, and geographical information systems.

Load–Distance Method

In every facility location analysis, attractive candidate locations must be identified and compared on the basis of quantitative factors. The load–distance method is one way to facilitate this step. Several location factors relate directly to distance: proximity to markets, average distance to target customers, proximity to suppliers and resources, and proximity to other company facilities. The **load–distance method** is a mathematical model used to evaluate locations based on proximity factors. This approach assumes that there is only one facility to be located, it must serve a predetermined set of nodes (customers, suppliers) in a logistics network, and it is independent of

load–distance method
A mathematical model used to evaluate locations based on proximity factors.

any other facility that may be in the network. The objective is to select a location that minimizes the sum of the loads to be transported from the facility to each node, multiplied by the distance the load travels. Depending on the application, a *load* may be tons of materials from suppliers to plants or between plants to customers, the number of trips between existing facilities and the new one, or the number of people (customers or employees) traveling to and from the facility over a certain period of time. Time may be used instead of distance if so desired.

Distance Measures

Euclidean distance
The straight-line distance, or shortest possible path, between two points.

For a rough calculation, which is all that is needed for the load–distance method, either a Euclidean or rectilinear distance measure may be used. **Euclidean distance** is the straight-line distance, or shortest possible path, between two points. To calculate this distance, we create a graph, such as the one in Figure 13.1, where we have the location of three customers that must receive shipments from a new facility located at the **red** node with coordinates (8, 12).

The scale of the graph can be in miles or any suitable measure of distance, and the customers can be located on the graph in the same relative location they have in real life. Each customer has an (x,y) coordinate on the graph. The distance between two points, say, the location of customer i and the location of the proposed facility, is

$$d_i = \sqrt{(x_i - x^*)^2 + (y_i - y^*)^2}$$

where

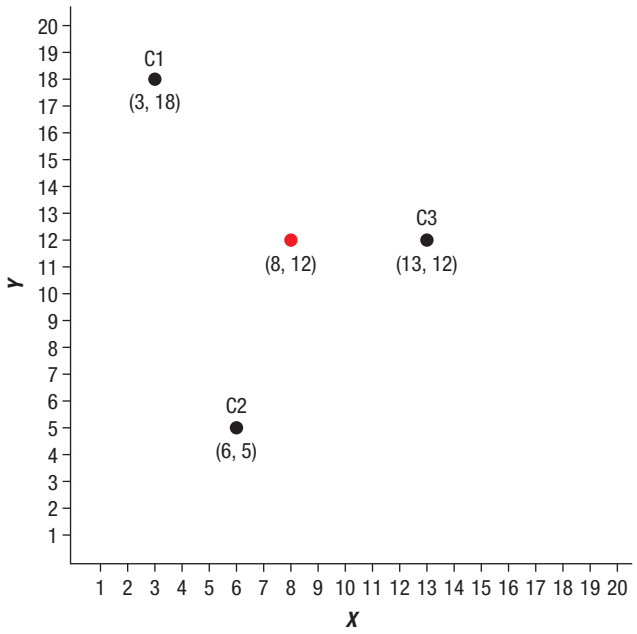
d_i = distance between customer i and the proposed facility
x_i = x-coordinate of customer i
y_i = y-coordinate of customer i
x^* = x-coordinate of proposed facility
y^* = y-coordinate of proposed facility

For example, suppose the unit of measurement in Figure 13.1 is miles. The Euclidean distance between Customer 1, located at (3, 18), and the proposed site, located at (8, 12), is

$$d_1 = \sqrt{(3 - 8)^2 + (18 - 12)^2} = 7.81 \text{ miles}$$

Rectilinear distance measures the distance between two points with a series of 90-degree turns, as along city blocks. The distance traveled in the x-direction is the absolute value of the difference between the x-coordinates. Adding this result to the absolute value of the difference between the y-coordinates gives

$$d_i = |x_i - x^*| + |y_i - y^*|$$



▲ **FIGURE 13.1**
Graph Showing Locations of Three Customers Relative to Proposed Facility

For example, the rectilinear distance between Customer 1 and the proposed site in Figure 13.1 is

$$d_1 = |3 - 8| + |18 - 12| = 11 \text{ miles}$$

rectilinear distance
The distance between two points with a series of 90-degree turns, as along city blocks.

Online Resource
Tutor 13.1 in OM Explorer provides an example to calculate both Euclidean and rectilinear distance measures.

For assistance in calculating distances using either measure, see Tutor 13.1 in OM Explorer.

Calculating a Load–Distance Score

Suppose that a firm seeking a new location wants to select a site that minimizes the distances that loads, particularly the larger ones, must travel to and from the site. The firm seeks to minimize its load–distance (ld) score, generally by choosing a location that ensures large loads go short distances.

The formula for the ld score is

$$ld = \sum_i l_i d_i$$

where

l_i = load traveling between location i and the proposed new facility

The score is the sum of the load–distance products. By selecting a new location based on the lowest ld scores, customer service is improved or transportation costs are reduced.

Center of Gravity

center of gravity
A good starting point to evaluate locations in the target area using the load–distance model.

Testing different locations with the load–distance model is relatively simple if a systematic search process is followed. **Center of gravity** is a good starting point to evaluate locations in the target area using the load–distance method. The first step is to determine the x- and y-coordinates of different locations either in the form of the longitude and latitude of the locations or by creating a two-dimensional graph. The center of gravity's x-coordinate, denoted x^*, is found by multiplying each node's x-coordinate (either the longitude of the location or the x-coordinate on a graph), by its load (l_i), summing these products ($\sum l_i x_i$), and then dividing by the sum of the loads ($\sum l_i$). The center of gravity's y-coordinate (either the latitude or the y-coordinate on a grid), denoted y^*, is found the same way. The formulas are as follows:

$$x^* = \frac{\sum_i l_i x_i}{\sum_i l_i} \quad \text{and} \quad y^* = \frac{\sum_i l_i y_i}{\sum_i l_i}$$

The goal is to find one acceptable facility location that minimizes the *ld* score, where the location is defined by its x-coordinate and y-coordinate or the longitude and the latitude. By this point you are probably wondering why you cannot just use one of the GIS apps on your smartphone to find the best location. Indeed, to calculate the *ld* score for any potential location, you could use the actual distance between any two points using a geographical information system (GIS) such as Google Maps or Waze and simply multiply the loads flowing to and from the facility by the distances traveled. However, to find the lowest load–distance score with this approach would involve a lot of trial and error, as each prospective location would have to be evaluated. Alternatively, rectilinear or Euclidean measures can be used as an approximation for distance using the x- and y-coordinates for each node in the network. The use of coordinates on a two-dimensional graph such as Figure 13.1 superimposed on a map of the area, in conjunction with a mathematical model, can be helpful in finding a good starting point for a final location. In fact, practical considerations rarely allow managers to select the exact location prescribed by the center-of-gravity model anyway. Land might not be available there at a reasonable price or other location, or geographical factors may make the site undesirable. Nonetheless, the center-of-gravity location is still an excellent starting point. Search for feasible sites in the region of the center of gravity using the location factors we discussed earlier, along with the GIS apps. Example 13.1 shows how to find the center of gravity using the load–distance method.



Lynnette Peizer/Alamy Stock Photo

The Forks Community Hospital, located in Forks, Washington, is one of five community hospitals serving Callum County. The population of Callum County is 77,331, while the population of Forks is 3,862. The locations of the community hospitals are chosen to provide the easiest access to most citizens in the county.

EXAMPLE 13.1 Finding the Center of Gravity for an Electric Utilities Supplier

Online Resources

Tutor 13.2 in OM Explorer provides another example on how to calculate the center of gravity.

Active Model 13.1 provides insight into the center of gravity method.

A supplier to the electric utility industry produces power generators, replacement parts, and maintenance items and also supplies fuel; the transportation costs are high. The supplier is looking for a location for a new plant that would service the lower part of the Great Lakes region and the upper portion of the southeastern region. More than 600,000 tons per year are expected to be shipped to eight major customer locations, as shown here:

Customer Location	Tons Shipped	*x*-, *y*- Coordinates
C1: Three Rivers, MI	5,000	(7, 13)
C2: Fort Wayne, IN	92,000	(8, 12)
C3: Columbus, OH	70,000	(11, 10)
C4: Ashland, KY	35,000	(11, 7)
C5: Kingsport, TN	9,000	(12, 4)
C6: Akron, OH	227,000	(13, 11)
C7: Wheeling, WV	16,000	(14, 10)
C8: Roanoke, VA	153,000	(15, 5)

What is the center of gravity for the electric utilities' supplier? Using rectilinear distance, what is the resulting load–distance score for this location?

SOLUTION

The center of gravity is calculated (with tons-shipped values in thousands) as shown here:

$$\sum_i l_i = 5 + 92 + 70 + 35 + 9 + 227 + 16 + 153 = 607$$

$$\sum_i l_i x_i = 5(7) + 92(8) + 70(11) + 35(11) + 9(12) + 227(13) + 16(14) + 153(15)$$

$$= 7{,}504$$

$$x^* = \frac{\sum_i l_i x_i}{\sum_i l_i} = \frac{7{,}504}{607} = 12.4$$

$$\sum_i l_i y_i = 5(13) + 92(12) + 70(10) + 35(7) + 9(4) + 227(11) + 16(10) + 153(5) = 5{,}572$$

$$y^* = \frac{\sum_i l_i y_i}{\sum_i l_i} = \frac{5{,}572}{607} = 9.2$$

Figure 13.2 shows the center-of-gravity location (**red**) relative to the customer locations. The resulting load–distance score is

$$ld = \sum_i l_i d_i = 5(5.4 + 3.8) + 92(4.4 + 2.8) + 70(1.4 + 0.8) + 35(1.4 + 2.2)$$
$$+ 9(0.4 + 5.2) + 227(0.6 + 1.8) + 16(1.6 + 0.8) + 153(2.6 + 4.2)$$
$$= 2{,}662.4$$

where

$$d_i = |x_i - x^*| + |y_i - y^*|$$

DECISION POINT

The center of gravity is (12.4, 9.2) and the load–distance score is 2,662,400. Solved Problem 3 at the end of this chapter illustrates an example of using latitude and longitude rather than grid coordinates for finding the center of gravity.

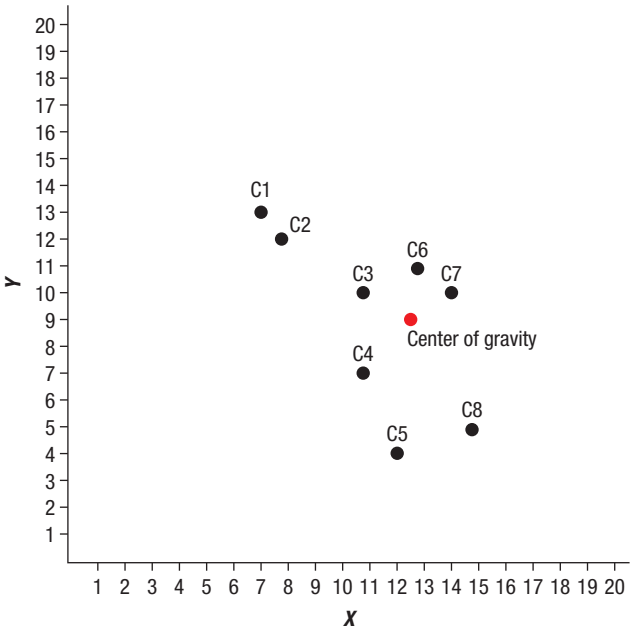


FIGURE 13.2
Center of Gravity for Electric Utilities' Supplier

Break-Even Analysis

Break-even analysis can help a manager compare location alternatives on the basis of quantitative factors that can be expressed in terms of total cost (see Supplement A, "Decision Making"). Given a set of potential locations for a facility, break-even analysis is particularly useful when the manager wants to define the ranges of volume over which each alternative is best. The basic steps for graphic and algebraic solutions are as follows:

1. Determine the variable costs and fixed costs for each potential site. Recall that *variable costs* are the portion of the total cost that varies directly with the volume of output. Recall that *fixed costs* are the portion of the total cost that remains constant regardless of output levels.
2. Plot the total cost lines—the sum of variable and fixed costs—for all the sites on a single graph (for assistance, see Tutors A.1 and A.2 in OM Explorer).
3. Identify the approximate ranges for which each location has the lowest cost.
4. Solve algebraically for the break-even points over the relevant ranges.

Example 13.2 demonstrates the use of break-even analysis for a location decision involving four proposed sites.

EXAMPLE 13.2 Break-Even Analysis for Location

Management narrowed the search for a new facility location to four communities. The annual fixed costs (land, property taxes, insurance, equipment, and buildings) and the variable costs (labor, materials, transportation, and variable overhead) are as follows:

Community	Fixed Costs per Year	Variable Costs per Unit
A	$150,000	$62
B	$300,000	$38
C	$500,000	$24
D	$600,000	$30

Notice that no community dominates the set of alternatives; that is, no community has both the lowest fixed costs and the lowest variable costs per unit. If that were so, that community would be the best location.

Online Resources

Active Model 13.2 provides insight on defining the three relevant ranges for this example.

Tutor 13.3 in OM Explorer provides another example to practice break-even analysis for location decisions.

Step 1. Plot the total cost curves for all the communities on a single graph. Identify on the graph the approximate volume range over which each community provides the lowest cost.

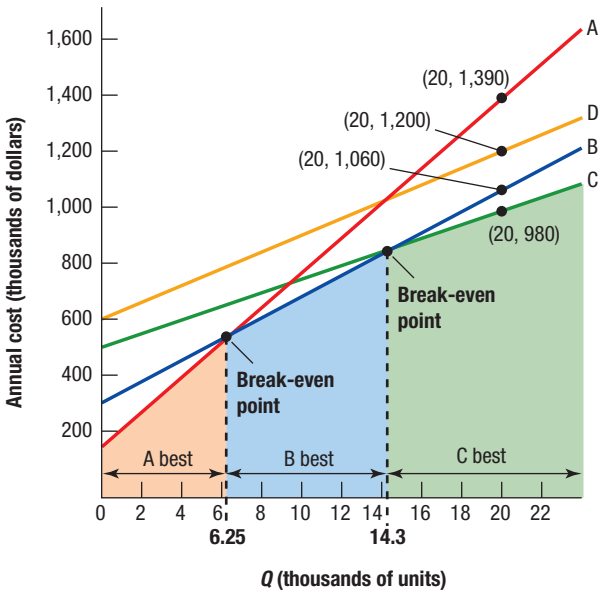
Step 2. Using break-even analysis, calculate the break-even quantities over the relevant ranges. If the expected demand is 15,000 units per year, what is the best location?

SOLUTION

Step 1. To plot a community's total cost line, let us first compute the total cost for two output levels: $Q = 0$ and $Q = 20{,}000$ units per year. For the $Q = 0$ level, the total cost is simply the fixed costs. For the $Q = 20{,}000$ level, the total cost (fixed plus variable costs) is as follows:

Community	Fixed Costs	VARIABLE COSTS (Cost per Unit) (No. of Units)	TOTAL COST (Fixed + Variable)
A	$150,000	$62(20,000) = $1,240,000	$1,390,000
B	$300,000	$38(20,000) = $760,000	$1,060,000
C	$500,000	$24(20,000) = $480,000	$980,000
D	$600,000	$30(20,000) = $600,000	$1,200,000

Figure 13.3 shows the graph of the total cost lines. The line for community A goes from (0, 150) to (20, 1,390). The graph indicates that community A is best for low volumes, B for intermediate volumes, and C for high volumes. We should no longer consider community D, because both its fixed *and* its variable costs are higher than community C's.



▲ **FIGURE 13.3**
Break-Even Analysis of Four Candidate Locations

Step 2. The break-even quantity between A and B lies at the end of the first range, where A is best, and the beginning of the second range, where B is best. We find it by setting both communities' total cost equations equal to each other and solving:

(A)	(B)
$150,000 + 62Q$ = $300,000 + 38Q$	
Q = 6,250 units	

The break-even quantity between B and C lies at the end of the range over which B is best and the beginning of the final range where C is best. It is

(B)	(C)
$300,000 + 38Q$ = $500,000 + 24Q$	
Q = 14,286 units	

No other break-even quantities are needed. The break-even point between A and C lies above the shaded area, which does not mark either the start or the end of one of the three relevant ranges.

DECISION POINT

Management located the new facility at community C, because the 15,000 units-per-year demand forecast lies in the high-volume range. These results can also be used as an input for a final decision using a preference matrix, where other nonquantitative factors could also be incorporated into the decision-making process.

Transportation Method

When a firm with a network of existing facilities plans a new facility, one of two conditions exists: (1) Either the facilities operate independently (examples include a chain of restaurants, health clinics, banks, or retail establishments) or (2) the facilities interact by moving materials or products to each other or share in the servicing of particular customers (examples include component manufacturing plants, assembly plants, and warehouses). Independently operating units can be located by treating each as a separate single facility, as we assumed with the load–distance method and break-even analysis. When facilities are interactive, the location of a new facility affects the shipping pattern of other facilities in the network. It also introduces new issues, such as how to allocate work between the facilities and how to determine the best capacity for each. Multiple-facility location problems have three dimensions—location, allocation, and capacity. Consequently, we need to use other methods to determine the best location.

The **transportation method for location problems** is a quantitative approach that can help solve multiple-facility location problems. We use it here to determine the allocation pattern that minimizes the cost of shipping products from two or more plants, or *sources of supply*, to two or more warehouses, or *destinations*. We focus on the setup and interpretation of the problem, leaving the rest of the solution process to a software package on a computer such as POM for Windows. A fuller development of this method can be found in Supplement D, "Linear Programming," and textbooks covering quantitative methods and management science.

transportation method for location problems

A quantitative approach that can help solve multiple-facility location problems.

The transportation method does not solve *all* facets of the multiple-facility location problem. It only finds the *best* shipping pattern between plants and warehouses for a particular set of plant locations, each with a given capacity. The analyst must try a variety of location–capacity combinations and use the transportation method to find the optimal distribution for each one. Distribution costs (variable shipping and possibly variable production costs) are but one important input in evaluating a particular location–allocation combination. Investment costs and other fixed costs also must be considered, along with various qualitative factors. This complete analysis must be made for each reasonable location–capacity combination. Because of the importance of making a good decision, this extra effort is well worth its cost.

Setting Up the Initial Tableau

The first step in solving a transportation problem is to format it in a standard matrix, sometimes called a *tableau*. The basic steps in setting up an initial tableau are as follows:

1. Create a row for each plant (existing or new) being considered and a column for each warehouse.
2. Add a column for plant capacities and a row for warehouse demands and insert their specific numerical values.
3. Each cell not in the requirements row or capacity column represents a shipping route from a plant to a warehouse. Insert the unit costs in the upper-right-hand corner of each of these cells.

The Sunbelt Pool Company is considering building a new 500-unit plant because business is booming. One possible location is Atlanta. Figure 13.4 shows a tableau with its plant capacity, warehouse requirements, and shipping costs. The tableau shows, for example, that shipping one unit from the existing Phoenix plant to warehouse 1 in San Antonio, Texas, costs $5.00. Costs are assumed to increase linearly with the size of the shipment; that is, the cost is the same *per unit* regardless of the size of the total shipment.

In the transportation method, the sum of the shipments in a row must equal the corresponding plant's capacity. For example, in Figure 13.4, the total shipments from the Atlanta plant to warehouses 1, 2, and 3 located in San Antonio, Texas; Hot Springs, Arkansas; and Sioux Falls, South Dakota, respectively, must add up to 500. Similarly, the sum of shipments in a column must equal the corresponding warehouse's demand requirements. Thus, shipments to warehouse 1 in San Antonio, Texas, from Phoenix and Atlanta must total 200 units.

▼ **FIGURE 13.4**
Initial Tableau

Plant	Warehouse			Capacity
	San Antonio, TX (1)	Hot Springs, AR (2)	Sioux Falls, SD (3)	
Phoenix	5.00	6.00	5.40	400
Atlanta	7.00	4.60	6.60	500
Requirements	200	400	300	900 / 900

Dummy Plants or Warehouses

The transportation method also requires that the sum of capacities equal the sum of demands, which happens to be the case at 900 units (see Figure 13.4). In many real problems, total capacity exceeds requirements, or vice versa. If

capacity exceeds requirements by r units, we add an extra column (a *dummy warehouse*) with a demand of r units and make the shipping costs \$0 in the newly created cells. Shipments are not actually made, so they represent unused plant capacity. Similarly, if requirements exceed capacity by r units, we add an extra row (a *dummy plant*) with a capacity of r units. We assign shipping costs equal to the stockout costs of the new cells. If stockout costs are unknown or are the same for all warehouses, we simply assign shipping costs of \$0 per unit to each cell in the dummy row. The optimal solution will not be affected because the shortage of r units is required in all cases. Adding a dummy warehouse or dummy plant ensures that the sum of capacities equals the sum of demands. Some software packages, such as POM for Windows, automatically add them when you make the data inputs.

Finding a Solution

After the initial tableau has been set up, the goal is to find the least-cost allocation pattern that satisfies all demands and exhausts all capacities. This pattern can be found by using the transportation method, which guarantees the optimal solution. The initial tableau is filled in with a feasible solution that satisfies all warehouse demands and exhausts all plant capacities. Then a new tableau is created, defining a new solution that has a lower total cost. This iterative process continues until no improvements can be made in the current solution, signaling that the optimal solution has been found. When using a computer package, all that you have to input is the information for the initial tableau.

Another procedure is the simplex method (see Supplement D, "Linear Programming"), although more inputs are required. The transportation problem is actually a special case of linear programming, which can be modeled with a decision variable for each cell in the tableau, a constraint for each row in the tableau (requiring that each plant's capacity be fully utilized), and a constraint for each column in the tableau (requiring that each warehouse's demand be satisfied).

Example 13.3 uses the transportation method to find the optimal shipping pattern for a proposed new plant in Atlanta.

EXAMPLE 13.3 Interpreting the Optimal Solution

▼ **FIGURE 13.5** POM for Windows Screens for Sunbelt Pool Company

The optimal solution for the Sunbelt Pool Company, found with POM for Windows, is shown in Figure 13.5. Figure 13.5(a) displays the data inputs, with the cells showing the unit costs, the bottom row showing the demands, and the last column showing the supply capacities. Figure 13.5(b) shows how the existing network of plants supplies the three warehouses to minimize costs for a total of \$4,580. Verify that each plant's capacity is exhausted and that each warehouse's demand is filled. Finally, Figure 13.5(c) shows the total quantity and cost of each shipment. The total optimal cost reported in the upper-left corner of Figure 13.5(b) is \$4,580, or 200(\$5.00) + 200(\$5.40) + 400(\$4.60) + 100(\$6.60) = \$4,580.

FIGURE 13.5a Input Data

	San Antonio	Hot Springs	Sioux Falls	SUPPLY
Phoenix	5	6	5.4	400
Atlanta	7	4.6	6.6	500
DEMAND	200	400	300	

FIGURE 13.5b Optimal Shipping Pattern

Optimal cost = \$4580	San Antonio	Hot Springs	Sioux Falls
Phoenix	200		200
Atlanta		400	100

FIGURE 13.5c Cost Breakdown

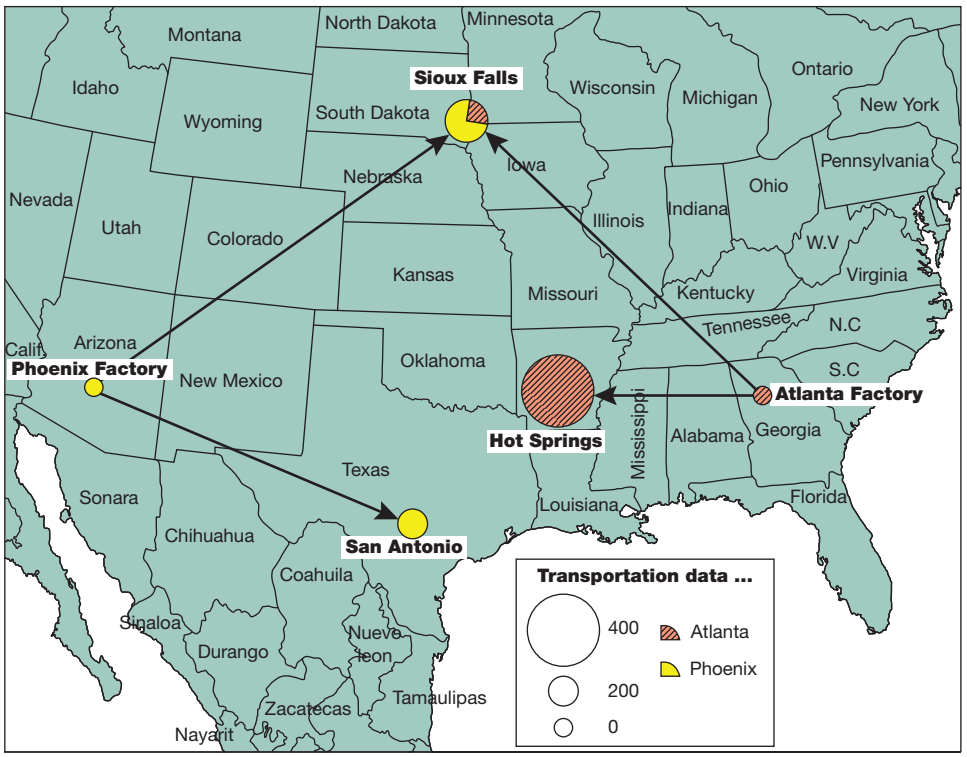
	San Antonio	Hot Springs	Sioux Falls
Phoenix	200/\$1000		200/\$1080
Atlanta		400/\$1840	100/\$660

SOLUTION

Figure 13.6 is a map from the solution in Figure 13.5 that shows how the plants supply the three warehouses. The arrows represent the shipments from each plant. The size of the circles for the three warehouses represents their capacities and how much of that capacity is being supplied from which plant. For example, Phoenix ships 200 units to warehouse 1 in San Antonio, Texas, and 200 units to warehouse 3 in Sioux Falls, South Dakota, exhausting its 400-unit capacity but only satisfying a portion of warehouse 3's requirements, as represented by the pie chart. Atlanta ships 100 units to warehouse 3 to fulfill its total demand requirements of 300 units and ships 400 units of its remaining 500-unit capacity to warehouse 2 in Hot Springs, Arkansas. Atlanta ships 400 units of its 500-unit capacity to warehouse 2 in Hot Springs, Arkansas, and the remaining 100 units to warehouse 3 in Sioux Falls, South Dakota. All warehouse demand is satisfied: Warehouse 1 in San Antonio, Texas, is fully supplied by Phoenix and warehouse 2 in Hot Springs, Arkansas, by Atlanta. Warehouse 3 in Sioux Falls, South Dakota, receives 200 units from Phoenix and 100 units from Atlanta, satisfying its 300-unit demand. The total transportation cost is 200(\$5.00) + 200(\$5.40) + 400(\$4.60) + 100(\$6.60) = \$4,580.

DECISION POINT

Management must evaluate other plant locations before deciding on the best one. The optimal solution does not necessarily mean that the best choice is to open an Atlanta plant. It just means that the best allocation pattern for the current choices on the other two dimensions of this multiple-facility location problem (that is, a capacity of 400 units at Phoenix and the new plant's location at Atlanta) results in total *transportation* costs of $4,580. The analyst should also evaluate other capacity and location combinations. For example, one possibility is to expand in Phoenix and build a smaller plant at Atlanta. Alternatively, a new plant could be built at another location, or several new plants could be built. The analyst must repeat the analysis for each such likely location strategy.



▲ **FIGURE 13.6**
Optimal Transportation Solution for Sunbelt Pool Company

Geographical Information Systems

A **geographical information system (GIS)** is a system of computer software, hardware, and data that the firm's personnel can use to manipulate, analyze, and present information relevant to a location decision. A GIS can also integrate different systems to create a visual representation of a firm's location choices. Among other things, it can be used to (1) store databases, (2) display maps, and (3) create models that can take information from existing data sets, apply analytic functions, and write results into newly derived data sets. Together, these three functionalities of data storage, map displays, and modeling are critical parts of an intelligent GIS and are used to a varying extent in all GIS applications.

geographical information system (GIS)

A system of computer software, hardware, and data that the firm's personnel can use to manipulate, analyze, and present information relevant to a location decision.

Using a GIS

A GIS can be a really useful decision-making tool because many of the decisions made by businesses today have a geographical aspect. A GIS stores information in several databases that can be naturally linked to places, such as customer sales and locations, or a census tract, or the percentage of residents in the tract that make a certain amount of money a year. The demographics of an area include the number of people in the metropolitan statistical area, city, or ZIP code; average income; number of families with children; and so forth. These demographics may all be important variables in the decision of how best to reach the target market. Similarly, the road system—including bridges and highways, the location of nearby airports and seaports, and the terrain (mountains, forests, lakes, etc.)—plays an important role in facility location decisions. As such, a GIS can have a diverse set of location-related applications in different industries such as the retail, real estate, government, transportation, and logistics industries.

Managerial Practice 13.1 illustrates how fast-food chains use a GIS to select sites.

MANAGERIAL PRACTICE 13.1 Fast-Food Site Selection Using GIS

It is not too difficult to identify successful fast-food restaurants. The tables are full, the lines are long, the waiting time is reasonable, and the food is good. Of course, there are two major operational reasons for success: management, who makes sure that service is good, food preparation exceeds customer expectations, and the operations of the restaurant are efficient; and location. If the restaurant had a poor location, the tables would not be full and the lines would be short. Even copious advertising may not right the ship.

Suppose you had the task of finding the next site location for a Wendy's restaurant. Keeping in mind that the land that sits under a Wendy's restaurant is typically owned by the parent company, the location decision is actually an investment decision for the long term. What data would you use to make your decision? While the list of data sources could be extensive, you would probably be interested in local age and average income data from the U.S. Census Bureau, which helps determine where customers and employees are likely to be. For example, in an affluent area, the customers tend to spend more per transaction but do not come in as often. Also, it is more difficult to find employees for a Wendy's restaurant there. You would also be interested in the proportion of family households in the area, as opposed to empty nesters. Auto traffic, safety information, and the commercial mix are also important. You would probably also want decades of sales data from similar restaurants in the area—numbers that are commonly available through third-party vendors.

Now, armed with all of that data, what are you going to do with it? Perhaps do as Wendy's, Starbucks Coffee, Culver's, and Chick-fil-A do: use a GIS to assist in their location-based analytics because of its capability to represent spatial data graphically with data overlays. It makes the geographical data easier to understand than if you were using GPS coordinates on a spreadsheet. In a GIS, demographic information is stored and collected as thematic layers, linked by geography, and pulled in and out to make location decisions much easier. The strategy of competitors can also be visualized using a GIS. For example, the site selection strategies of KFC, McDonald's, and A&W, among others, in Jakarta, Indonesia, were analyzed with ArcGIS®Desktop 10.0 for Windows® to reveal that the restaurants tended to cluster in a diagonal fashion across the city rather than to spatially distance themselves to the outer edges of the city. A new entry to that market can decide whether clustering with competitors is wise. The amount of pedestrian activity in the area of a proposed site can also be important. For example, Starbucks used a GIS to find a site in Nanjing, China. One of a host of thematic layers critical to the decision was the foot traffic from several office buildings under construction. Once the data were overlaid on a map of the area, viable sites for the new Starbucks became evident. In the United States, in conjunction with its effort to add beer and wine to store menus, Starbucks used a GIS to find locations with two thematic layers: high local spending patterns and a large number of wine-away-from-home drinkers. Now you can find beer and wine on the Starbucks menus of higher-end Reserve and Roastery restaurants in—guess where?—affluent neighborhoods with ample wine-away-from-home drinkers.[2]



Kristina Blokhin/Alamy Stock Photo

Chick-fil-A uses GIS to locate its fast-food restaurants, such as this one in Manhattan, NYC in Herald Square.

Governmental data can provide a statistical mother lode of information used to make better GIS-based location decisions. Internet sites on Yahoo!, MapQuest, and Waze, among others, allow people to pull up maps, distances and travel times, and routes between locations, such as between Toronto, Ontario, and San Diego, California. In addition, search engines such as Google can be integrated with population demographics to create information of interest in social and business domains. Websites are using Google Maps to display high crime areas, the location of cheap gas, and apartments for rent.

Many different types of GIS packages are available, such as ArcGIS Business Analyst (from ESRI), MapInfo Pro (from Pitney Bowes), Maptitude (from Caliper Corporation), and SAS/GIS (from SAS Institute, Inc.). Many of these systems are tailored to a specific application, such as locating retail stores, redistricting legislative districts, analyzing logistics and marketing data, and environmental management.

GIS can be useful for identifying locations that relate well to a firm's target market based on customer demographics. When coupled with other location models, sales forecasting models,

[2] *Sources*: Dyah Lestari Widaningrum, Isti Surjandari, and Aniati Murni Arymurthy, "Spatial Data Utilization for Location Pattern Analysis," ScienceDirect, *Procedia Computer Science 124* (2017), pp. 69–76; Neal Ungerleider, "How Fast Food Chains Pick Their Next Location," https://www.fastcompany.com (August 25, 2014); Mohana Ravindranath, "Wendy's Uses Mapping Software from California Firm ESRI to Pick New Locations," *The Washington Post* (August 7, 2014); "Restaurants Optimize Site Locations: Wendy's, Arby's, Culver's," http:/www.esri.com/esri-news/arcnews (Spring 2013); "What Is Geographic Information Systems (GIS)," *GISGeography* (January 22, 2017).

and geo-demographic systems, it can give a firm a formidable array of decision-making tools for its location decisions.

The GIS Method for Locating Multiple Facilities

GIS tools help visualize customer locations and data, as well as the transportation structure of roads and interstate highways. These capabilities allow the analyst to quickly arrive at a reasonable solution to the multiple-facility location problems. Load–distance score and center-of-gravity data can be merged with customer databases in Excel to arrive at trial locations for facilities, which can then be evaluated for annual driving time or distance. A five-step framework that captures the use of a GIS for locating multiple facilities is outlined here.

1. Map the data for existing customers and facilities in the GIS.
2. Visually split the entire operating area into the number of parts or subregions that equal the number of facilities to be located.
3. Assign a facility location for each region based on the visual density of customer concentration or other factors. Alternatively, determine the center of gravity for each part or subregion identified in step 2 as the starting location point for the facility in that subregion.
4. Search for alternate sites around the center of gravity to pick a feasible location that meets management's criteria, such as environmental issues, availability to major metropolitan areas, or proximity to highways.
5. Compute total load–distance scores and perform capacity checks before finalizing the locations for each region.

Such an approach can have many applications, including the design of supply chain logistics networks.

Warehouse Strategy in Logistics Networks

In this chapter we have discussed the factors that should be considered in making location decisions and the techniques that can be used to quantitatively analyze alternatives. Measures such as cost, distance, and load have been covered. However, we have not yet discussed the key factors of closeness to market or closeness to customers as they may relate to inventories and their effect on location decisions for warehouses. Further, with warehouses being an integral part of the logistics network, their efficiency and agility to cope with their assignments will be a major contributor to the competitive performance of the firm. Here we will discuss two strategic decisions that can affect the competitive capability of a firm: the placement of inventories in the logistics network, which implies the location of warehouses to support the strategy, and the degree of automation in the warehouses.

Inventory Placement

A fundamental supply chain design decision that affects performance is where to position an inventory of finished goods. Positioning inventories can have strategic implications, as in the case of international companies locating *distribution centers* (DCs) in foreign countries to preempt local competition by reducing customer delivery times. However, the issue for any firm producing standardized products is where to position the inventory in the supply chain. At one extreme, the firm could use **centralized placement**, which means keeping all the inventory of a product at a single location, such as a firm's manufacturing plant or a warehouse, and shipping directly to each of its customers. The advantage would come from what is referred to as **inventory pooling**, which is a reduction in inventory and safety stock because of the merging of uncertain and variable demands from the customers. A higher-than-expected demand from one customer can be offset by a lower-than-expected demand from another so that the total demand remains fairly stable. A disadvantage of placing inventory at a central location, however, is the added cost of shipping smaller, uneconomical quantities directly to customers over long distances. Figure 13.7 shows that centralized placement of inventories can involve considerable logistics costs.

Another approach is to use **forward placement**, which means locating stock closer to customers at a warehouse, DC, wholesaler, or retailer. Forward placement can have two advantages—faster delivery times and reduced transportation costs—that can stimulate sales. However, as inventory is placed closer to the customer, such as at a DC, the pooling effect of the inventories is reduced because safety stocks for the item must increase to take care of uncertain demands at each DC rather than just a single location. Nonetheless, the time to get the product to the customer is reduced. Consequently, service to the customer is quicker, and the firm can take advantage of larger, less costly shipments to the DCs from the manufacturing plant at the expense of larger overall inventories, as shown in Figure 13.8.

centralized placement

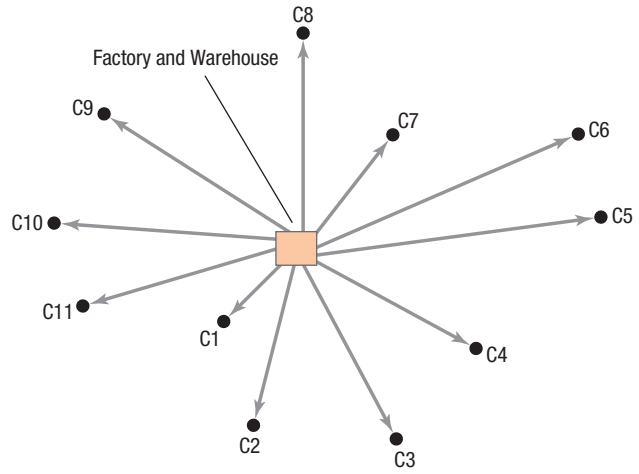
Keeping all the inventory of a product at a single location such as at a firm's manufacturing plant or a warehouse and shipping directly to each of its customers.

inventory pooling

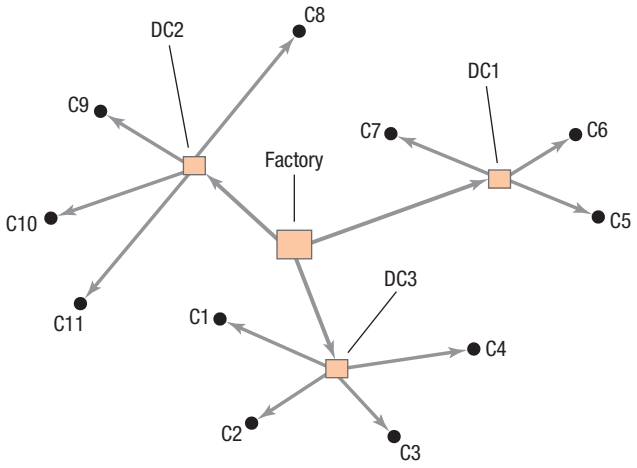
A reduction in inventory and safety stock because of the merging of variable demands from customers.

forward placement

Locating stock closer to customers at a warehouse, DC, wholesaler, or retailer.



▲ **FIGURE 13.7**
Centralized Placement with Inventory Pooling



▲ **FIGURE 13.8**
Forward Placement of Inventories

Amazon takes the forward placement strategy to a whole new level. Its multitier inventory system rests on aggregating stock in well-placed distribution centers, often near large metropolitan areas, and spreads inventory among them to ensure that supply meets demand. This strategy supports Amazon's push marketing strategy, which aggressively promotes products held in the warehouses located for quick delivery. However, Amazon has a large supporting cast of many different types of facilities in its network of warehouses, including cross-dock centers; fulfillment centers; sortation centers; delivery stations; Prime Now Hubs, which deliver a limited set of products within 2 hours; and a Prime Air Hub. Further, Amazon Marketplace, the online shopping network where other retailers can sell their products on the Amazon site, places millions of products closer to the customer without additional investment in facilities and inventories. All of these warehouse operations work in concert to implement the forward placement strategy[3].

Autonomous Warehouse Operations

Regardless of the inventory placement strategy, technology can be used to enhance warehouse operations. By some estimates, with the latest technological advancements, warehouse labor costs can be cut by as much as 70 percent and warehouses can be operated day and night with little difference in costs irrespective of night or day operations. Inventory counts can be updated daily. We have already introduced the concept of the autonomous supply chain in Chapter 12, "Supply Chain Design." Now we will discuss the technology available for autonomous operations in warehouses.

Robotics in an industrial setting have been with us since 1956, when Unimation introduced the first robot capable of moving material a dozen feet, or so. Today, robotic automation is becoming commonplace largely due to developments in artificial intelligence (AI) and machine learning, sensors and response capability, and warehouse management software (WMS). AI can be divided into two categories for supply chain application: (1) *augmentation*, which assists humans in their day-to-day tasks, and (2) *automation*, which allows machines to function without human intervention. Robots can also be equipped with high-tech sensors that allow them to perceive their surroundings with visual and auditory capability. They can also measure the ambient temperature on a surface and even perceive touch. Warehouse management software allows information to flow seamlessly from sales channels to order fulfillment and on to packing and shipping. All of these recent developments have contributed to making warehouse operations a competitive weapon[4]. Here are some examples.

Automated Guided Vehicles (AGV) Automated guided vehicles transport inventory around the warehouse. They use sensors to identify magnetic stripes or tracks to guide them and are loaded with a map of the warehouse with locations of the inventory.

[3]"How the Amazon Supply Chain Works," https://amzadvisers.com/amazon-supply-chain-works/, (May 7, 2019).

[4]See the following for additional information: Steve Banker and Chris Cunnane, "Robots and the Autonomous Supply Chain," https://www.forbes.com/sites/stevebanker/2020/04/02/robots-and-the-autonomous-supply-chain/#7157053b787a (April 2, 2020); Ruthie Bowles, "Warehouse Robotics: Everything You Need to Know in 2019," Logiwa.com/blog/warehouse-robotics (Updated May 18, 2020).

Autonomous Mobile Robots (AMR) Unlike AGVs, autonomous mobile robots do not need a set route between locations. Instead they use computers, onboard sensors, and maps to navigate their environment. There are two types of AMR: those that operate with bigger payloads and are routed from an origin to a destination, and those that have a smaller payload and focus on picking orders and loading them in cartons and totes. These smaller robots can travel all over the warehouse and have sensors to help them avoid obstacles and traffic jams. They also have the ability to identify information on each package and sort it precisely, thereby relieving workers from a redundant process to take on more creative tasks. Consequently, warehouses can experience a higher level of inventory accuracy.



devilmaya/Alamy Stock Photo

Autonomous warehouse operations can be a strategic weapon in logistics networks. Here aerial drones pick up orders in a warehouse, assisted by an autonomous robot in the background.

Aerial Drones Drones are used in warehouses for inventory management. Using a combination of computer vision technology, AI, and inventory sensors, drones are able to perform management tasks within the warehouse faster and more accurately. They can connect automatically to the WMS to access inventory information. Aerial drones do not need markers or lasers for guidance. Currently, most of the drones are AI augmentation robots, controlled by their operator on a mobile device.

We now turn to a discussion of how to use all of the data and analysis regarding a location decision in a process for making a final decision.

A Systematic Location Selection Process

Quantifiable costs and other measures as well as various qualitative factors must be considered as parts of a complete evaluation. For example, the impact on the environment must be balanced against the land and construction costs of a new plant. How does one proceed with a comprehensive analysis? A systematic location selection process begins after perception or evidence indicates that opening a retail outlet, warehouse, office, or plant in a new location will improve performance. The process of selecting a new facility location involves a series of steps.

1. Identify the important location factors and categorize them as dominant or secondary.
2. Consider alternative regions; then narrow the choices to alternative communities and finally to specific sites.
3. Collect data on the alternatives from location consultants, state development agencies, city and county planning departments, chambers of commerce, land developers, electric power companies, banks, and onsite visits. Some of these data and information may also be contained inside the GIS.
4. Analyze the data collected, beginning with the *quantitative* factors—factors that can be measured in dollars, such as annual transportation costs or taxes. The quantitative factors can also be measured in terms other than dollars, such as driving time and miles. These values may be broken into separate cost categories (e.g., inbound and outbound transportation, labor, construction, and utilities) and separate revenue sources (say sales, stock or bond issues, and interest income). These financial factors can then be converted to a single measure of financial merit such as total costs, return on investment (ROI), or net present value (NPV) and used to compare two or more sites, especially if capital costs for the new facility are also considered.
5. Bring the qualitative factors pertaining to each site into the evaluation. A *qualitative* factor is one that cannot be evaluated in dollar terms, such as community attitudes, environmental factors, or quality of life. To merge quantitative and qualitative factors, some managers review the expected performance of each factor, while others assign each factor a weight of relative importance and calculate a weighted score for each site using a preference matrix (see Supplement A, "Decision Making"). What is important in one situation may be unimportant or less important in another. The site with the highest weighted score is best. Example 13.4 shows how a preference matrix can help determine the best location.

EXAMPLE 13.4 Calculating Weighted Scores in a Preference Matrix

A new medical facility, Health-Watch, is to be located in Erie, Pennsylvania. The following table shows the location factors, weights, and scores (1 = poor, 5 = excellent) for one potential site. The weights in this case add up to 100 percent. A weighted score (*WS*) will be calculated for each site. What is the *WS* for this site?

Online Resource

Tutor 13.4 in OM Explorer provides another example to practice with a preference matrix for location decisions.

Location Factor	Weight	Score
Total patient miles per month	25	4
Facility utilization	20	3
Average time per emergency trip	20	3
Expressway accessibility	15	4
Land and construction costs	10	1
Employee preferences	10	5

SOLUTION

The *WS* for this particular site is calculated by multiplying each factor's weight by its score and adding the results:

$$\begin{aligned} WS &= (25 \times 4) + (20 \times 3) + (20 \times 3) + (15 \times 4) + (10 \times 1) + (10 \times 5) \\ &= 100 + 60 + 60 + 60 + 10 + 50 \\ &= 340 \end{aligned}$$

The total *WS* of 340 can be compared with the total weighted scores for other sites being evaluated.

6. After thoroughly evaluating all potential sites, those making the study prepare a final report containing site recommendations, along with a summary of the data and analyses on which they are based. An audiovisual presentation of the key findings usually is delivered to top management in large firms.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
13.1 Identify the factors affecting location choices within a supply chain logistics network.	See the section "Factors Affecting Location Decisions." Focus on understanding the key differences between locating manufacturing versus service facilities.	
13.2 Find the center of gravity using the load–distance method.	The section "Load–Distance Method" discusses the distance measures, the load–distance metric, and the calculations for the center of gravity. Study Solved Problem 1, which shows how to employ the method using longitude and latitude as coordinates.	**Active Model:** 13.1: Center of Gravity **OM Explorer Solver:** Center of Gravity **OM Explorer Tutors:** 13.1: Distance Measures; 13.2: Center of Gravity **POM for Windows:** Two-Dimensional Siting
13.3 Use financial data with break-even analysis to identify the location of a facility.	See the section "Break-Even Analysis" for a demonstration of how financial data can be used in selecting the location of a facility. Solved Problem 2 shows how to find the range of volumes over which each location option may be effective.	**Active Model:** 13.2: Break-Even Analysis for Location **OM Explorer Tutor:** 13.3: Break-Even Analysis for Location **OM Explorer Solver:** Break-Even Analysis **POM for Windows:** Cost-Volume Analysis
13.4 Determine the location of a facility in a network using the transportation method.	Review the section "Transportation Method," which shows how to use the POM for Windows software and interpret the results. Be sure to understand how to read an output from the analysis. Solved Problem 3 shows the setup, solution, and interpretation of a location problem.	**POM for Windows:** Transportation Method (Location)
13.5 Understand the role of geographical information systems in making location decisions.	The section "Geographical Information Systems"and Managerial Practice 13.1 show you how firms are using GIS software packages to make demographic-data-driven location decisions that are inexpensive as well as effective in simultaneously considering several location decision variables.	
13.6 Explain the implications of warehouse strategy as it relates to inventory placement and autonomous warehouse operations .	See the section "Warehouse Strategy in Logistics Networks" and study Figures 13.7 and 13.8 to understand the implications of the inventory placement decision.	

Learning Objective	Guidelines for Review	Online Resources
13.7 Use a preference matrix to evaluate proposed locations as part of a systematic location selection process.	The section "A Systematic Location Selection Process" describes a process that leads to a rational selection of a facility location given a set of alternatives. Be sure to review how a preference matrix can be used to include both qualitative and quantitative factors in the final analysis. Solved Problem 4 shows a detailed example.	**OM Explorer Tutor:** 13.4: Preference Matrix for Location **OM Explorer Solver:** Preference Matrix **POM for Windows:** Weighting Method

Key Equations

Load–Distance Method

1. Euclidean distance: $d_i = \sqrt{(x_i - x^*)^2 + (y_i - y^*)^2}$
2. Rectilinear distance: $d_i = |x_i - x^*| + |y_i - y^*|$
3. Load–distance score: $ld = \sum_i l_i d_i$
4. Center of gravity: $x^* = \dfrac{\sum_i l_i x_i}{\sum_i l_i}$ and $y^* = \dfrac{\sum_i l_i y_i}{\sum_i l_i}$

Key Terms

center of gravity 565
centralized placement 573
critical mass 562
distribution center (DC) 559
Euclidean distance 564
facility location 559
forward placement 573
geographical information system (GIS) 571
inventory pooling 573
load–distance method 563
quality of life 561
rectilinear distance 564
transportation method for location problems 569

Solved Problem 1

The new Health-Watch facility is targeted to serve seven census tracts in Erie, Pennsylvania, whose latitudes and longitudes are shown in Table 13.1, along with the population in each census tract (in thousands). Customers will travel from the seven census-tract centers to the new facility when they need health care. What is the target area's center of gravity for the Health-Watch medical facility?

TABLE 13.1 | LOCATION DATA AND CALCULATIONS FOR HEALTH-WATCH

Census Tract	Population	Latitude	Longitude	Population × Latitude	Population × Longitude
15	2,711	42.134	−80.041	114,225.27	−216,991.15
16	4,161	42.129	−80.023	175,298.77	−332,975.70
17	2,988	42.122	−80.055	125,860.54	−239,204.34
25	2,512	42.112	−80.066	105,785.34	−201,125.79
26	4,342	42.117	−80.052	182,872.01	−347,585.78
27	6,687	42.116	−80.023	281,629.69	−535,113.80
28	6,789	42.107	−80.051	285,864.42	−543,466.24
Total	**30,190**			**1,271,536.04**	**−2,416,462.80**

SOLUTION

We solve for the center of gravity x^* and y^*. Because the coordinates are given as longitude and latitude, x^* is the longitude and y^* is the latitude for the center of gravity.

$$x^* = \frac{1{,}271{,}536.05}{30{,}190} = 42.1178$$

$$y^* = \frac{-2{,}416{,}462.81}{30{,}190} = -80.0418$$

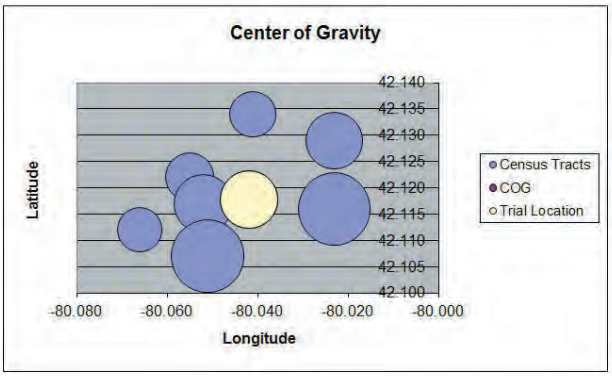
FIGURE 13.9 ▶
Center of Gravity for Health-Watch

Center of Gravity

Reset Data | Questions

Census Tract	Population	Latitude	Longitude	Population * Longitude	Population * Latitude	Distance to trial location: miles	Distance to trial location: kilometers	Load Distance: Population times miles	Load Distance: Population times kilometers
15	2,711	42.134	-80.041	114,225.27	-216,991.15	1.122	1.806	3,042.018	4,895.654
16	4,161	42.129	-80.023	175,298.77	-332,975.70	1.239	1.994	5,154.302	8,295.046
17	2,988	42.122	-80.055	125,860.54	-239,204.34	0.736	1.184	2,198.747	3,538.540
25	2,512	42.112	-80.066	105,785.34	-201,125.79	1.303	2.097	3,273.792	5,268.657
26	4,342	42.117	-80.052	182,872.01	-347,585.78	0.525	0.844	2,278.292	3,666.555
27	6,687	42.116	-80.023	281,629.69	-535,113.80	0.974	1.567	6,512.884	10,481.471
28	6,789	42.107	-80.051	285,864.42	-543,466.24	0.882	1.420	5,989.645	9,639.399
Total	30,190			1,271,536.05	-2,416,462.81				
		Center of Gravity		42.118	-80.042				
						Total Load-Distance Score with Trial Location		28,449.680	45,785.322

Trial Location	42.118	-80.042



Active Model 13.1 confirms these calculations. Figure 13.9 shows the relative population sizes of each census tract and how the center-of-gravity solution, which has been designated the trial solution, relates to them. Other alternative locations can be explored as well.

Solved Problem 2

The operations manager for Mile-High Lemonade narrowed the search for a new facility location to seven communities. Annual fixed costs (land, property taxes, insurance, equipment, and buildings) and variable costs (labor, materials, transportation, and variable overhead) are shown in Table 13.2.

a. Which of the communities can be eliminated from further consideration because they are dominated (both variable and fixed costs are higher) by another community?

b. Plot the total cost curves for all remaining communities on a single graph. Identify on the graph the approximate range over which each community provides the lowest cost.

c. Using break-even analysis, calculate the break-even quantities to determine the range over which each community provides the lowest cost.

TABLE 13.2 | FIXED AND VARIABLE COSTS FOR MILE-HIGH LEMONADE

Community	Fixed Costs per Year	Variable Costs per Barrel
Aurora	$1,600,000	$17.00
Boulder	$2,000,000	$12.00
Colorado Springs	$1,500,000	$16.00
Denver	$3,000,000	$10.00
Englewood	$1,800,000	$15.00
Fort Collins	$1,200,000	$15.00
Golden	$1,700,000	$14.00

SOLUTION

a. Aurora and Colorado Springs are dominated by Fort Collins because both fixed and variable costs are higher for those communities than for Fort Collins. Englewood is dominated by Golden.

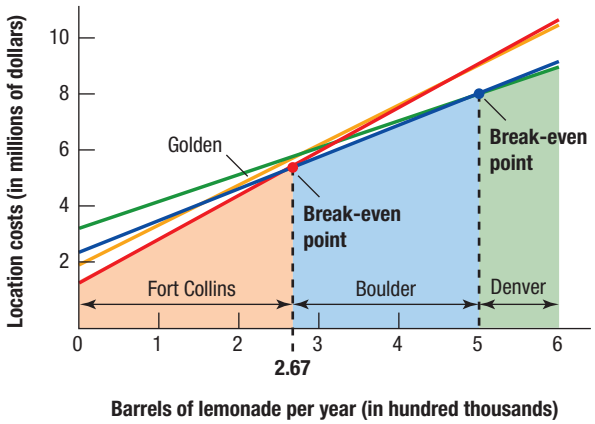
b. Figure 13.10 shows that Fort Collins is best for low volumes, Boulder for intermediate volumes, and Denver for high volumes. Although Golden is not dominated by any community, it is the second or third choice over the entire range. Golden does not become the lowest-cost choice at any volume.

c. The break-even point between Fort Collins and Boulder is

$$\$1{,}200{,}000 + \$15Q = \$2{,}000{,}000 + \$12Q$$
$$Q = 266{,}667 \text{ barrels per year}$$

d. The break-even point between Denver and Boulder is

$$\$3{,}000{,}000 + \$10Q = \$2{,}000{,}000 + \$12Q$$
$$Q = 500{,}000 \text{ barrels per year}$$



▲ **FIGURE 13.10**
Break-Even Analysis for Mile-High Lemonade

Solved Problem 3

The Arid Company makes canoe paddles to serve distribution centers in Worchester, Rochester, and Dorchester from existing plants in Battle Creek and Cherry Creek. Arid is considering locating a plant near the headwaters of Dee Creek. Annual capacity for each plant is shown in the right-hand column, while annual demand is shown in the bottom row of the tableau in Figure 13.11. Transportation costs per paddle are shown in the tableau in the small boxes. For example, the cost to ship one paddle from Battle Creek to Worchester is $4.37. The optimal allocations using the transportation method for location problems are also shown in Figure 13.11. For example, Battle Creek ships 12,000 units to Rochester. What are the estimated transportation costs associated with this allocation pattern?

Source	Destination			Capacity
	Worchester	Rochester	Dorchester	
Battle Creek	$4.37	$4.25 **12,000**	$4.89	12,000
Cherry Creek	$4.00 **6,000**	$5.00 **4,000**	$5.27	10,000
Dee Creek	$4.13	$4.50 **6,000**	$3.75 **12,000**	18,000
Demand	6,000	22,000	12,000	40,000

▲ **FIGURE 13.11**
Optimal Solution for Arid Company

SOLUTION

The total cost is $167,000.

Ship 12,000 units from Battle Creek to Rochester @ $4.25.	Cost = $ 51,000
Ship 6,000 units from Cherry Creek to Worchester @ $4.00.	Cost = $ 24,000
Ship 4,000 units from Cherry Creek to Rochester @ $5.00.	Cost = $ 20,000
Ship 6,000 units from Dee Creek to Rochester @ $4.50.	Cost = $ 27,000
Ship 12,000 units from Dee Creek to Dorchester @ $3.75.	Cost = $ 45,000
	Total = $167,000

Solved Problem 4

An electronics manufacturer must expand by building a second facility. The search is narrowed to four locations, all of which are acceptable to management in terms of dominant factors. Assessment of these sites in terms of seven location factors is shown in Table 13.3. For example, location A has a factor score of 5 (excellent) for labor climate; the weight for this factor (20) is the highest of any.

Calculate the weighted score for each location. Which location should be recommended?

SOLUTION

Based on the weighted scores shown in Table 13.4, location C is the preferred site, although location B is a close second.

TABLE 13.3 | FACTOR INFORMATION FOR ELECTRONICS MANUFACTURER

Location Factor	Factor Weight	Factor Score for Each Location			
		A	B	C	D
1. Labor climate	20	5	4	4	5
2. Quality of life	16	2	3	4	1
3. Transportation system	16	3	4	3	2
4. Proximity to markets	14	5	3	4	4
5. Proximity to materials	12	2	3	3	4
6. Taxes	12	2	5	5	4
7. Utilities	10	5	4	3	3

TABLE 13.4 | CALCULATING WEIGHTED SCORES FOR ELECTRONICS MANUFACTURER

Location Factor	Factor Weight	Weighted Score for Each Location			
		A	B	C	D
1. Labor climate	20	100	80	80	100
2. Quality of life	16	32	48	64	16
3. Transportation system	16	48	64	48	32
4. Proximity to markets	14	70	42	56	56
5. Proximity to materials	12	24	36	36	48
6. Taxes	12	24	60	60	48
7. Utilities	10	50	40	30	30
Totals	100	348	370	374	330

Discussion Questions

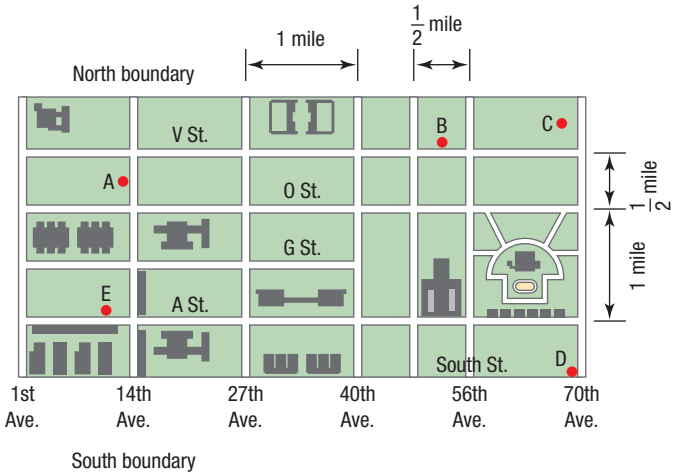
1. Select two organizations, one in services and one in manufacturing. What are the key factors that each organization would consider in locating a new facility? What data would you want to collect before evaluating the location options, and how would you collect the data? Explain.
2. London, New York, Tokyo, Singapore, and Shanghai are some of the world's largest cities. Discuss from a logistical perspective the reason behind the success of these cities?
3. A firm in Ohio is thinking of buying a plant from a regional business group located in a Southeast Asian country. The business group selling the plant has questionable labor and management practices, some of which are also in conflict with the OSHA (Occupational Safety and Health Administration) and EPA (Environmental Protection Agency) regulations. What ethical and environmental factors should the U.S. firm consider before finalizing the plant location decision?

Problems

The OM Explorer, POM for Windows, and Active Models software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations.

Load–Distance Method

1. The following coordinates are the locations of different warehouse facilities of an e-commerce retailer: (15,15), (40,5), and (40,50). The coordinates are in kilometers.
   - **a.** Calculate the Euclidean distances (in kilometers) between each of the three pairs of facilities.
   - **b.** Calculate these distances using rectilinear distances.
2. West Gorham High School is to be located at the population center of gravity of three communities: Westbrook, population 16,000; Scarborough, population 22,000; and Gorham, population 36,500. Westbrook is located at 43.6769°N, 70.3717°W; Scarborough is located at 43.5781° N, 70.3222° W; and Gorham is located at 43.6795° N, 70.4447° W.
   - **a.** Where should West Gorham High School be located?
   - **b.** If only two pieces of adequate land are available for sale—Baker's Field at 43.6784° N, 70.3827° W; or Lonesome Acres at 43.5119° N, 70.3856° W—using rectilinear distances, which is closer to the site located in part (a)?
3. Val's Pizza is looking for a single central location to make pizza for delivery only. This college town is arranged on a grid with arterial streets, as shown in Figure 13.12. The main campus (A), located at 14th and R, is the source of 4,000 pizza orders per week. Three smaller campuses (B, C, and D) are located at 52nd and V, at 67th and Z, and at 70th and South. Orders from the smaller campuses average 1,000 pizzas per week. In addition, the State Patrol headquarters (E) at 10th and A orders 500 pizzas per week.



▲ **FIGURE 13.12**
Map of Campus Area

   - **a.** At about what intersection should Val start looking for a suitable site? (Estimate coordinates for the major demands accurate to the nearest one-quarter mile, and then find the center of gravity.)
   - **b.** What is the rectilinear weekly load–distance score for this location?
   - **c.** If the delivery person can travel 1 mile in 2 minutes on arterial streets and $^1/_4$ mile per minute on residential streets, going from the center-of-gravity location to the farthest demand location will take how long?
4. A larger and more modern main post office is to be constructed at a new location in Davis, California. Growing suburbs caused a shift in the population density from where it was 40 years ago, when the current facility was built. Annette Werk, the postmaster, asked her assistants to draw a grid map of the seven points where mail is picked up and delivered in bulk. The coordinates and trips per day to and from the seven mail source points and the current main post office, M, are shown in the following table. M will continue to act as a mail source point after relocation.

Mail Source Point	Round Trips Per Day	*x*-, *y*-Coordinates (miles)
1	6	(2, 8)
2	3	(6, 1)
3	3	(8, 5)
4	3	(13, 3)
5	2	(15, 10)
6	7	(6, 14)
7	5	(18, 1)
M	3	(10, 3)

   - **a.** Calculate the center of gravity as a possible location for the new facility (round to the nearest whole number).
   - **b.** Compare the load–distance scores for the location in part (a) and the current location, using rectilinear distance.
5. A milk processing factory is investigating which locations would best position its new plant relative to three important retail customers (located in cities A, B, and C). As shown in the table, all three customers require multiple daily deliveries. Management limited the search for this plant to those three locations and compiled the following information:

Location	Coordinates (miles)	Deliveries per Day
A	(75, 150)	80
B	(375, 50)	40
C	(75, 50)	30

   - **a.** Which of these three locations yields the smallest total travel distance, based on Euclidean distances?
   - **b.** Calculate the ideal location decision, based on rectilinear distances.
   - **c.** Identify the coordinates of the center of gravity.
6. A television manufacturer in Seoul plans to export television sets to India through either Chennai or Visakhapatnam ports. It has distribution centers in Bhopal, Mumbai, and Hyderabad and will ship to them from whichever city is chosen as the port of entry. TV sets are transported to the distribution centers via large containers. Each container can carry 400 units. Overall transportation cost is the only criterion for choosing the port. Use the load–distance model and the information in Table 13.5 to select the more cost-effective city.

TABLE 13.5 | DISTANCES AND COSTS FOR TV EXPORTER

		Distribution Center (units/year)		
		Bhopal	Mumbai	Hyderabad
		10,000	16,000	20,000
	Visakhapatnam			
	Distance (kilometers)	1,100	1,300	630
	Shipping cost (₹/km)	35	35	35
PORT OF ENTRY				
	Chennai			
	Distance (kilometers)	1,500	1,200	630
	Shipping cost (₹/km)	33	33	33

7. **[D]** Golf Bar wants to open a new indoor golf center for the busy working professionals of London Borough. It, however, has only enough capital to build one facility. Golf Bar wants it to be centered by population, as determined by the center-of-gravity method. The following information is given:

London Borough	Population	*x*-Coordinate	*y*-Coordinate
City of London	10,000	5	10
City of Westminster	260,000	4	10
Lambeth	326,000	4	13
Wandsworth	33,000	3	13
Camden	270,000	4	8
Southwark	320,000	5	11

Identify the ideal location where Golf Bar should build its course.

Break-Even Analysis

8. Two alternative locations are under consideration for a new plant: Jackson, Mississippi, and Dayton, Ohio. The Jackson location is superior in terms of costs. However, management believes that sales volume would decline if this location were chosen because it is farther from the market, and the firm's customers prefer local suppliers. The selling price of the product is $250 per unit in either case. Use the following information to determine which location yields the higher total profit per year:

Location	Annual Fixed Cost	Variable Cost per Unit	Forecast Demand per Year
Jackson	$1,500,000	$50	30,000 units
Dayton	$2,800,000	$85	40,000 units

9. Thiru is a coconut oil extraction company based in Chennai, India. Management is considering four locations for a new plant: Trichy, Villupuram, Thiruvannamalai, and Nagapattinam. Annual fixed costs and variable costs per ton are shown in the below table.

Location	Annual Fixed Costs	Variable Costs per Ton
Trichy	₹14,000	₹400
Villupuram	₹5,000	₹350
Tiruvannamalai	₹17,000	₹75
Nagapattinam	₹13,000	₹200

a. Plot the total cost curves for all the locations on a single graph (see Solved Problem 2). Identify on the graph the range in volume over which each location would be best.

b. What break-even quantity defines each range?

Although Trichy's fixed and variable costs are dominated by those of the other locations, Thiru believes that both the demand and the price would be higher for oil extracted in Trichy than for oil extracted in the other locations. The following table shows those projections:

Location	Price per Ton	Forecast Demand per Year
Trichy	₹600	650 units
Villupuram	₹450	450 units
Tiruvannamalai	₹400	430 units
Nagapattinam	₹400	400 units

c. Determine which location yields the highest total profit per year.

d. Is this location decision sensitive to forecast accuracy? At what minimum sales volume does Trichy become the location of choice?

10. Wiebe Trucking, Inc., is planning a new warehouse to serve the western United States. Denver, Santa Fe, and Salt Lake City are under consideration. For each location, annual fixed costs (rent, equipment, and insurance) and average variable costs per shipment (labor, transportation, and utilities) are listed in the following table. Sales projections range from 550,000 to 600,000 shipments per year.

Location	Annual Fixed Costs	Variable Cost per Shipment
Denver	$5,000,000	$4.65
Santa Fe	$4,200,000	$6.25
Salt Lake City	$3,500,000	$7.25

a. Plot the total cost curves for all the locations on a single graph.

b. Which city provides the lowest overall costs?

11. Sam Hutchins is planning to operate a specialty bagel sandwich kiosk but is undecided about whether to locate in the downtown shopping plaza or in a suburban shopping mall. Based on the following data, which location would you recommend?

Location	Downtown	Suburban
Annual rent, including utilities	$12,000	$8,000
Expected annual demand (sandwiches)	30,000	25,000
Average variable costs per sandwich	$1.50	$1.00
Average selling price per sandwich	$3.25	$2.85

12. **[D]** Green Paper Recycling manufactures paper plates and cups from recycled paper and cardboard. The company has narrowed its potential choices for its new manufacturing facility to four cities in France. Management has gathered the following information about the manufacturing and shipping costs of locating in each of these four cities:

City	Fixed Costs per Year	Variable Manufacturing Costs per 1,000 Units	Variable Shipping Costs per Unit
Paris	€350,000	€10.00	€5.00
Marseille	€675,000	€8.00	€4.00
Lyon	€1,300,000	€4.00	€3.00
Toulouse	€1,800,000	€6.00	€5.00

a. Use break-even analysis to determine where Green Paper should locate.

b. Based solely on the break-even quantity, if Green Paper's manufacturing forecast for the foreseeable future is 500,000 units annually, where should it locate?

Transportation Method

13. Prescott Industries transports sand and stone extracted from its open-pit mines located in Odessa and Bryan to its concrete block manufacturing facilities in Abilene, Tyler, and San Angelo. For the capacities, locations, and shipment costs per truckload shown in Figure 13.13, determine the shipping pattern that will minimize transportation costs. What are the estimated transportation costs associated with this optimal allocation pattern?

Source	Destination			Capacity
	Abilene	Tyler	San Angelo	
Odessa	$60	$50	$40	12,000
Bryan	$70	$30	$90	10,000
Demand	8,000	10,000	4,000	22,000

▲ **FIGURE 13.13**
Transportation Tableau for Prescott Industries

14. The Winston Company has four distribution centers (A, B, C, and D) that require 40,000, 60,000, 30,000, and 50,000 gallons of de-ionized water, respectively, per month for cleaning its long-haul trucks. Three de-ionized water wholesalers (1, 2, and 3) indicated their willingness to supply as many as 50,000, 70,000, and 60,000 gallons, respectively. The total cost (shipping plus price) of delivering 1,000 gallons of de-ionized water from each wholesaler to each distribution center is shown in the following table:

	Distribution Center			
Wholesaler	**A**	**B**	**C**	**D**
1	$1.30	$1.40	$1.80	$1.60
2	$1.30	$1.50	$1.80	$1.60
3	$1.60	$1.40	$1.70	$1.50

a. Determine the optimal solution. Show that all capacities have been exhausted and that all demands can be met with this solution.

b. What is the total cost of the solution?

15. The Acme Company operates four factories that ship products to five warehouses. The shipping costs, requirements capacities, and optimal allocations are shown in Figure 13.14. What is the total cost of the optimal solution?

Factory	Shipping Cost per Case to Warehouse					Capacity
	W1	W2	W3	W4	W5	
F1	$1 **60,000**	$3 **20,000**	$4	$5	$6	80,000
F2	$2	$2	$1 **50,000**	$4 **10,000**	$5	60,000
F3	$1	$5	$1	$3 **20,000**	$1 **40,000**	60,000
F4	$5	$2 **50,000**	$4	$5	$4	50,000
Demand	60,000	70,000	50,000	30,000	40,000	250,000

▲ **FIGURE 13.14**
Optimal Solution for Acme Company

16. **[D]** The Giant Farmer Company processes food for sale in discount food stores. It has two plants: one in Chicago and one in Houston. The company also operates warehouses in Miami, Florida; Denver, Colorado; Lincoln, Nebraska; and Jackson, Mississippi. Forecasts indicate that demand soon will exceed supply and that a new plant with a capacity of 8,000 cases per week is needed. The question is where to locate the new plant. Two potential sites are Buffalo, New York, and Atlanta, Georgia. The following

two tables give data on capacities, forecasted demand, and shipping costs that have been gathered.

For each alternative new plant location, determine the shipping pattern that will minimize total transportation costs. Where should the new plant be located?

Plant	Capacity (Cases per Week)	Warehouse	Demand (Cases per Week)
Chicago	10,000	Miami	7,000
Houston	7,500	Denver	9,000
New plant	8,000	Lincoln	4,500
	Total 25,500	Jackson	5,000
			Total 25,500

	Shipping Cost to Warehouse (per Case)			
Plant	Miami	Denver	Lincoln	Jackson
Chicago	$7.00	$2.00	$4.00	$5.00
Houston	$3.00	$1.00	$5.00	$2.00
Buffalo (alternative 1)	$6.00	$9.00	$7.00	$4.00
Atlanta (alternative 2)	$2.00	$10.00	$8.00	$3.00

17. **[D]** Consider the facility location problem at the Giant Farmer Company described in Problem 16. Management is considering a third site, at Memphis. The shipping costs per case from Memphis are $3 to Miami, $11 to Denver, $6 to Lincoln, and $5 to Jackson. Find the minimum cost plan for an alternative plant in Memphis. Would this result change the decision in Problem 16?

18. **[D]** The Thor International Company operates four factories that ship products to five warehouses. The shipping costs, requirements, and capacities are shown in Figure 13.15. Use the transportation method to find the shipping schedule that minimizes shipping cost.

Factory	Shipping Cost per Case to each Warehouse						Capacity
	W1	W2	W3	W4	W5	Dummy	
F1	$2	$3	$3	$2	$6	$0	50,000
F2	$2	$3	$2	$4	$5	$0	80,000
F3	$4	$2	$4	$2	$3	$0	80,000
F4	$3	$4	$4	$5	$2	$0	40,000
Demand	45,000	30,000	30,000	35,000	50,000	60,000	250,000

▲ **FIGURE 13.15**
Transportation Tableau for Thor International

19. **[D]** Consider further the Thor International Company situation described in Problem 18. Thor decides to close F4 because of high operating costs. The logistics manager is worried about the effect of this move on transportation costs. Currently, F4 is shipping 40,000 units to W5 at a cost of $80,000 [or 40,000($2)]. If this warehouse were to be served by F1 (currently not being used), the cost would increase to $240,000 [or 40,000(6)]. As a result, the logistics manager requests a budget increase of $160,000 (or $240,000 – $80,000).

a. Should the logistics manager get the budget increase?

b. If not, how much would you budget for the increase in shipping costs?

20. **[D]** Balaji Limited manufactures and markets spare parts for agricultural machineries, which it stocks in various warehouses throughout the country. Most of the machineries it supports are reaching the end of their warranty periods and the company is expecting an increase in demand for spare parts. Its market research group compiled a forecast indicating an additional demand of 20,000 units. The company has decided to satisfy this demand by constructing new plant capacity. Balaji already has plants in Chennai and Delhi and has no desire to relocate those facilities. Each plant is capable of producing 690,000 units per year.

After a thorough search, the company has been presented with two alternatives. Alternative 1 is to build a plant in Coimbatore that can fulfil all additional demand. Alternative 2 is to split the demand by building two plants at two locations: Coimbatore and Bangalore. The company's warehouses distribute the product to retailers. The market research study provided the following data.

Warehouse	Expected Annual Demand
Srinagar	100,000
Bhopal	450,000
Hyderabad	750,000
Madurai	800,000

The logistics department compiled the following cost table specifying the cost per unit to ship the product from each plant to each warehouse in the most economical manner, subject to the reliability of the various carriers involved.

Plant	Warehouse			
	Srinagar	Bhopal	Hyderabad	Madurai
Chennai	₹40	₹33	₹35	₹32
Delhi	₹37	₹37	₹39	₹40
Coimbatore (alternative 1)	₹41	₹38	₹35	₹32
Bangalore (alternative 2)	₹40	₹38	₹35	₹35

As one part of the location decision, management wants an estimate of the total distribution cost for each alternative. Use the transportation method to calculate these estimates.

A Systematic Location Selection Process

21. Calculate the weighted score for each location (A, B, C, and D) shown in Table 13.6. Which location would you recommend?

TABLE 13.6 | FACTORS FOR LOCATIONS A–D

		Factor Score for Each Location			
Location Factor	**Factor Weight**	**A**	**B**	**C**	**D**
1. Labor climate	5	5	4	3	5
2. Quality of life	30	2	3	5	1
3. Transportation system	5	3	4	3	5
4. Proximity to markets	25	5	3	4	4
5. Proximity to materials	5	3	2	3	5
6. Taxes	15	2	5	5	4
7. Utilities	15	5	4	2	1
Total	100				

22. Wang Lei and Li Mei Cai are newlyweds trying to decide among several available rentals. Alternatives were scored on a scale of 1 to 5 (5 = best) against weighted performance criteria, as shown in Table 13.7. The criteria included rent, proximity to work and recreational opportunities, security, and other neighborhood characteristics associated with the couple's values and lifestyle. Alternative A is an apartment, B is a bungalow, C is a condo, and D is a downstairs apartment in Li Mei's parents' home.

Which location is indicated by the preference matrix? What qualitative factors might cause this preference to change?

TABLE 13.7 | FACTORS FOR NEWLYWEDS

		Factor Score for Each Location			
Location Factor	**Factor Weight**	**A**	**B**	**C**	**D**
1. Rent	25	3	1	2	5
2. Quality of life	20	2	5	5	4
3. Schools	5	3	5	3	1
4. Proximity to work	10	5	3	4	3
5. Proximity to recreation	15	4	4	5	2
6. Neighborhood security	15	2	4	4	4
7. Utilities	10	4	2	3	5
Total	100				

23. Wagner Remodelers Inc. is looking for a new city in which to relocate its home remodeling business. The company employs highly skilled craftspeople who rehabilitate old housing. Most of their current craftspeople will relocate with the company; however, additional workers at the new location will be hired. The most important location factors for the company were weighted, and three target cities were scored against these factors.

		Factor Score for Each City		
Location Factor	**Factor Weight**	**Coptic**	**Sparta**	**Royce**
1. Proximity to run-down housing stock	15	3	5	1
2. Community population size	15	3	5	5
3. Proximity to the sources of building materials	5	5	5	5
4. Transportation infrastructure	5	5	1	5
5. Availability of skilled workers	10	5	2	5
6. Favorable zoning processes	15	5	5	5
7. Low city property tax rates	5	5	3	3
8. Availability of excellent primary education	5	3	1	5
9. Availability of family entertainment	5	3	1	5
10. Attitude of community to building rehabilitation	10	2	3	3
11. Proximity to real estate sales firms	10	2	5	5
Total	100			

a. Which location is indicated by the preference matrix?

b. Would the best location change if the company decided not to relocate any of its current craftspeople but instead hired only from the population at its new location? Assume that factors 8 and 9 are now given no weight and factor 5 is twice as important.

24. Silky Industries is looking for a location for its second telephone remanufacturing facility. Two cities are under consideration. The two most important location factors are Factor A, "availability of resources," and Factor B, "availability of customers." However, the company is having great difficulty assigning relative weights to these factors.

Location Factor	**Factor Weight**	**Factor Score for Each City**	
		Blake	**Irmo**
A. Availability of resources		5	6
B. Availability of customers		10	7
Total	100		

Assuming that the factor weights must sum to 100, what range of weights would make Blake the superior location?

Active Model Exercise

Active Model 13.1 is available online. It allows you to find the location that minimizes the total load–distance score.

QUESTIONS

1. What is the total load–distance score to the new HealthWatch medical facility if it is located at the center of gravity?
2. Fix the *y*-coordinate, and use the scroll bar to modify the *x*-coordinate. Can you reduce the total load–distance score?
3. Fix the *x*-coordinate, and use the scroll bar to modify the *y*-coordinate. Can you reduce the total load–distance score?
4. The center of gravity does not necessarily find the site with the minimum total load–distance score. Use both scroll bars to move the trial location, and see whether you can improve (lower) the total load–distance score.

CASE R.U. Reddie for Location

The R.U. Reddie Corporation, located in Chicago, manufactures clothing specially designed for stuffed cartoon animals such as Snoopy and Wile E. Coyote. Among the popular products are a wedding tuxedo for Snoopy and a flak jacket for Wile E. Coyote.

For many sales, the company relies upon the help of incorrigible children who refuse to leave the toy store until their parents purchase a wardrobe for their stuffed toys. Rhonda Ulysses Reddie, owner of the company, is concerned over the market projections that indicate demand for the product is substantially greater than current plant capacity. The "most likely" projections indicate that the company will be short by 400,000 units next year, and thereafter 700,000 units annually. As such, Rhonda is considering opening a new plant to produce additional units.

Background

The R.U. Reddie Corporation currently has three plants located in Boston, Cleveland, and Chicago. The company's first plant was the Chicago location, but as sales grew in the Midwest and Northeast, the Cleveland and Boston plants were built in short order. As the demand for wardrobes for stuffed animals moved west, warehouse centers were opened in St. Louis and Denver. The capacities of the three plants were increased to accommodate the demand. Each plant has its own warehouse to satisfy demands in its own area. Extra capacity was used to ship the product to St. Louis or Denver.

The new long-term forecasts provided by the sales department contain both good news and bad news. The added revenues will certainly help Rhonda's profitability, but the company would have to buy another plant to realize the added profits. Space is not available at the existing plants, and the benefits of the new technology for manufacturing stuffed animal wardrobes are tantalizing. These factors motivate the search for the best location for a new plant. Rhonda identifies Denver and St. Louis as possible locations.

Rhonda's Concerns

A plant addition is a big decision. Rhonda has started to think about the net present value of each alternative, as it will be an important factor in making the final decision. She also wanted to take into account the nonquantifiable factors. First, the availability of a good workforce is much better in Denver than St. Louis because of the recent shutdown of a Beanie Baby factory. The labor market is much tighter in St. Louis and the prognosis is for continued short supply in the foreseeable future. Second, the Denver metropolitan area just instituted strict environmental regulations. Rhonda's new plant would adhere to existing laws, but the area is highly environmentally conscious, and more regulations may be coming in the future. It is costly to modify a plant once operations begin. Finally, Denver has a number of good suppliers with the capability to assist in production design (new wardrobe fashions). St. Louis also has suppliers, but they cannot help with product development. Proximity to suppliers with product development capability is a "plus" for this industry.

Data

The following data have been gathered for Rhonda:

1. The per-unit shipping cost based on the average ton-mile rates for the most efficient carriers is $0.0005 per mile. The average revenue per outfit is $8.00.
2. The company currently has the following capacity (in thousands) constraints:

	Capacity
Boston	400
Cleveland	400
Chicago	500

3. Data concerning the various locations are found in Table 13.8.
4. New plant information:

Alternative	Building and Equipment[1,2]	Annual Fixed Costs (SGA)[1,3]	Variable Production Costs/Unit	Land[1]
Denver	$12,100	$550	$3.15	$1,200
St. Louis	$10,800	$750	$3.05	$800

[1]Figures are given in thousands.

[2]Net book value of plant and equipment with remaining depreciable life of 10 years.

[3]Annual fixed costs do not include depreciation on plant and equipment.

TABLE 13.8 | LOCATION DATA FOR R.U. REDDIE

City	Most Likely Demand First Year[1]	Most Likely Demand After Years 2–10[1]	Current Costs, Building and Equipment[1,2]	Annual Fixed Costs (SGA)[1,3]	Variable Production Costs/Unit	Land[1]
Boston	80	140	$9,500	$600	$3.80	$500
Cleveland	200	260	$7,700	$300	$3.00	$400
Chicago	370	430	$8,600	$400	$3.25	$600
St. Louis	440	500				
Denver	610	670				

[1]Figures are given in thousands.

[2]Net book value of plant and equipment with remaining depreciable life of 10 years.

[3]Annual fixed costs do not include depreciation on plant and equipment.

5. The road mileage between the cities is as follows:

	Boston	Cleveland	Chicago	St. Louis	Denver
Boston	—	650	1,000	1,200	2,000
Cleveland		—	350	600	1,400
Chicago			—	300	1,000
St. Louis				—	850
Denver					—

6. Basic assumptions you should follow:

- Terminal value (in 10 years) of the new investment is 50 percent of plant, equipment, and land cost.
- The tax rate is 40 percent.
- Straight-line depreciation is used for all assets over a 10-year life.
- R.U. Reddie is a 100 percent equity company with all equity financing and a weighted average cost of capital (WACC) of 11 percent.
- Capacity of the new plant production for the first year will be 500 (000) units.
- Capacity of the new plant production thereafter will be 900 (000) units.
- Cost of goods sold (COGS) equals variable costs of production plus total transportation costs.
- Costs to ship from a plant to its own warehouse are zero; however, variable production costs are applicable.

7. R.U. Reddie operations and logistics managers determined the shipping plan and cost of goods sold for the option of *not* building a new plant and simply using the existing capacities to their fullest extent (status quo solution).

Year 1	COGS = $4,692,000
Boston to Boston	80
Boston to St. Louis	320
Cleveland to Chicago	80
Cleveland to Cleveland	200
Cleveland to St. Louis	120
Chicago to Chicago	290
Chicago to Denver	210

Years 2–10	COGS = $4,554,000
Boston to Boston	140
Boston to St. Louis	260
Cleveland to Cleveland	260
Cleveland to St. Louis	140
Chicago to Chicago	430
Chicago to St. Louis	70

QUESTIONS

Your team has been asked to determine whether R.U. Reddie should build a new plant and, if so, where it should be located.

1. Write a memo from your team to R.U. Reddie indicating your recommendation and a brief overview of the supporting evidence.
2. Use the transportation method for location problems and POM for Windows to find the optimal distribution pattern and the cost of goods sold for both the Denver and St. Louis alternatives. First solve the problem with Denver as the new plant and then do the same for St. Louis. The unit costs for each cell of the transportation matrix should be the sum of the shipping costs and the variable costs of production. For example, the unit costs for producing and shipping a unit from Denver to Boston would be $3.15 + $0.0005(2,000) = $4.15. Use Figures 13.4 and 13.5 as guides in your formulation. The "optimal cost" in each case will be the cost of goods sold.
3. Compute the NPV of each alternative. Use the results from the transportation models for the COGS for each alternative. (*Hint:* Your analysis will be simplified if you think in terms of incremental cash flows.) Create an easy-to-read spreadsheet for each alternative.

Addendum

Here are some hints for your analysis.

1. Define your variables to be "thousands of units shipped," and omit the three zeroes after each demand and capacity value. Then remember to multiply your final decisions and total variable costs by a thousand after you get your solution from the model.
2. Because the capacity and demand changes from year 1 to year 2, you need to run your model twice for each location to get the necessary data.

VIDEO CASE Continental Tire: Pursuing a Winning Plant Decision

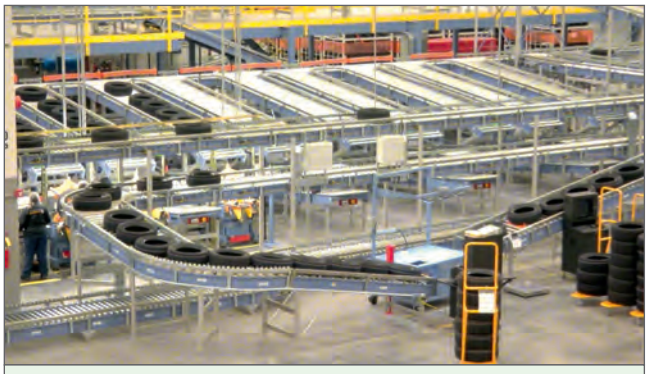
As the world's largest automotive company and fourth-largest tire manufacturer, Continental's global business operations cover a diverse set of enterprises. Perhaps best known for its passenger and light truck tires, this sector of the Hanover, Germany–based company's total tire activities only make up about 30 percent of total revenues, which topped 33 billion euro ($44.5 billion USD) in 2013. The rest comes from chassis and safety equipment, powertrain, interior systems such as infotainment and navigation, and its ContiTech division that produces marine hoses, conveyer belts, vehicle springs, and other automotive hoses and trim components. With over 300 manufacturing sites in 49 countries, the company recently undertook an ambitious $500 million project to build a new passenger and light truck (PLT) tire plant near its customers in the United States and Canada.

While the decision at hand focused on locating a single facility, it is a decision that was affected by Continental's existing U.S.-based manufacturing plants in Mount Vernon, Illinois, and other plants in Mexico, Europe, and Latin America. Plants in the network operate independently of one another, yet may share raw materials sources and customers such as Walmart or Ford Motor Company. The existing network of warehouses and distribution centers located within the United States to handle the distribution needs had to be considered. Of particular concern was the cost of labor in the production of tires, which led senior management to direct Scott Barnette, central controller of the Americas–Finance, to analyze two potential locations with perceived low labor costs: Mexico and Costa Rica.

Scott was well aware that three of Continental's four core values—trust, passion to win, and freedom to act—empowered him to explore beyond the locations initially favored by the company. The fourth core value, "for one another," that encompasses teamwork also played a role. So, when he suggested adding a potential location in the United States to the list that might meet or exceed established internal rate of return hurdles, he was instructed to go ahead, but to continue with a primary focus on Mexico and Costa Rica.

In 2011, Scott began gathering all the necessary data to incorporate into his linear programming optimization software program. This program was designed to analyze all costs, called "landed costs" at Continental, which covered the entire stream from raw materials through to the customer, not just production costs at the plant. Approaches used in the past focused more on production costs than landed costs. Raw materials include natural rubber from Asia, synthetic rubber from Germany and Japan, textiles from Georgia and Asia, steel from Asia and domestic sources, chemicals from numerous global sources, and carbon black—the powdered petroleum processing by-product that makes tires black and helps enhance durability. Continental is not a vertically integrated enterprise, so all materials must be procured from these global sources.

The seven groups of factors that dominate manufacturing plant location decisions, as noted in this text, were all present for Continental. Prior to construction of the new plant, Continental had been importing tires for the U.S. and Canadian markets from Europe and Asia. The initial production output from the new plant would be 4 million tires annually to meet this demand. Company estimates for growth in domestic demand placed the need for an additional 4 million units per year from this plant, so Scott made sure the company's location choice had adequate room for expansion. Additional acreage at the plant site with ample energy access was critical. The remaining global demand of 22 million units would be handled by plants in Illinois, Brazil, Europe, India, and China, near to those markets.



Pearson Education

Using state-of-the-art technology, Continental Tire makes 4 million tires annually at its new Sumter, South Carolina, manufacturing facility. The $500 million investment created nearly 1,600 new jobs and greatly enhanced the economy of South Carolina.

In a typical location decision, most organizations create 5-year models to fully understand the impact of their choices. After all, locating a physical plant is a huge investment intended to span decades of operations. For Scott and Continental, a 20-year model was created. With a plan to invest up to $500 million and create close to 1,600 jobs, Scott wanted to be sure the effect of any midterm, location-specific community incentives such as real estate, tax, and other breaks wouldn't cloud the long-term cash and profitability picture.

After considering both the Mexican and Costa Rican sites, 12 U.S. locations were scoped, and eventually narrowed down to South Carolina. The state had a history of stable business, manufacturing experience, low manufacturing costs, an international influence, a proactive business approach, and a solid logistics infrastructure with both the Port of Charleston and major highways nearby. The chosen site near Sumter, South Carolina, also had a small but experienced manufacturing population of approximately 60,000 people who could immediately benefit from the new plant's investment.

After considering Scott's analysis, Continental awarded Sumter the plant and broke ground in March 2012. It took an average of 300 people over 626,000 hours to complete the construction. Operations started in late October 2013, and full ramp-up and expansion are expected to run through 2021. It's now the largest land site for manufacturing of any kind in the world for the company. When company officials were asked what the intended use was for the sizeable plot of land they purchased, they simply smiled and responded, "We have big plans, and we are not constructing a golf course."

QUESTIONS

1. Consider the dominant factors for manufacturing as described in the text. Briefly describe how each one may have influenced Continental's decision to locate its new plant in Sumter, South Carolina, instead of Mexico or Costa Rica.
2. South Carolina is also home to manufacturing plants for major tire competitors Michelin and Bridgestone. How might these two plants factor into the company's location decision?
3. Explain why locating a plant solely on the basis of low labor costs may be the wrong approach.

14 SUPPLY CHAIN INTEGRATION

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

14.1 Identify the major causes of disruptions in a supply chain.

14.2 Explain how firms can mitigate the operational, financial, and security risks in a supply chain.

14.3 Describe how cloud computing and blockchains can be used to integrate supply chains.

14.4 Describe the four major nested processes in the new service or product development process.

14.5 Explain the five major nested processes in the supplier relationship process and use total cost analysis and preference matrices to identify appropriate sources of supply.

14.6 Identify the four major nested processes in the order fulfillment process and use the expected value decision rule to determine the appropriate capacity of logistic resources.

14.7 Define the three major nested processes in the customer relationship process.

Oasis of the Seas



Solarisys/Shutterstock

The Oasis of the Seas, one of the largest passenger ships ever constructed, visits many popular destinations in the Caribbean. Here, passengers disembark in Labadee, Haiti.

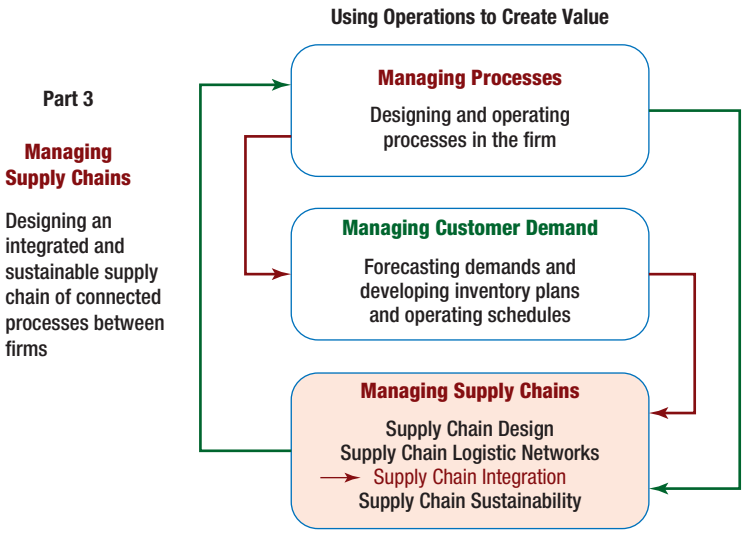
Regardless of where you are right now, or what the weather is like in your hometown, think of lounging on the deck of Royal Caribbean's *Oasis of the Seas* somewhere in the Caribbean. The view is gorgeous, the breezes soft and cool; you find it difficult to contemplate that you and 6,000 other guests are in a large floating hotel with amenities that range from a movie theater to a casino with every game of chance a gambler ever wanted. There are three swimming pools, a park with 12,175 plants and 56 trees all open to the sky, and 11 bars and night clubs to entertain guests into the wee hours of the morning.

While all those amenities may sound good, there is one thing that most cruise liner guests look forward to—and that is dining. There are 19 restaurants on board the *Oasis*, offering everything from top-quality dry-aged steaks to on-the-run hot dogs to edamame-stuffed portobello mushrooms. When the meals arrive in front of you, have you ever wondered how the food got there? The supply of food, and its preparation, puts a tremendous strain on the coordination of supply chain processes for the *Oasis*, especially with 6,000 guests and 2,100 crew members onboard. Here, 4 days at sea, the hotel manager just cannot call the suppliers and say that he forgot the carrots, the butter, and the sugar. Running out of stock is not an acceptable option. Pure volume is a complicating factor. For example, on an average 7-day cruise, the *Oasis* will use 46,800 eggs, 5,400 lobsters, 15,000 pounds of potatoes, 9,000 pounds of tomatoes, 19,723 pounds of chicken, 7,070 pounds of fish, and 18,314 pounds of beef, plus much more. The galley employees prepare between 28,000 and 30,000 meals daily, all washed down with 6,000 bottles of wine and 32,800 bottles or cans of beer a cruise. Not everything is purchased, nor can all that food be stored on board at one time. Certain items such as ice cream, dessert pastries, and breads are produced onboard to ensure their freshness. Other items must be restocked at selected ports on a schedule put in place long in advance of the cruise. Not all the islands visited along the cruise have the quality, or quantity, of supplies to meet the needs of the ship. This fact places a high burden on coordination between Royal Caribbean and suppliers. While the guests are enjoying a port of call, the ship personnel are restocking the hold with food from suppliers in that area that have been proven to supply the best quality. Cruise ships must be very careful not to accept food that will cause sickness onboard.

Even a well-oiled wagon can run off the road, and so it can with the supply chain of a cruise ship. Good planning, including contingency plans, and quick reactions are desirable attributes. Natural disasters, such as hurricanes, earthquakes, or epidemics, can cause cruise ships to reschedule their ports of call, which can disrupt the scheduled supply of food, boutique items, hotel supplies, and maintenance items. The coronavirus pandemic of 2020 hit the cruise ship industry especially hard. Some ships that were out to sea when the crisis hit could not find a port to disembark their passengers and had to anchor at sea until receiving clearance to enter the port. Obviously, all supplies, especially medical supplies, experienced shortages and required immediate attention. In times of crisis, close coordination up and down the supply chain is required.

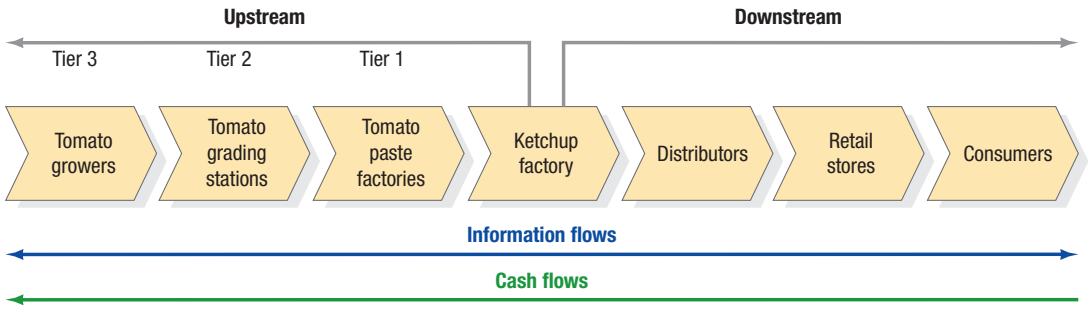
Cruise ships strive to provide the best possible experience for their guests. High levels of supply chain integration across multiple commodity groups and suppliers, as well as numerous ordering, delivery, and stocking points, are at the heart of that effort.[1]

The development and delivery of services and products has become increasingly complex in today's global economy. We have already discussed the strategic design of supply chains and logistics networks; however, there is a critical piece of the puzzle that still needs to be addressed: coordination. The *Oasis of the Seas*, one of several cruise liners owned and operated by Royal Caribbean Line, is an example of how a firm can excel at coordinating its supply chain for competitive advantage. To be effective, accurate inventory and demand information has to be available combined with considerable collaboration between the ship and its suppliers along the cruise itinerary. The Royal Caribbean Line is successful at **supply chain integration**, which is the effective coordination of supply chain processes through the seamless flow of information up and down the supply chain. Supply chain integration provides each member of the supply chain visibility into the capacities and inventories of other members of the supply chain to aid in planning and scheduling. It facilitates collaboration between firms in a supply chain; in effect, it is an enabler of supply chain management and is at the core of reducing the risks of supply disruption.



supply chain integration
The effective coordination of supply chain processes through the seamless flow of information up and down the supply chain.

Supply chain integration involves internal as well as external processes. Figure 14.1 shows just how interconnected processes and firms in a supply chain can be. Think of a supply chain as a river that flows from raw material suppliers to consumers. For example, a ketchup factory gets its major supply from the tomato paste factories, which for the ketchup factory is a tier 1 supplier. In turn, the tomato paste factories get their major supplies from the tomato grading stations, which are tier 2 suppliers of the ketchup factory. Finally, the tomato growers ship their product directly to the tomato grading stations. The tier 1, tier 2, and tier 3 suppliers are all *upstream* from the ketchup factory, which means that they control the flow of supply to the ketchup factory. Suppose the tomato paste factory has a major process failure. The flow of tomato paste to the ketchup factory would dwindle to a trickle, as if someone built a dam across a river. Indeed, even those entities *downstream* from the ketchup factory could feel the effects after inventories of ketchup have been consumed. When a link in the supply chain fails, whether it is an internal process or one at a supplier, the rest of the chain feels the effects.



◀ **FIGURE 14.1**
Supply Chain for a Ketchup Factory

[1] *Sources*: Jad Mouawad, "A Luxury Liner Docks, and the Countdown's On," *The New York Times*, https://www.nytimes.com/2015/03/22/business/a-luxury-liner-docks-and-the-countdowns-on.html (March 21, 2015); David Fiske, "You Won't Believe the Size of the Food Order for the Oasis of the Seas!" Reasons to Cruise, https://www.reasonstocruise.com/oasis-seas-food-drink/ (July 5, 2020); Scott Mayerowitz, "What It Takes to Stock a Cruise Ship: 10,680 Hot Dogs and a Boatload of Wine," Associated Press, https://mashable.com/2016/02/26/cruise-ship-food/ (February 26, 2016).

Mitigating the effects of supply chain disruptions is an important benefit of supply chain integration. Information flows, both upstream and downstream, provide visibility to supply chain members regarding supplies, capacities, and plans. Cash flows move upstream and are affected by pricing, promotional programs, supply contracts, and exchange rates. Every supply chain faces an undeniable risk in operational disruptions, security failures, and financial performance. Understanding the implications of these disruptions for supply chain performance is important for all employees in an organization.

In the first half of this chapter, we address the need for supply chain integration and the technologies that can be used to accomplish it. In the second half, we explore the four major processes that are instrumental in developing and producing a service or product and how they are integrated internally and externally.

Supply Chain Disruptions

When a company expands from a local or regional presence to a more global one, supply chain strategy often needs to be adjusted. In a global arena, different products are directed to more diverse customers via different distribution channels, which require different supply chains. These supply chains are typically more complex and are exposed to both domestic and international disruptions. In this section, we identify the causes of supply chain disruptions, discuss how they cause supply chain dynamics, and show how supply chain integration can mitigate those effects.

Causes of Supply Chain Disruptions

Supply chain disruptions could result in cost increases, loss of reputation, civil and criminal penalties, bankruptcy, lost customers, or reduced revenue, profit, and market share. The more complex the supply chain, the less predictable the likelihood and the impact of a disruption, and the greater the risk to the effectiveness of the supply chain. Disruptions can emanate from outside the firm as well as inside the firm.



Philip Scalia/Alamy Stock Photo

The Kinzua Viaduct Bridge in northwest Pennsylvania, constructed in 1882, was the longest railroad bridge in the world, spanning 2,053 feet and reaching a maximum height of 301 feet. It facilitated the flow of raw materials from the east to the Great Lakes regions. The trestle bridge was destroyed by a tornado in 2003. It takes reminders such as this to highlight the importance of integrated supply chains to avoid disrupting the flow of products and supplies.

External Causes A firm has the least amount of control over its external customers and suppliers, who can periodically cause disruptions. Typical external disruptions include the following:

- *Environmental Disruptions.* Natural disasters, terrorism, political instability or war affecting supplier operations, regulatory changes, quotas, strikes, and epidemics, as with the 2020 coronavirus pandemic, all can disrupt the normal flow of materials and services in a supply chain.
- *Supply Chain Complexity.* Increases in the dependencies between supply chain entities (suppliers, partners, and customers), increases in the number of supply chain entities, and changes in the configuration of the extended supply chain (the suppliers to suppliers) all have the potential to cause disruptions in the supply of materials, products, and services.
- *Loss of Major Accounts.* A loss of significant demand volume is the result of losing a large customer. This disruption is compounded when the firm has a concentrated customer base.
- *Loss of Supply.* Losing the supply of key materials or services can slow or even stop the operations in a supply chain. Downtime due to equipment failures or quality issues is a common cause. This disruption is amplified if the firm is too consolidated in its supply markets.
- *Customer-Induced Volume Changes.* Customers may change the quantity of a customized service or product they had ordered for a specific date or they may unexpectedly demand more of a standard service or product, which can happen if they think the manufacturer will ration the limited supply of a product to all customers demanding it based on the quantities ordered. If the market demands short lead times, the firm needs a quick reaction from its suppliers.

- *Service and Product Mix Changes.* Customers may change the mix of items in an order and cause a ripple effect throughout the supply chain. For example, a major appliance store chain may change the mix of washing machines in its orders from 60 percent Whirlpool brand and 40 percent Kitchen Aid brand to 40 percent Whirlpool and 60 percent Kitchen Aid. This decision changes the production schedule of the Whirlpool plant that makes both brands, causing imbalances in its inventories. In addition, the tier 1 supplier that makes the face plates for the washing machines must change its schedules, thereby affecting *its* suppliers.
- *Late Deliveries.* Late deliveries of materials or delays in essential services can force a firm to switch its schedule from production of one product model to another. Firms that supply model-specific items may have their schedules disrupted. For example, the Whirlpool plant may find that a component supplier for its Model A washing machine could not supply the part on time. To avoid shutting down the assembly line, which is an expensive action, Whirlpool may decide to switch to Model B production. Suddenly, the demand on the suppliers of Model B–specific parts increases.
- *Underfilled Shipments.* Suppliers that send partial shipments do so because of disruptions at their own plants. The effects of underfilled shipments are similar to those of late shipments, unless the underfilled shipment contains enough materials to allow the firm to operate until the next shipment.

Internal Causes A firm's own operations can be the culprit in what becomes the source of constant disruption in the supply chain. Typical internal disruptions include the following:

- *Internally Generated Shortages.* A shortage of parts manufactured by a firm may occur because of machine breakdowns, lengthy setup times, limited capacity and bottlenecks, or inexperienced workers. Internal shortages can cause a change in the firm's production schedule, thus affecting suppliers.
- *Quality Failures.* Product recalls, such as the record number of automobiles recalled by General Motors in 2013 and 2014, can cause huge costs and supply chain disruptions. Even if quality failures do not involve product recalls, they restrict the flow of services or products and negatively affect the performance of the supply chain.
- *Poor Supply Chain Visibility.* The inability to "see" the inventories and capabilities of suppliers and the inventories of customers, as well as the pipeline of materials and products, poses a risk to the performance of a firm. Often this risk arises because of a lack of collaborative planning and forecasting (see Chapter 8, "Forecasting").
- *Engineering Changes.* Changes to the design of services or products can have a direct impact on suppliers. For example, a major fast-food restaurant switching from Styrofoam packaging to biodegradable packaging for its sandwiches will affect the demand experienced by the suppliers of Styrofoam.
- *Order Batching.* Suppliers may offer a quantity discount, which gives an incentive to firms to purchase large quantities of an item less frequently, thereby raising the variability in orders to the supplier. Order batching may also result in transportation economies; larger orders may enable full-truckload shipments, thereby reducing the cost to ship materials but creating more variability in the supply chain.
- *New Service or Product Introductions.* A firm decides on the number of new service or product introductions, as well as their timing, and hence introduces a dynamic in the supply chain. New services or products may even require a new supply chain or the addition of new members to an existing supply chain. The more complex a service or product is, the greater is the risk of a disruption.
- *Service or Product Promotions.* A common practice of firms producing standardized services or products is to use price discounts to promote sales. Price discounting creates a spike in demand that is felt throughout the supply chain.
- *Information Errors.* Demand forecast errors can cause a firm to order too many or too few services and materials or can precipitate expedited orders that force suppliers to react more quickly to avoid shortages in the supply chain. In addition, errors in the physical count of items in stock can cause shortages (leading to panic purchases) or too much inventory (leading to a slowdown in purchases). Finally, communication links between buyers and suppliers can be faulty.

Supply Chain Dynamics

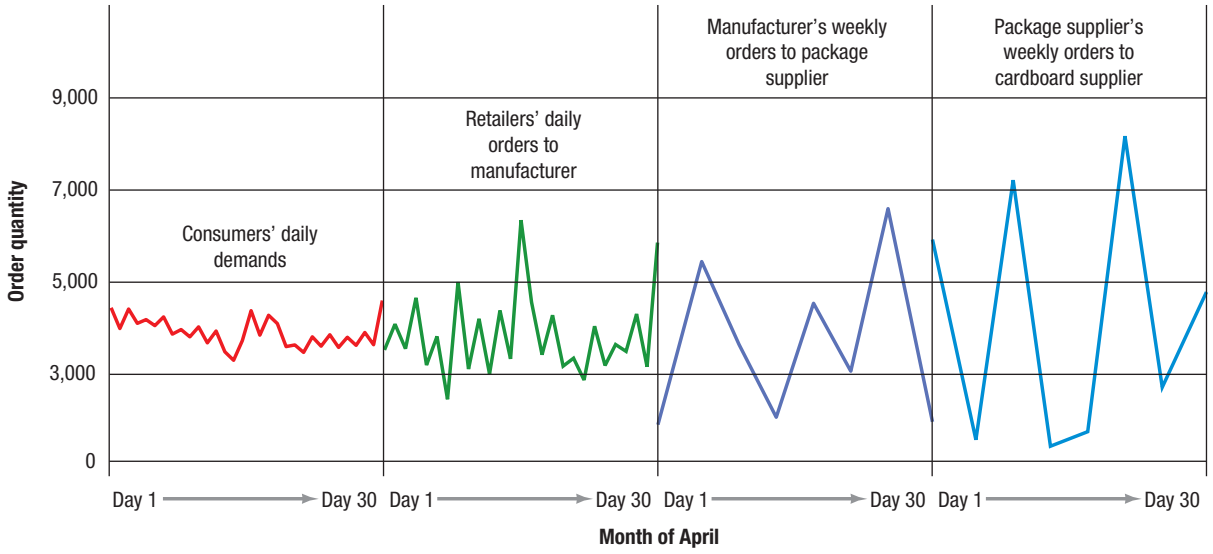
Why do these disruptions pose a risk to supply chain operations? Each firm in a supply chain depends on other firms for services, materials, or the information needed to supply its immediate external customer in the chain. Because firms are typically owned and managed independently, the actions of downstream supply chain members (positioned nearer the end user of the service or product) can affect the operations of upstream members. The reason is that upstream members

of a supply chain must react to the demands placed on them by downstream members of the chain. These demands are a function of the policies downstream firms have for replenishing their inventories, the actual levels of those inventories, the demands of their customers, and the accuracy of the information they have to work with. As you examine the order patterns of firms in a supply chain, you will frequently see the variability in order quantities increase as you proceed upstream. This increase in variability is referred to as the **bullwhip effect**, which gets its name from the action of a bullwhip—the handle of the whip initiates the action; however, the tip of the whip experiences the wildest action. The slightest change in customer demands can ripple through the entire chain, with each member receiving more variability in demands from the member immediately downstream. A firm contributes to the bullwhip effect if the variability of the orders to its suppliers exceeds the variability of the orders from its immediate customers.

bullwhip effect
The phenomenon in supply chains whereby ordering patterns experience increasing variance as you proceed upstream in the chain.

Figure 14.2 shows the bullwhip effect in a supply chain for facial tissue. The variability in the orders increases as you go upstream in the supply chain. Because supply patterns do not match demand patterns, inventories accumulate in some firms and shortages occur in others. The firms with too much inventory stop ordering, and those that have shortages place expedited orders.

FIGURE 14.2 ▼
Supply Chain Dynamics for Facial Tissue

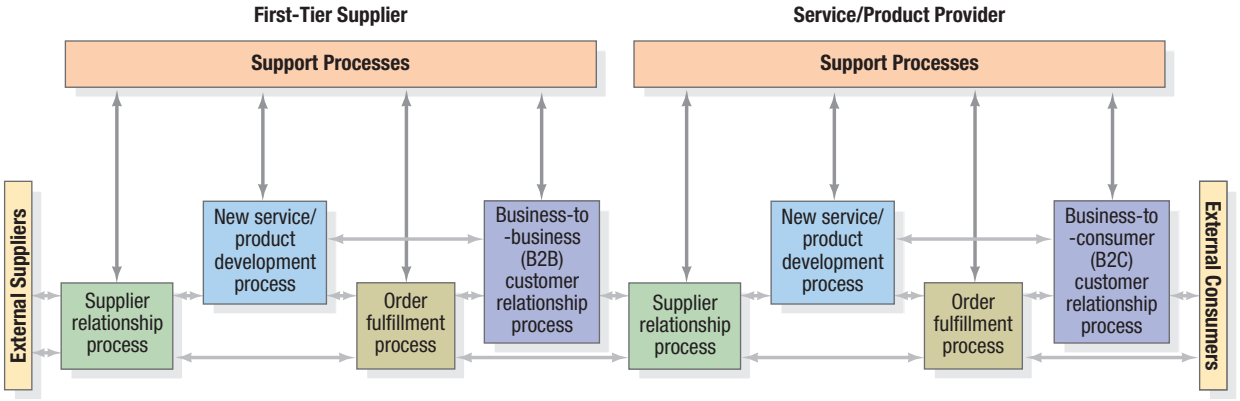


Integrated Supply Chains

Regardless of the supply chain design, minimizing supply chain disruptions begins with a high degree of functional and organizational integration. Such integration does not happen overnight; it must include linkages between the firm and its suppliers and customers, as shown in Figure 14.3. The new service or product development, supplier relationship, order fulfillment, and customer relationship processes, as well as their internal and external linkages, are integrated into the normal business routine. The firm takes on a customer orientation. However, rather than merely reacting to customer demand, the firm strives to work with its customers and suppliers so that everyone benefits from improved flows of services, materials, and information. The firm must also develop a better understanding of its suppliers' organizations, capacities, strengths, and weaknesses—and include its suppliers earlier into the design of new services or products.

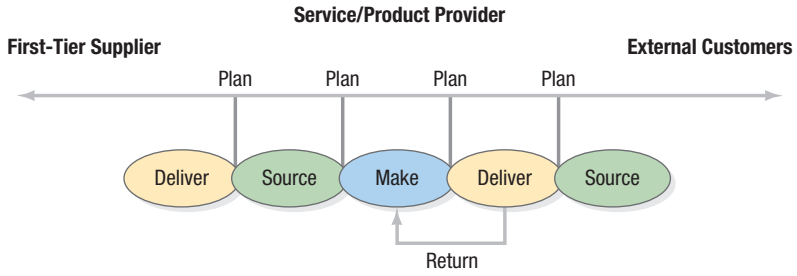
Another integrative frame of reference is the *supply chain operations reference model*, known as *SCOR*, developed by the Supply Chain Council with the assistance of 70 of the world's

FIGURE 14.3 ▼
External Supply Chain Linkages



leading manufacturing companies. Figure 14.4 shows that the **SCOR model** focuses on a basic supply chain of *plan*, *source*, *make*, *deliver*, and *return* processes, repeated again and again along the supply chain. The return processes handle the return of recyclable materials and defective products, which we will discuss in more detail in Chapter 15, "Supply Chain Sustainability." Much like our model shown in Figure 14.3, the SCOR model emphasizes that the design of an integrated supply chain is complex and requires a *process view*. We already provided some key insights into process design decisions in Parts 1 and 2 of the text. These insights must be applied to the new service or product development, supplier relationship, order fulfillment, and customer relationship processes. Beyond that, these processes need to be integrated both within a firm and across the supply chain. It is important to know that an integrated supply chain, implied by Figure 14.3 and the SCOR model in Figure 14.4, provides a framework for the operating decisions in a firm and that these processes play a major role.

SCOR model
A framework that focuses on a basic supply chain of plan, source, make, deliver, and return processes, repeated again and again along the supply chain.



◀ **FIGURE 14.4**
SCOR Model

Integrating the processes in a supply chain, upstream, downstream, and internally, involves a cross-functional effort, as the following Managerial Challenge shows.

MANAGERIAL CHALLENGE Information Technology

Food supply chains can be complex to manage, as Yasmita Apte, director of information technology for Crestview Food, Inc., knows. An enormous amount of information flows up and down the supply chain every second, and she is responsible for ensuring that it is accurate and it gets to where it needs to be on a timely basis. Crestview Food has 390 retail supermarkets in five midwestern states, with $5B in annual sales. The retail stores get their food products from four contracted distribution centers, who get their products, such as produce, staples, dairy, and bakery, from thousands of suppliers, making for a very complicated supply chain. This morning, Jake Alward, COO, called an emergency meeting with Agnes Wright, purchasing manager; Jevonte James, fulfilment manager; and Yasmita. Jake began by saying that most of the stores were experiencing severe stock outages in staple items and in some cases poor quality in the vegetables and dairy products. Customers were getting vocal in their complaints. Agnes chimed in and said that the areas hit particularly hard by shortages are the cleaning products, paper products, and bottled juices. Last year Crestview had an overstock of those items and literally gave them away with promotional pricing. However, this year demand has increased. She has already increased her order quantities to the distributor with an expedite status. So far it hasn't helped. Jevonte cautioned the group about jumping to conclusions regarding the distributors. The distributors get products from the suppliers, who get materials from their suppliers, and so on. Big unexpected increases in order quantities cause capacity shortages in the entire supply chain. He has been getting complaints from several distributors and a number of suppliers that they need more forward visibility into Crestview Food's purchasing plans. In general, the message is clear: The entire distribution channel wants better coordination from top to bottom. After all of the group had their say, there was a pause, and all heads turned toward Yasmita.

It was clear to Yasmita that Jake and the others were looking to her for a solution. The complaints focused on information flows. She already had systems in place that connected with the distributors. However, the suppliers, and their suppliers, were a black box. Crestview Food had no idea about supply problems upstream beyond the distributors. She wondered about the effectiveness of the information flows between each of Crestview's internal processes and whether these processes connect to their counterparts in entities upstream in the supply chain. Further, what role can she play in mitigating security risks in the food supply chain? In the past, some dishonest carriers would unscrupulously sell portions of their cargo along the transportation route and not take responsibility for the shortage. How can she facilitate information exchange up and down the supply chain and what form should it take? The remainder of this chapter will help Yasmita answer these questions.

Supply Chain Risk Management

supply chain risk management
The practice of managing the risk of any factor or event that can materially disrupt a supply chain, whether within a single firm or across multiple firms.

Now that we have discussed a framework for integrated supply chains, we can discuss how integrated supply chains can mitigate the risks of poor performance from unwanted dynamics. Here we focus on **supply chain risk management**, which is the practice of managing the risk of any factor or event that can materially disrupt a supply chain, whether within a single firm or across multiple firms. In this section, we address the management of operational, financial, and security risks.

Operational Risks

Operational risks are threats to the effective flow of materials, services, and products in a supply chain. The following options reduce the risk for operational disruptions and also minimize the bullwhip effect in supply chains.

- *Strategic alignment*—once an appropriate design is determined for the supply chain, make sure that all partners adhere to competitive priorities that are consistent with its strategic thrust. Misalignment of priorities, goals, and objectives can cause delays or disruptions in flows in a supply chain. Internal business functions should similarly be aligned.
- *Upstream/downstream supply chain integration*—working closely with customers and suppliers improves information flows and reduces surprises from demand spikes due to promotions or supply hang-ups because of poorly designed services or products. The integration should extend as far upstream in the supply chain as possible, beyond first- and second-tier suppliers. This process, referred to as *mapping*, is extremely useful for identifying suppliers who might be at risk during supply chain disruptions, such as the coronavirus pandemic in 2020. It can be costly. It took a team of 100 people at a semiconductor manufacturer 1 year to map the supply network deep into the lower tiers following the Great East Japan earthquake and tsunami in 2011.[2]
- *Visibility*—one source of dynamics in supply chains is the lack of visibility of end-user demand by suppliers upstream in the supply chain. To facilitate planning at all levels in the supply chain, point-of-sale (POS) data, which record actual customer purchases of the final service or product, forecasts, scheduled purchase quantities, and inventory levels throughout the supply chain, can be shared with all suppliers.
- *Flexibility and redundancy*—develop the right level of flexibility and redundancy across the supply chain to be able to absorb disruptions and adapt to change. Seek dual sources of critical materials and components, build in adequate capacity cushions, and adjust safety stocks and inventory levels to maintain desired flows.
- *Short replenishment lead times*—improving internal processes and working with suppliers to reduce lead times allow the firm to react quickly to a change in demand levels, thereby mitigating the bullwhip effect. In addition, shorter lead times lead to smaller pipeline inventories.
- *Small order lot sizes*—working on ways to reduce the costs associated with ordering, transporting, and receiving inventory throughout the supply chain will reduce order lot sizes and thereby decrease the amount of fluctuation in the size of orders in the supply chain.
- *Rationing short supplies*—when a shortage exists, customers sometimes artificially inflate their orders to protect themselves, only to cancel them later when the shortage is relieved. To counteract this behavior, suppliers can ration short supplies to customers on the basis of their past sales, rather than their current orders.
- *Everyday low pricing (EDLP)*—promotional or discount pricing encourages spikes in demand. Using a stable pricing program such as EDLP, as is done by Walmart, discourages customers from buying excess stock at discounted prices so they can offer price promotions, a practice called *forward buying*. EDLP levels the demand spikes that are driven by price fluctuations.
- *Cooperation and trustworthiness*—being cooperative in solving supply issues and providing information that can be trusted serves to reduce costs for all members of the supply chain and mitigates the deleterious effects of supply chain dynamics.

Managerial Practice 14.1 shows how an unexpected event of major proportions can cause massive shortages of a product we all love, and raises the need for sound operational risk-management practices.

[2]Thomas Choi, Dale Rogers, and Bindiya Vakil, "Coronavirus Is a Wake-up Call for Supply Chain Management," https://hbr.org/2020/03/coronavirus-is-a-wake-up-call-for-supply-chain-management (March 27, 2020).

MANAGERIAL PRACTICE 14.1 Coronavirus and the Supply Chain: Where Is the Toilet Paper?

What do you fear the most? Falling into a pit of spiders? Getting eaten by a zombie? Running out of toilet paper? If it is the latter, you are not alone. The coronavirus pandemic of 2020 has caused shortages of many products, but running out of toilet paper causes nightmares. What could be worse than walking into your local supermarket, armed with your mask and maintaining social distancing, and seeing the paper-products aisle as barren as the Grand Canyon in January? Asking a stock clerk about the toilet paper gets you a shrug of the shoulders and a promise that an order has been placed with the distributor; relief will take a week or two.

Before we get into theories of why this has happened, let's take a peek at the supply chain for toilet paper. Toilet paper is made from one of two sources: virgin pulp from trees in Canada and the United States, or recycled pulp obtained from materials like discarded copy paper that is reprocessed and turned into pulp. The pulp is delivered to paper mills that turn it into large rolls of paper over 100 inches wide. The rolls are then shipped to a paper-converting facility, which then cuts and packages them into the designated end product like toilet paper or kitchen towels, depending on the quality of the paper. Packaging and shipping are the final steps in the chain. The mills typically run 24 hours, 7 days a week—in other words, fixed capacity. However, with the pandemic, mills have adjusted their work hours for the safety of their employees, eroding their capacity to respond to demand increases. Retailers have a set amount of toilet paper inventory that is determined on the basis of historic demand levels; however, a shock to demand can exceed the safety stocks in their warehouses.

Odds are that you are thinking your neighbors are causing this shortage. That is a reasonable theory, given that we have all seen customers flocking out of Costco stores with grocery carts full of Charmin Ultra-Soft toilet paper. It's not as though people are using the bathroom more often, so why are they filling their closets with a product that is not an effective way to prevent getting the coronavirus? One explanation is that customers are apprehensive about supply being secure and decided to build an inventory they will need for the next several months in anticipation of the store running out of stock, which, of course, is a self-fulfilling prophesy. A "herd mentality" takes over: "If they want more toilet paper, then so do I."

There is another theory to consider. While hoarding and panic buying may contribute to the shortages, they are not the only reason. There are two separate markets for toilet paper: commercial and consumer. The pandemic has shifted the lion's share of the demand to the latter. People actually do have to buy more toilet paper, not because they are going to the bathroom more often, but because they are using more of it at home. It is estimated that the demand for consumer toilet paper increased 40 percent, a huge increase for a supply chain designed for constant demand. That leaves a lot of commercial toilet paper unused. Why not send that to the retailers and produce more consumer toilet paper on the machinery? There are two reasons why not. First, shifting distribution channels from commercial to consumer would require new contracts between suppliers, distributors, and stores, different packaging, and new truck routes, all of which would take considerable time and effort for a low margin product. Second, how would you like to hang a roll of toilet paper on your wall that is a foot in diameter, made from recycled pulp with no aloe, and thin enough to read a newspaper through? Not likely. The bottom line is that the mills can only modestly increase production of consumer toilet paper because of their fixed-capacity equipment and coronavirus limitations on the use of their employees.

Eventually, production will meet demand as buying decreases; however, the bullwhip effect will rear its ugly head unless the supply chains in this industry undertake the tactics listed above to minimize the operational risks brought on by the coronavirus pandemic.[3]



Aydin Kamber/Shutterstock

Large rolls of toilet paper are shipped to a paper-converting facility to produce the product you buy in the store. Here the rolls have been cut to the proper size and are conveyed to the packaging process.

Financial Risks

While operational risks affect material flows, financial risks are threats to the financial flows in a supply chain, such as prices, costs, and profits. Buyers may purchase services or products at an agreed-upon fixed price. With a commitment made at a certain price, factors outside the control of a buyer may threaten the profitability of the buyer. For example, market conditions could cause overcapacity at the supplier or oversupply of a product such that the price of the service or product plummets, which means that the buyer's profits will be lower than they could have been, and competitors purchasing these same items at a lower price could take advantage. Alternatively, even without changes in the supply of the service or product, the exchange rate in currencies

[3] *Sources*: Parija Kavilanz, "Toilet Paper Makers: What We Are Dealing with Here Is Uncharted," https://www.cnn.com/2020/03/17/business/toilet-paper-supply-chain-coronavirus/index.html (March 17, 2020); Will Oremus, "What Everyone's Getting Wrong About the Toilet Paper Shortage," https://marker.medium.com/what-everyones-getting-wrong-about-the-toilet-paper-shortage-c812e1358fe0 (April 2, 2020); Matt Leonard, "What Procurement Managers Should Expect from a 'Bullwhip on Crack,'" https://www.supplychaindive.com/news/coronavirus-supply-chain-bullwhip-demand-grocery-medical-covid/574784/.

between the buyer and seller could make the agreed-upon price more expensive for the buyer. To show the effect of fluctuations in exchange rates, consider an Italian firm that supplies cotton to a firm in the United States. The currency chosen for the transaction was the U.S. dollar (USD). A contract in July 2012 called for $100,000 in shipments per month, to end in January 2013. In July 2012, the exchange rate was 1,589 ITL/USD, or equivalently 1,589,000 lire in revenues per month for the Italian supplier. However, by the end of the contract in January 2013, the dollar depreciated relative to the Italian lira; the exchange rate fell to 1,430 ITL/USD. Because the Italian supplier had to pay all of its expenses in lire, its profits fell 10 percent even though actual operating costs did not change. A similar situation can occur when service or product prices change during a supply contract because of market conditions.

How can financial risks in a supply chain be managed? One way is to reduce unnecessary costs in supply chain operations, both upstream and downstream, which we have already discussed in this text. This approach provides some protection against cost increases due to operational issues or exchange rates. Another way is to use a new low-cost source of supply, also known as *low-cost hopping*, which could benefit a firm in the short run. However, it is not conducive to effective supply chain integration over the long term. Perhaps the most often used approach to protect against financial risks is called **hedging**, which is a supply chain risk-management strategy used in limiting or offsetting the probability of loss from fluctuations in the prices of commodities or currencies. In effect, hedging is a transfer of risk without buying insurance policies. One way to hedge in a supply chain is to take advantage of the flexibility in operations to reallocate production across facilities in different regions of the world to improve financial flows. This approach, referred to as *production shifting*, moves the production of products to countries where exchange rates or commodity prices are favorable. Production facilities must be flexible enough to change their production assignments, which could entail a different mix of products and shipping schedules.

hedging

A supply chain risk-management strategy used in limiting or offsetting the probability of loss from fluctuations in the prices of commodities or currencies.

Another way of hedging is to use a **futures contract**, which is a contractual agreement, generally made on the trading floor of a futures exchange, to buy or sell a particular commodity or financial instrument at a predetermined price in the future. Just like the price of blueberries at a grocery store, the prices of commodities such as metals and oil or currencies change on a weekly or daily basis. If the price goes up, the *buyer* of the futures contract makes money because the buyer gets the product at the agreed-upon price and can now sell it at today's higher market price. If the price goes down, the futures *seller* makes money because the seller can buy the item at today's lower price and sell it to the futures buyer at the higher agreed-upon price. Often, the commodity is not actually delivered to the buyer of a futures contract. To fulfill the contract, the seller of the futures contract only has to show proof that the item is at the warehouse; the contract can be settled between the two parties by paying the cash difference.[4]

futures contract

A contractual agreement, generally made on the trading floor of a futures exchange, to buy or sell a particular commodity or financial instrument at a predetermined price in the future.

The mechanics of setting up a futures contract is beyond the scope of this text; however, a simple example can demonstrate its use in a supply chain. Suppose that Action Pro, a manufacturer of cotton sporting apparel, wants to secure its supply of cotton for the next year. The price of cotton has been volatile because of global stockpiling by large Asian manufacturers. Action Pro is not interested in speculation and only wants to break even with a hedge against future cotton prices. It is now December, currency exchange rates have been stable, and the market price for cotton is $70 per 100 pounds (CWT). If the cotton price stayed at $70, Action Pro could make a reasonable profit; however, the cotton supplier is not willing to accept a fixed price because of the possibility of a rise in global cotton prices due to the Asian activity. Consequently, Action Pro entered into a contract with the supplier for 100,000 pounds of cotton per month starting in January at market prices. To counter the risk of higher cotton prices, Action Pro entered into a futures contract with a financial institution for 100,000 pounds of cotton per month at $70/CWT. In this contract, Action Pro agrees to pay the financial institution $70/CWT in exchange for the institution paying Action Pro whatever the market price of cotton is each month.[5] Table 14.1 contains two snapshots that demonstrate how the hedge helped Action Pro break even with regard to cotton prices.

Security Risks

Security risks are threats to a supply chain that could potentially damage stakeholders, facilities, or operations; destroy the integrity of a business; or jeopardize its continuation. The actions that form the basis of these threats are intentional and are designed to do physical or financial

[4]For more information about futures contracts, see Kimberly Amadeo, "What a Commodity Is and How Its Trading Market Works" at https://www.thebalance.com/what-are-commodities-3306236 (February 7, 2020).

[5]This contract is actually called a "swap," which is a form of futures contract. To keep things simple, we will ignore the fees paid to the financial institution for services.

TABLE 14.1 | HEDGING THE MARKET PRICE OF COTTON

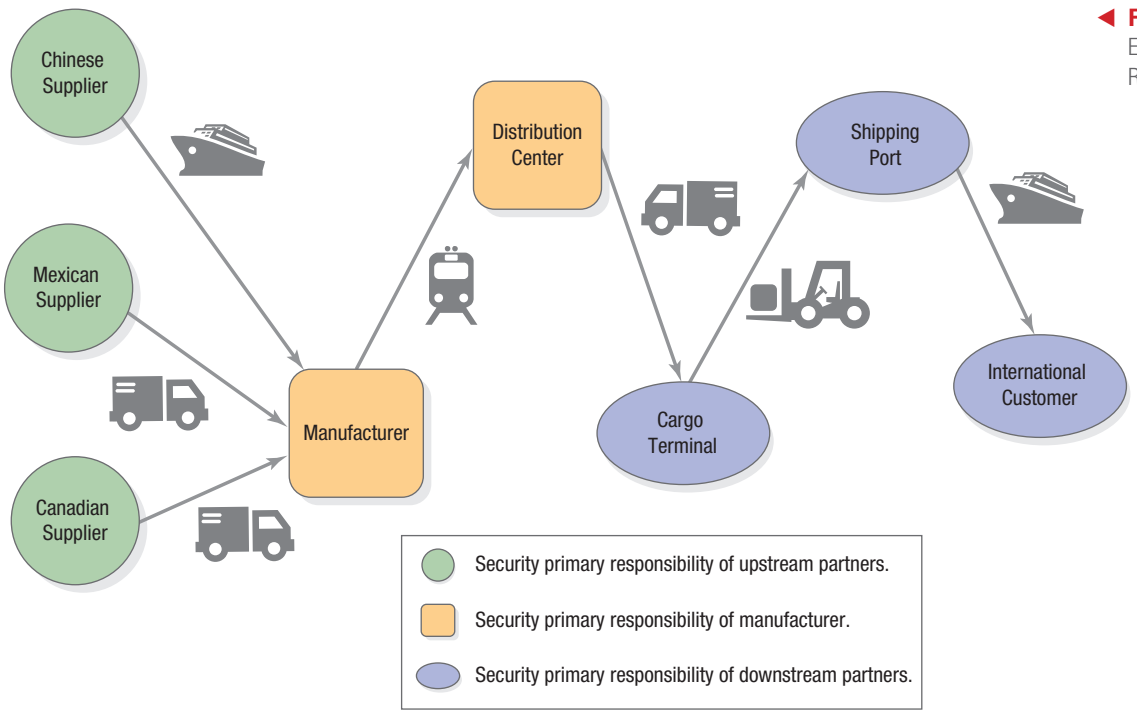
(a) It is now January and the market price of cotton has risen to $87/CWT.

Financial Result	Physical Result
Paid for 100,000 pounds of cotton on the futures contract for January at $70/CWT.	Purchased 100,000 pounds of cotton at market price of $87/CWT for January delivery.
Sold 100,000 pounds of cotton for cash at the new price of $87/CWT.	It now costs more than budgeted to produce the cotton apparel.
Financial profit = $87 − $70 = $17/*CWT*.	**Physical loss in profits relative to budget** = $70 − $87 = −$17/*CWT*.
The financial profit achieved by hedging has compensated for the increased price of cotton in the physical market. This means that Action Pro has been able to maintain its budgeted target of $70/CWT for its cotton supplies.	

(b) It is now June and the market price of cotton has dropped to $65/CWT.

Financial Result	Physical Result
Paid $70/CWT for 100,000 pounds of cotton on the futures contract for the month of June.	Purchased 100,000 pounds of cotton at the market price of $65/CWT for June delivery.
Sold 100,000 pounds of cotton for cash at the new price of $65/CWT.	It is now less expensive to produce the cotton apparel.
Financial loss = $65 − $70 = −$5/*CWT*.	**Physical increase in profits relative to budget** = $70 − $65 = $5/*CWT*.
The financial loss is balanced by the increase in physical profits. Active Pro has achieved the budgeted cost of $70/CWT.	

damage. A supply chain is *secure* when it can fend off unauthorized acts that are designed to cause intentional harm or damage to the supply chain and the materials (human and otherwise) that flow through its processes. A risk is amplified if the threat has a high probability of occurrence and a high level of severity. Firms interested in achieving a high level of supply chain security have a big job; there are many elements in a typical supply chain and they are not all under the direct control of the firm. Figure 14.5 shows examples in a supply chain where security programs are needed.



◀ **FIGURE 14.5**
Elements of a Supply Chain Requiring a Security Program



Chip Somodevilla/Getty Images News/Getty Images

Security guards check truck drivers' paperwork as they enter the Seagrit Marine Terminal in Baltimore, Maryland. The guards can check the manifest against the items in the truck to prohibit the shipment of undocumented hazardous materials, illegal weapons, or other forms of contraband.

Primary security responsibility shifts from suppliers, to the manufacturer, to downstream partners, and ultimately to the customer as the goods flow through the supply chain. Security programs should assess the severity of the threats, such as terrorism, cargo theft, hijacking, drug or contraband smuggling, undeclared hazardous goods, and government instability. These programs should also assess how vulnerable the supply chain is regarding procedures for security, physical access controls, container and trailer security, and information technology security, for example. Finally, the consequences of a breach in security to factors such as demand volume, the firm's competitive priorities, and the impact of lost business should be assessed. As the responsibility for security is paramount and distributed among many entities in a supply chain, it is clear that the more integrated a supply chain is, the more effective security measures can be.

While security programs vary in content depending on the application, here are some typical security activities:

- *Access control.* Check IDs of all visitors, vendors, drivers, and, in general, all participants in the supply chain. Employ real-time monitored systems that document entry, exit, and movement of materials and cargo.
- *Physical security.* Conduct random facility inspections and ensure compliance to established security standards. Monitor CCTV and alarm systems that allow for immediate real-time response. Perform penetration tests and audits of compliance.
- *Shipping and receiving.* Screen and validate the contents of the cargo being shipped and received. Provide advanced notification of the contents to the destination country. Use specialized packing material, unique shipping markings, and high-security seals.
- *Transportation service provider.* Ensure the security of cargo while in transit via the use of locks and tamper-proof seals. Ensure that the carrier does not make stops in security "red zones." Require GPS tracking for the tractors and trailers and regular communication with the drivers. Require notification of the use of any subcontractors and make sure they adhere to the same security requirements as the primary carrier.
- *ISO 28000.* Recognizing the need of the international community for supply chain security, the International Standards Organization has established **ISO 28000:2007**, which is a set of requirements for a supply chain security management system that includes aspects of financing, manufacturing, information systems, and the facilities for packing, storing, and transferring goods between modes of transportation and locations. Certification in ISO 28000:2007 enables firms to demonstrate their compliance with stated security management policies.

ISO 28000:2007

A set of requirements for a supply chain security management system that includes aspects of financing, manufacturing, information systems, and the facilities for packing, storing, and transferring goods between modes of transportation and locations.

Cloud Computing and Blockchains

A key element to successfully integrating a supply chain and implementing supply chain risk-management tactics is information technology—all entities in a supply chain must have the necessary information and forward visibility to make informed decisions. Two new technologies have emerged to enable supply chain coordination: cloud computing and blockchains.

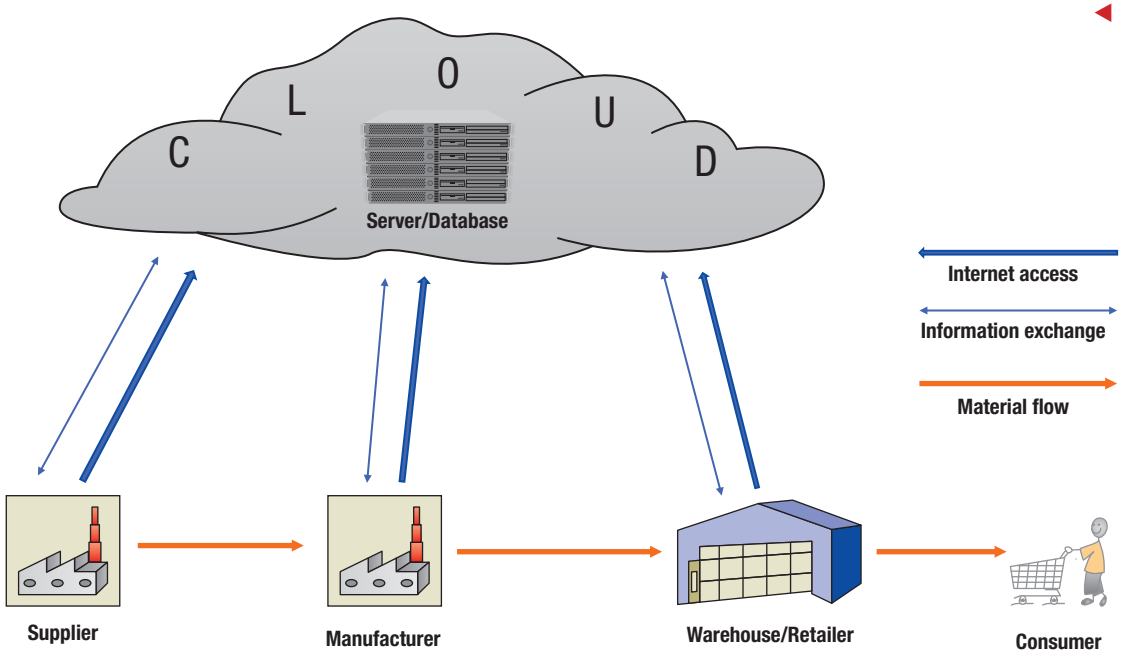
Cloud Computing

cloud computing

The practice of using a network of remote servers hosted on the Internet to store, manage, and process data.

Cloud computing, the practice of using a network of remote servers hosted on the Internet to store, manage, and process data, rather than a local server or personal computer, is an enabler for businesses to deploy digital platforms and software services for the whole supply chain network. Implementing a cloud-based platform helps to coordinate the supply chain's participants and gather more accurate data for demand forecasting and planning. Cloud computing also enables every participant in the supply chain to receive the right information, at the right place, and at the

right time. For example, a firm can create a system to automatically collect shipping information and the status of orders from suppliers as well as share updates on future demand up and down the supply chain so that all parties can adjust their operations to avoid disruptions. Figure 14.6 shows a cloud-based platform for a supply chain.



◀ **FIGURE 14.6**
Cloud-Based Platform for a Supply Chain

Supply chain coordination can exist at three levels[6]:

1. Transaction integration, such as providing access to purchase orders, work orders, and sales orders, invoices, or payments.
2. Management information, such as sharing forecasts, shipping plans, bills of material (BOM), and inventory levels.
3. Strategic collaboration, such as working with participants at improving forecast accuracy, resolving critical supply chain events, creating unified pricing plans, and improving production capacities.

This capability helps supply chains cope with the problems of the bullwhip by providing greater visibility into customer demand and supplier performance, while concurrently lowering inventory levels and increasing inventory turnover, reducing transportation and warehouse costs, and shortening lead times.

It may seem that *cloud computing* is the ultimate solution to supply chain integration. While it can be a cost-effective way to deal with digitally connecting the participants in a supply chain, there is one major shortcoming that should be considered: data security and privacy. Data in the cloud should be accessed only by authorized members. Nonetheless, sending sensitive data such as inventory levels, work in progress levels, order data, and demand data to a third party, who is hosting the cloud, poses the threat of hacking the system because all the data are held in a central location. Cloud computing systems cannot always ensure confidentiality, which raises the prospect of competitors accessing key performance and financial records.

Blockchains

Blockchains were created to overcome the problem of data security and accessibility. A **blockchain** is a digital record of transactions in which individual records, called blocks, are linked together in a single list, called a chain. The transactions are duplicated and distributed across the entire network of computer systems on the blockchain. Blockchains used in supply chains are typically

blockchain
A digital record of transactions in which individual records, called blocks, are linked together in a single list, called a chain.

[6]Jan Keil, "How Can Cloud Computing and Blockchain Reduce the Bullwhip Effect in Supply Chain?" https://www.infopulse.com/blog/how-can-cloud-computing-and-blockchain-reduce-the-bullwhip-effect-in-supply-chain (July 30, 2019).

private, which means that the data records are restricted to members of the supply chain, who are known and trusted parties. Members are given *permission* by the owner of the blockchain (such as Walmart or Maersk) to add or update blocks of data in the blockchain. Blockchains were initially used for financial transactions involving cryptocurrencies such as Bitcoin. Hence, the level of security built into the chain is extremely high.

How Does It Work? Think of a spreadsheet, or a ledger, that is duplicated hundreds of times across a network of computers, each called a node.[7] Suppose that when a participant in the network submits an update to the ledger, such as a shipment, delivery, payment, or forecast, the database uses an automated process to ensure the legitimacy of the update, all without the need for a third party to check the veracity of the change, which can be time consuming and costly. Approved updates are time stamped, cryptographically signed, and added to the block. The new block becomes part of the blockchain, an immutable record of all transactions of interest to the participants. Once information is stored, it is very difficult to change or delete because altering a record retroactively will affect all subsequent blocks in the network. For example, if someone introduced a forged transaction, removed a transaction, or duplicated a transaction, all the other users in the blockchain would notice a mathematical irregularity and would reject the new data. To date, hacking such a system has been virtually impossible.

What Are the Benefits? Supply chains using blockchains take advantage of three major properties:

1. *Decentralization.* Before the advent of Bitcoin and other cryptocurrencies, the typical server model was the client-server model whereby the database is centralized, which requires the user to go through a third party to interact with another participant in the supply chain. The database is located in one place; consequently, significant downtime due to data corruption or server system failure is a possibility. With blockchains, the network is decentralized. The information is not stored by one single entity; everyone in the network owns the information. Also, participants can interact directly with each other without going through a third party.
2. *Transparency.* Every authorized user of the blockchain can see the data and update it easily. However, that does not mean that individual users can be identified. Each user's identity is hidden via complex cryptography and represented only by his or her public address.
3. *Immutability.* Blockchains maintain the *integrity* of the data, which is its accuracy, completeness, and validity. They also provide *security* for the data, which means that a database will remain complete, accurate, and valid no matter how long it is stored or how often it gets accessed. Protecting the data against unauthorized access or corruption is necessary for data integrity. Once something has been entered into the blockchain, it cannot be tampered with. This is accomplished by using a cryptographic hash function that is associated with each input. Each block in the chain is linked to the address of the previous block and has a pointer to the hash of the data contained therein. Minute changes to the data of the previous block, however, cause huge changes to the hash associated with it, which makes tampering with the data so noticeable. For example, suppose we had the input "This is a test" and we were using SHA-256, the hashing program used by Bitcoin.[8] The hash would be as follows:

INPUT	HASH
This is a test	C7BE1ED902FB8DD4D48997C6452F5D7E509FBCDBE2808B16BCF4EDCE4C07D14E

Now suppose we changed the input to "this is a test," changing only the case of the first letter. Notice how different the hash is:

INPUT	HASH
this is a test	2E99758548972A8E8822AD47FA1017FF72F06F3FF6A016851F45C398732BC50C

An unauthorized change such as this would break the chain because the hash in the previous block is no longer equal to the hash for that input stored in the current block. This feature of blockchains is what makes the data record immutable.

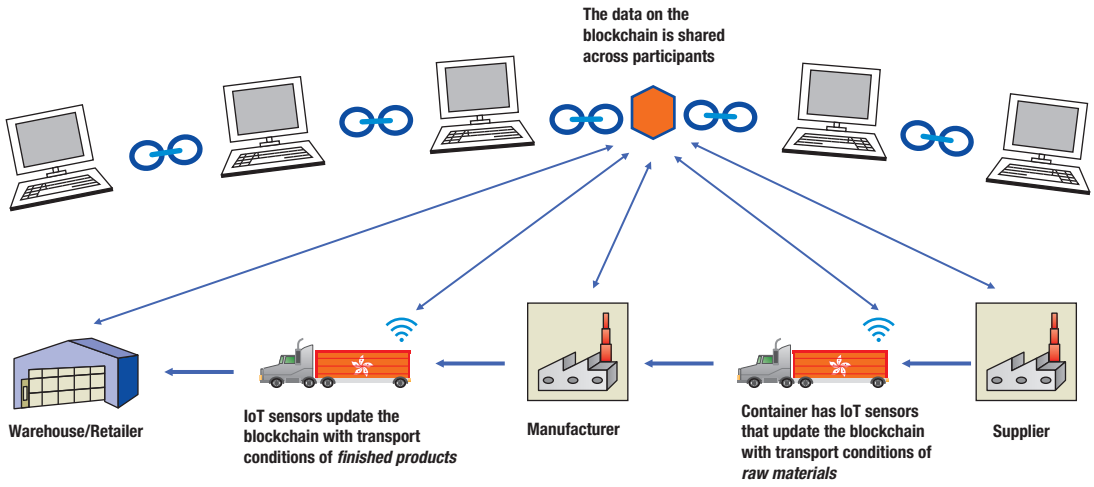
[7]Ameer Rosic, "What Is Blockchain Technology? A Step-by-Step Guide for Beginners," https://blockgeeks.com/guides/what-is-blockchain-technology/ (2016).

[8]https://blockgeeks.com/guides/video-guide-what-is-hashing/; https://static.blockgeeks.com/wp-content/uploads/2019/02/word-image-55.png.

How Is It Used? Blockchains provide the mechanism to increase visibility across all areas of a supply chain, from suppliers, strategic sourcing, procurement, and supplier quality to detailed operations such as shop floor processes and machine-level monitoring. This capability can be used to minimize the disruptions caused by the bullwhip effect. Here are some other uses of blockchains:

- *Integration of IoT.* As we have discussed in Chapter 1, "Using Operations to Create Value," the Internet of Things (IoT) allows for the collection and dissemination of data over a network without human intervention. A blockchain is one such network with the added ability to share that data with the entities in the supply chain. A popular approach is to use **radio frequency identification (RFID)**, a method for identifying items through the use of radio signals from a tag attached to the item. The tag has information about the item and sends signals to a device that can read the information and even write new information on the tag. Data from the tags can be transmitted wirelessly from one place to another through electronic product code (EPC) networks and the Internet, making it possible to uniquely identify every item a company produces and track it. Combining IoT and blockchain can provide real-time data on shipping container conditions, tamper-proof storage, each shipment's locational history, and any changes in a shipment's temperature as measured by a sensor.[9] Figure 14.7 shows a blockchain with an integrated IoT.

radio frequency identification (RFID)
A method for identifying items through the use of radio signals from a tag attached to an item.



◀ **FIGURE 14.7**
Blockchain with Integrated IoT

- *Tracking and Traceability.* The amalgamation of IoT and blockchain enables firms to track shipments along each leg. For example, when you click on the package-tracking link on an Amazon order, you find out where it is and when it is scheduled for delivery, all with the help of a blockchain and IoT. Further, blockchains are indispensable when it comes to traceability, which has become a top priority concern for industries such as consumer packaged goods, aerospace and defense, pharmacy, medical devices, automobile, and food. Blockchain technology can be used to trace the sources of product defects to the responsible suppliers or manufacturers. In the food industry, retailers can provide selected product-related data through an app to customers who demand locally grown and organic products. Using a simple QR-code scan on their smartphone, customers could validate every step the product has taken through the supply chain to see if the product meets their expectations. Walmart uses the IBM Food Trust blockchain to trace berries, mangoes, baby food, chicken, lettuce, spinach, and other greens. It has required the suppliers of those foods, and the farmers, logistics firms, and business partners of those suppliers, to join the blockchain.[10] The capability of blockchains to trace the path of products from their origins helps to mitigate the high costs of product recalls and enhances product safety.
- *Smart Contracts.* In conventional systems, verifying the conditions of a contract, with either suppliers or customers, requires the time and effort of a number of employees and intermediaries. Consequently, the payment often gets delayed because of the time required for validation of the contract requirements and obtaining management approvals. After the

[9]Toshendra Kumar Sharma, "Role of Blockchain in the Manufacturing Industry," https://www.blockchain-council.org/blockchain/role-of-blockchain-in-the-manufacturing-industry/ (January 27, 2019).

[10]Kim S. Nash, "Walmart Requires Lettuce, Spinach Suppliers to Join Blockchain," https://blogs.wsj.com/cio/2018/09/24/walmart-requires-lettuce-spinach-suppliers-to-join-blockchain/ (September 24, 2018).

smart contracts
Codified agreements that self-execute when the conditions are met.

work is done and invoices are generated, they are emailed to customers, who, in turn, enter them manually into their system and then decide when and how to pay them. On the contrary, blockchains with embedded IoT can make use of **smart contracts**, which are codified agreements that self-execute when the conditions are met. Contractual compliance can be monitored along the product's journey. For example, sensors can detect a change in a shipment's temperature and send alerts regarding contractual compliance of perishable meats and produce, thereby averting the potential of bad product quality and rejected shipments once they reach their destination. Payments for shipments meeting contractual agreements can be automatically released without any intermediaries.[11,12]

Now that we have reviewed the new technologies aimed at integrating firms in a supply chain to collectively combat the disruptions and risks commonly experienced in today's business world, we turn to those internal processes in a firm shown in Figure 14.3 that develop and produce the product or service and generate the data and information that become essential elements of a cloud-based platform or a blockchain. The efficient and accurate information flow between these internal processes is just as important as those between external partners in the supply chain.

New Service or Product Development Process

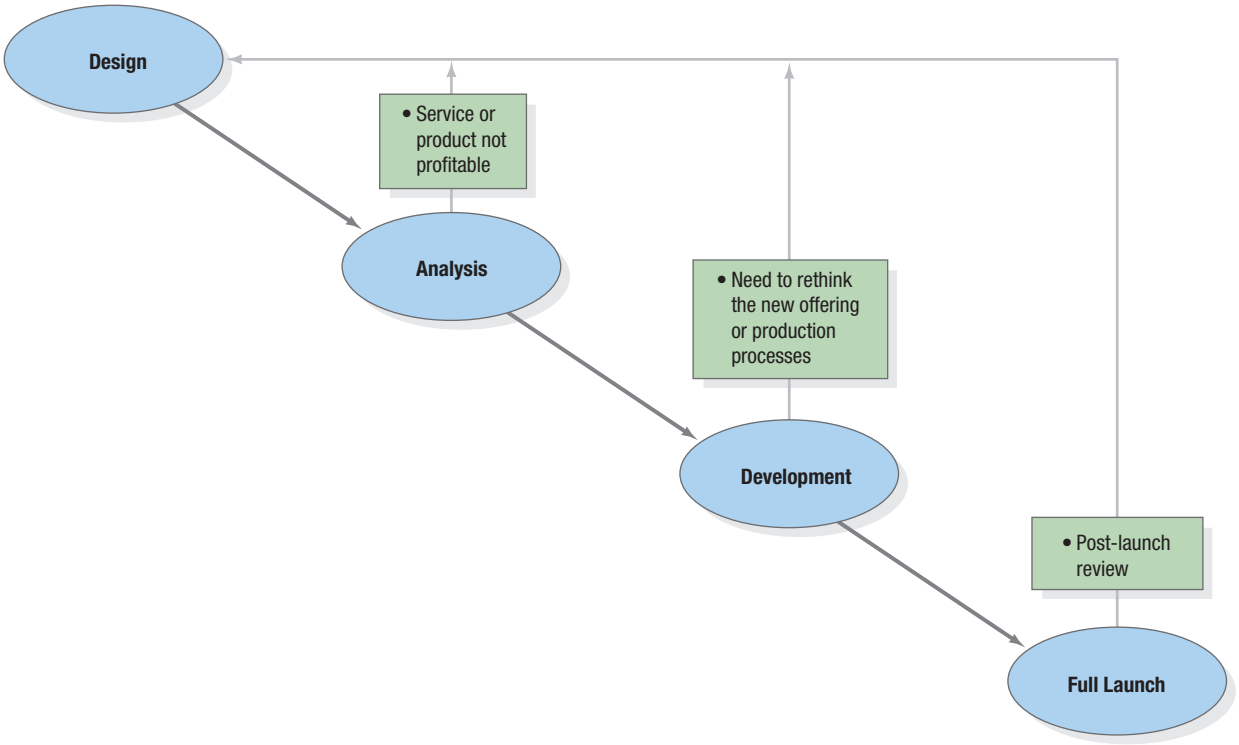
Competitive priorities help managers develop services and products that customers want. New services or products are essential to the long-term survival of the firm. *New* refers to both brand-new services or products and major changes to existing services or products. The new service or product development process is an integral element in a firm's supply chain because it defines the nature of the materials, services, and information flows the supply chain must support. It should be a highly collaborative process that both accounts for and helps to determine sourcing requirements, production methods, marketing, sales, and other aspects of how goods are made and how they are handled at the end of their lives. This is especially important because product life cycles are becoming increasingly shorter, placing a premium on integrative technologies such as cloud computing and blockchains so that the flows of information, materials, and finances are coordinated. Instead of only considering functionality and cost and assuming that products will just be thrown out after their useful lives, firms should ingrain in their new service or product development process a notion of managing the entire life cycle of its products in order to maximize the value of them and their component materials. As shown in Figure 14.8, it begins with the consideration of the development strategy and ends with the launch of the new offering. There are four key nested processes, or stages, in the new service or product development process: design, analysis, development, and full launch. Here are some considerations for supply chain managers.

Design

The *design* stage is critical because it links the creation of new services or products to the corporate strategy of the firm and defines the requirements for the firm's supply chain. As we have already noted, the corporate strategy specifies the long-term objectives and the markets in which the firm wishes to compete. In the design stage, ideas for new offerings are proposed and screened for feasibility and market worthiness. These ideas specify how the customer connects with the service or manufacturing firm, the benefits and outcomes for the customer, and the value of the service or product. The design process should begin with observing customers in their everyday lives to learn about their material needs and about how well (or poorly) those needs are met. Further, in light of the need to offer environmentally friendly products and services, designers should seek to provide value to customers by using a minimum of resources and materials. Consequently, proposals should specify how the new offering will be produced and delivered—an important consideration for the supply chain. Often, critical choices must be made, such as the raw materials, degree of modularity in the design, or the nature of the logistical services needed to get the service or product to market. Even though many of the detailed specifics of the service or product and its processes have not yet been developed, the inputs of designers, engineers, suppliers, supply chain managers, and potential customers in this stage can avoid costly mistakes.

[11]Louis Columbus, "How Blockchain Can Improve Manufacturing In 2019," https://www.forbes.com/sites/louiscolumbus/2018/10/28/how-blockchain-can-improve-manufacturing-in-2019/#2ef065125db6 (October 28, 2018).

[12]Paul Brody, "How Blockchain Revolutionizes Supply Chain Management," https://www.ey.com/Publication/vwLUAssets/ey-blockchain-and-the-supply-chain-three/$FILE/ey-blockchain-and-the-supply-chain-three.pdf, (August 23, 2017–September 6, 2017).



▲ **FIGURE 14.8**
New Service/Product Development Process

Analysis

The second stage, *analysis*, involves a critical review of the new offering and how it will be produced to make sure that it fits the corporate strategy, is compatible with regulatory standards, presents an acceptable market risk, and satisfies the needs of the intended customers. The resource requirements for the new offering must be examined from the perspective of the core capabilities of the firm and the need to acquire additional resources. The existing supply chain must be evaluated for its appropriateness for the new offering. If change is needed, the supply chain design might have to be revised (efficient or responsive) or new capabilities acquired by forming strategic partnerships with new firms. If the analysis reveals that the new offering has good market potential and that the firm has the capability (or can acquire it), the authorization is given to proceed to the next stage.

Development

The third stage, *development*, brings more specificity to the new offering. The required competitive priorities are used as inputs to the design (or redesign) of the processes that will be involved in delivering the new offering. The processes are analyzed, including those of suppliers; each activity is designed to meet its required competitive priorities and to add value to the service or product. Once the new offering is specified and the capability of the processes verified, the market program can be designed. Finally, personnel are trained and some pilot runs can be conducted to iron out the kinks in production and supply. At this stage it is possible that some unforeseen problems may arise, forcing a reconsideration of the service or product or the processes required to produce it. The supply chain might have to be redesigned as well.

To avoid costly mismatches between the design of a new offering and the capability of the processes and supply chain required to produce it, many firms engage in a concept called **concurrent engineering**, which brings product engineers, process engineers, marketers, buyers, information specialists, quality specialists, and suppliers together to design a product and the processes that will meet customer expectations. Changes are much simpler and less costly at this stage. However, problems with the design of the new offering or the capability to deliver it may be discovered during this stage. The proposal for the new offering may have to be scrapped or completely rethought.

concurrent engineering
A concept that brings product engineers, process engineers, marketers, buyers, information specialists, quality specialists, and suppliers together to design a product and the processes that will meet customer expectations.

Full Launch

The final stage, *full launch*, involves the coordination of many internal processes as well as those both upstream and downstream in the supply chain. Promotions for the new offering must be initiated, sales personnel briefed, distribution processes activated, and old services or products that the new offering is to replace withdrawn. A particular strain is placed on the supply chain

during a period referred to as *ramp-up*, when the production processes must increase volume to meet demands while coping with quality problems and last-minute design changes. The more integrated the supply chain, particularly with the use of cloud computing or blockchains, the easier the ramp-up period because suppliers get visibility into the future requirements for materials and components and can be prepared for the upsurge in demand. Flexibility in the supply chain is a desirable attribute during the ramp-up period. Later, as the service or product matures and volume increases sufficiently, a supply chain based on efficiency may have to be developed.

Regardless of the service or product, a post launch review should compare the competitive priorities of the supply chain to its competitive capabilities, perhaps signaling a need to rethink the original service or product idea or the supply chain. The review should also get inputs from customers, who may divulge their experiences and may share ideas for change.

Supplier Relationship Process

The nature of the service or product determines the design requirements for the upstream supply chain. The supplier relationship process, which focuses on the interaction of the firm with upstream suppliers, includes five major nested processes: (1) sourcing, (2) design collaboration, (3) negotiation, (4) buying, and (5) information exchange. For many firms, these processes are the organizational responsibility of **purchasing**, also referred to as *procurement*, which is the activity that decides the suppliers to use, negotiates contracts, maintains information flows, and determines whether to buy locally.

purchasing
The activity that decides which suppliers to use, negotiates contracts, and determines whether to buy locally.

Sourcing

The sourcing process is involved in the selection, certification, and evaluation of suppliers and, in general, the management of supply contracts.

Supplier Selection A starting point for selecting suppliers is to perform a total cost analysis. There are four key costs to consider for each supplier.

- *Material costs.* Negotiating with suppliers for the provision of a service or product results in a price per unit (or application of the service). Material costs equal annual requirements (D) multiplied by the price per unit, p.

$$\text{Annual material costs} = pD$$

- *Freight costs.* The costs of transporting the product or the equipment and personnel who will perform the service can vary greatly depending on the location of the supplier, the size of the shipments (full truckload [TL] shipments are cheaper per pound than less-than-truckload [LTL] shipments), the number of shipments per year, and the mode of transportation (air transportation is more expensive than truck or rail transportation).
- *Inventory costs.* Buyers interested in purchasing products must consider the shipping quantity and the lead time from the supplier. The shipping quantity, Q, will determine the cycle inventory the buyer must maintain until the next shipment of the product.

$$\text{Cycle inventory} = Q/2$$

The lead time, L, and the average requirements per day (or week) $\bar{d}$, will determine the level of the pipeline inventory, which also may be the responsibility of the buyer. Assuming a constant lead time,

$$\text{Pipeline inventory} = \bar{d}L$$

The buyer must pay inventory holding costs on the cycle and pipeline inventories. Annual inventory costs equal the sum of the cycle and pipeline inventories multiplied by the annual holding cost per unit, H. See Chapter 9, "Inventory Management" for a review of inventory holding costs and cycle and pipeline inventories.

$$\text{Annual inventory costs} = (Q/2 + \bar{d}L)H$$

- *Administrative costs.* Supply contacts must be monitored and frequent interactions with the supplier may be required. Administrative costs include the managerial time, travel, and other variable costs associated with interacting with a supplier. These costs may vary greatly depending on the location of the supplier; more distant suppliers typically require more administrative attention.

The total annual cost for a supplier is the sum of these costs:

$$\text{Total Annual Cost} = pD + \text{Freight costs} + (Q/2 + \bar{d}L)H + \text{Administrative costs}$$

Example 14.1 shows how total cost analysis is used to select suppliers.

EXAMPLE 14.1 Total Cost Analysis for Supplier Selection

Compton Electronics manufactures laptops for major computer manufacturers. A key element of the laptop is the keyboard. Compton has identified three potential suppliers for the keyboard, each located in a different part of the world. Important cost considerations are the price per keyboard, freight costs, inventory costs, and contract administrative costs. The annual requirements for the keyboard are 300,000 units. Assume Compton has 250 business days a year. Managers have acquired the following data for each supplier.

	ANNUAL FREIGHT COSTS		
	Shipping Quantity (Units/Shipment)		
Supplier	10,000	20,000	30,000
Belfast	$380,000	$260,000	$237,000
Hong Kong	$615,000	$547,000	$470,000
Shreveport	$285,000	$240,000	$200,000

	KEYBOARD COSTS AND SHIPPING LEAD TIMES			
Supplier	Price/Unit	Annual Inventory Carrying Cost/Unit	Shipping Lead Time (Days)	Administrative Costs
Belfast	$100	$20.00	15	$180,000
Hong Kong	$96	$19.20	25	$300,000
Shreveport	$99	$19.80	5	$150,000

Which supplier provides the lowest annual total cost to Compton?

SOLUTION

The average requirements per day are

$$\bar{d} = 300{,}000/250 = 1{,}200 \text{ keyboards}$$

Each option must be evaluated with consideration for the shipping quantity using the following equation:

$$\begin{aligned}\text{Total Annual Cost} &= \text{Material costs} + \text{Freight costs} + \text{Inventory costs} + \text{Administrative costs}\\ &= pD + \text{Freight costs} + (Q/2 + \bar{d}L)H + \text{Administrative costs}\end{aligned}$$

For example, consider the Belfast option for a shipping quantity of Q = 10,000 units. The costs are

$$\begin{aligned}\text{Material costs} &= pD = (\$100/\text{unit})(300{,}000 \text{ units}) = \$30{,}000{,}000\\ \text{Freight costs} &= \$380{,}000\\ \text{Inventory costs} &= (\text{cycle inventory} + \text{pipeline inventory})H = (Q/2 + \bar{d}L)H\\ &= (10{,}000 \text{ units}/2 + 1{,}200 \text{ units/day (15 days)})\$20/\text{unit/year} = \$460{,}000\\ \text{Administrative costs} &= \$180{,}000\\ \textbf{Total Annual Cost} &= \$30{,}000{,}000 + \$380{,}000 + \$460{,}000 + \$180{,}000 = \$31{,}020{,}000\end{aligned}$$

The total costs for all three shipping quantity options are similarly calculated and are contained in the following table.

	TOTAL ANNUAL COSTS FOR THE KEYBOARD SUPPLIERS		
	Shipping Quantity		
Supplier	10,000	20,000	30,000
Belfast	$31,020,000	$31,000,000	$31,077,000
Hong Kong	$30,387,000	$30,415,000	$30,434,000
Shreveport	$30,352,800	$30,406,800	$30,465,800

DECISION POINT

Notice that the shipping quantity plays an important role; the lowest cost for the Belfast supplier comes with a shipping quantity of 20,000 keyboards. Nonetheless, based on the total cost analysis, the Shreveport supplier will provide the lowest cost to Compton. Compton should choose a shipping quantity of 10,000 keyboards, which implies that there will be 30 shipments a year (or 300,000/10,000). While the Hong Kong supplier had the lowest price per keyboard, the Shreveport supplier could deliver the keyboards to Compton with the lowest overall cost, which includes logistics, inventory, and administrative costs.

While total cost is an important consideration in the selection of suppliers, other performance dimensions may also be important. The quality of a supplier's materials may be critical, since hidden costs of poor quality may be high. Similarly, shorter lead times and on-time delivery may allow the buying firm to maintain acceptable customer service with less inventory. So management must review the market segments it wants to serve and accordingly relate its supplier selection needs to the supply chain. Competitive priorities and order winners for the firm are a good starting point in developing a list of performance criteria to be used. For example, if you were a manager of a food-service firm, in addition to total costs, you would likely use on-time delivery and quality as top criteria for selecting suppliers. These criteria reflect the requirements that food-service supply chains need to meet.

green purchasing

The process of identifying, assessing, and managing the flow of environmental waste and finding ways to reduce it and minimize its impact on the environment.

Another criterion that is important in the selection of suppliers is environmental impact. Many firms are engaging in **green purchasing**, which involves identifying, assessing, and managing the flow of environmental waste and finding ways to reduce it and minimize its impact on the environment. Suppliers are being asked to be environmentally conscious when designing and producing their services or products. Claims such as *green*, *biodegradable*, *natural*, and *recycled* must be substantiated when bidding on a contract. We will have more to say about this topic in Chapter 15, "Supply Chain Sustainability."

When faced with multiple criteria in the supplier selection problem, management can use a preference matrix as shown in Example 14.2. See Supplement A, "Decision Making" for a review of this approach.

EXAMPLE 14.2 Using a Preference Matrix for Selecting Suppliers

The management of Compton Electronics has done a total cost analysis for three international suppliers of keyboards (see Example 14.1). Compton also considers on-time delivery, consistent quality, and environmental stewardship in its selection process. Each criterion is given a weight (total of 100 points), and each supplier is given a score (1 = poor, 10 = excellent) on each criterion. The data are shown in the following table.

		SCORE		
Criterion	Weight	Belfast	Hong Kong	Shreveport
Total Cost	25	5	8	9
On-Time Delivery	30	9	6	7
Consistent Quality	30	8	9	6
Environment	15	9	6	8

SOLUTION

The weighted score for each supplier is calculated by multiplying the weight by the score for each criterion and arriving at a total. For example, the Belfast weighted score is

$$WS = (25 \times 5) + (30 \times 9) + (30 \times 8) + (15 \times 9) = 770$$

Similarly, the weighted score for Hong Kong is 740, and for Shreveport, 735. Consequently, Belfast is the preferred supplier.

DECISION POINT

Even though Belfast had a higher total cost based on the calculations in Example 14.1, it significantly outperformed the other suppliers on the criteria Compton considered very important. Given the weights placed on the criteria, it is clear that Compton is willing to pay extra for better delivery performance, quality, and environmental stewardship.

Supplier Certification and Evaluation Supplier certification programs verify that potential suppliers have the capability to provide the services or materials the buying firm requires. ISO 9001:2008 is one such program (see Chapter 3, "Quality and Performance," for more details). Nonetheless, certification typically involves site visits by a cross-functional team from the buying firm, which does an in-depth evaluation of the supplier's capability to meet cost, quality, delivery, and flexibility targets from process and information system perspectives. The team may consist of members from operations, purchasing, engineering, information systems, and accounting. Every aspect of producing the services or materials is explored. The team observes the supplier's processes in action and reviews the documentation for completeness and accuracy. Once certified, the supplier can be used by the purchasing department without its having to make background checks.

Certification does not give the supplier a free pass on future evaluation. Performance is regularly monitored and performance records are kept. Periodic visits by the certification team may take place. Recertification may be required after a certain period of time or if performance declines.

Design Collaboration

The design collaboration process focuses on jointly designing new services or products with key suppliers; it facilitates concurrent engineering by drawing key suppliers into the new service/product development process, particularly in the design and development stages. This process seeks to eliminate costly delays and mistakes incurred when many suppliers concurrently design service packages or manufactured components.

An approach that many firms are using in their design collaboration process is called **early supplier involvement**, which is a program that includes suppliers in the design phase of a service or product. Suppliers provide suggestions for design changes and materials choices that will result in more efficient operations and higher quality. In the automotive industry, an even higher level of early supplier involvement is known as **presourcing**, whereby suppliers are selected early in a product's concept development stage and are given significant, if not total, responsibility for the design of certain components or systems of the product. Presourced suppliers also take responsibility for the cost, quality, and on-time delivery of the items they produce.

Firms can also improve performance by engaging in **value analysis**, which is a systematic effort to reduce the cost or improve the performance of services or products, either purchased or produced. It is an intensive examination of the services, materials, processes, information systems, and flows of material involved in the production of a service or an item. Benefits include reduced production, materials, and distribution costs; improved profit margins; and increased customer satisfaction.

early supplier involvement

A program that includes suppliers in the design phase of a service or product.

presourcing

A level of supplier involvement in which suppliers are selected early in a product's concept development stage and are given significant, if not total, responsibility for the design of certain components or systems of the product.

value analysis

A systematic effort to reduce the cost or improve the performance of services or products, either purchased or produced.

Negotiation

The negotiation process focuses on obtaining an effective contract that meets the price, quality, and delivery requirements of the supplier relationship process's internal customers. The nature of the relations maintained with suppliers can affect the quality, timeliness, and price of a firm's services and products. The firm's orientation toward supplier relations will affect the negotiation and design collaboration processes.

Competitive Orientation The **competitive orientation** sees negotiations between buyer and seller as a zero-sum game: Whatever one side loses, the other side gains. Short-term advantages are prized over long-term commitments. The buyer may try to beat the supplier's price down to the lowest survival

competitive orientation

A supplier relation that views negotiations between buyer and seller as a zero-sum game: Whatever one side loses, the other side gains, and short-term advantages are prized over long-term commitments.



Helen Sessions/Alamy Stock Photo

While firms engage in green purchasing for raw materials, consumers often prefer products that are environmentally safe and biodegradable.

level or push demand to high levels during boom times and order almost nothing during recessions. In contrast, the supplier presses for higher prices for specific levels of quality, customer service, and volume flexibility. Which party wins depends largely on who has the most clout.

Purchasing power determines the clout that a firm has. A buyer has purchasing power when the purchasing volume represents a significant share of the supplier's sales or the purchased service or item is standardized and many substitutes are available. We refer to this condition as *economic dependency*. However, firms may have other sources of power in a relationship with suppliers. These sources include:

- *Referent*—the supplier values identification with the buyer. For example, the fact that a firm is supplying IBM may open the door for business with other customers.
- *Expert*—the buyer has access to knowledge, information, and skills desired by the supplier. For example, a supplier to UPS may get access to logistics planning skills possessed by UPS.
- *Reward*—the buyer has the ability to give rewards to the supplier. Often, the rewards may involve the promise for future business or the opportunity to become a partner sometime in the future.
- *Legal*—the buyer has the legal right to prescribe behavior for the supplier. For example, the buyer may demand strict compliance with the negotiated contract or else the matter will be taken to court.
- *Coercive*—the buyer has the ability to punish the supplier. For example, the buyer may threaten to cancel future business with the supplier unless the supplier adheres to the buyer's demands.

It should be noted that the buyer does not always possess the power in a relationship. Sometimes the supplier holds the power; consequently, the supplier could exercise these sources of power as well.

cooperative orientation
A supplier relation in which the buyer and seller are partners, each helping the other as much as possible.

Cooperative Orientation The **cooperative orientation** emphasizes that the buyer and the seller are partners, each helping the other as much as possible. A cooperative orientation means long-term commitment, joint work on quality and service or product designs, and support by the buyer of the supplier's managerial, technological, and capacity development. A cooperative orientation favors fewer suppliers of a particular service or item, with just one or two suppliers being the ideal number. As order volumes increase, the supplier gains economies of scale, which lowers costs. When contracts are large and a long-term relationship is ensured, the supplier might even build a new facility and hire a new workforce, perhaps relocating close to the buyer's plant. Suppliers become almost an extension of the buyer.

A cooperative orientation means that the buyer shares more information with the supplier about its future buying intentions. This forward visibility allows suppliers to make better, more reliable forecasts of future demand. The buyer visits suppliers' plants and cultivates cooperative attitudes. The buyer may even suggest ways to improve the suppliers' operations. This close cooperation with suppliers could even mean that the buyer does not need to inspect incoming materials. It also could mean involving the supplier more in designing services or products, implementing cost-reduction ideas, and sharing in savings.

One advantage of a cooperative orientation is that of reducing the number of suppliers in the supply chain, which reduces the complexity of managing them. However, reducing the number of suppliers for a service or item may increase the risk of an interruption in supply. It also means less opportunity to drive a good bargain unless the buyer has a lot of clout. **Sole sourcing**, which is the awarding of a contract for a service or item to only one supplier, can amplify any problems with the supplier that may crop up.

sole sourcing
The awarding of a contract for a service or item to only one supplier.

Both the competitive and cooperative orientations have their advantages and disadvantages. The key is to use the approach that serves the firm's competitive priorities best. Some companies utilize a mixed strategy, applying a competitive approach for its commodity-like supplies and a cooperative approach for its complex, high-valued, or high-volume services and materials.

Buying

The buying process relates to the actual procurement of the service or material from the supplier. This process includes the creation, management, and approval of purchase orders and determines the locus of control for purchasing decisions. Although not all purchasing opportunities involve the Internet, virtual marketplaces have provided firms with many opportunities to improve their buying and information exchange processes. Here we discuss four approaches to e-purchasing: (1) electronic data interchange, (2) catalog hubs, (3) exchanges, and (4) auctions, and close with the implications of choosing a locus of control.

Electronic Data Interchange A traditional form of e-purchasing is **electronic data interchange (EDI)**, a technology that enables the transmission of routine, standardized business documents from computer to computer. Special communications software translates documents into and out of a generic form, allowing organizations to exchange information even if they have different hardware and software components. Invoices, purchase orders, and payments information are some of the routine documents that EDI can handle—it replaces the phone call, fax, or mailed document. Its goal is to have "no people, no paper." EDI technology has been shown to be very useful in applications of blockchain.

electronic data interchange (EDI)
A technology that enables the transmission of routine business documents having a standard format from computer to computer.

Catalog Hubs **Catalog hubs** can be used to reduce the costs of placing orders to suppliers as well as the costs of the services or goods themselves. Suppliers post their catalog of items on the hub, and buyers select what they need and purchase them electronically. The hub connects the firm to potentially hundreds of suppliers through the Internet, saving the costs of EDI, which requires one-to-one connections to individual suppliers. Moreover, the buying firm can negotiate prices with individual suppliers for items such as office supplies, technical equipment, and services. The catalog that the buying firm's employees see consists only of the approved items and the prices the buyer has prenegotiated with its suppliers. Employees use their PCs to select the items they need, and the system generates the purchase orders, which are electronically dispatched to the suppliers.

catalog hubs
A system whereby suppliers post their catalog of items on the Internet and buyers select what they need and purchase them electronically.

Exchanges An **exchange** is an electronic marketplace where buying firms and selling firms come together to do business. The exchange maintains relationships with buyers and sellers, making it easy to do business without the aspect of contract negotiations or other types of long-term conditions. Exchanges are often used for "spot" purchases to satisfy an immediate need at the lowest possible cost. Commodity items such as oil, steel, or energy fit this category. However, exchanges can also be used for almost any item, such as hotel or hospital supplies.

exchange
An electronic marketplace where buying firms and selling firms come together to do business.

Auctions An extension of the exchange is the **auction**, where firms place competitive bids to buy something. For example, a site may be formed for a particular industry, and firms with excess capacity or materials can offer them for sale to the highest bidder. Bids can be either closed or open to the competition. Industries in which auctions have value include used autos, steel, and chemicals. Examples involving consumers include eBay and Priceline.com. An approach that has received considerable attention is the so-called *reverse auction*, where suppliers bid for contracts with buyers. Each bid is posted, so suppliers can see how much lower their next bid must be to remain in the running for the contract. Each contract has an electronic prospectus that provides all the specifications, conditions, and other requirements that are nonnegotiable. The only thing left to determine is the cost to the buyer. Savings to the buyer can be dramatic, sometimes as much as 20 to 30 percent over typical contract prices.

auction
A marketplace where firms place competitive bids to buy something.

Vendor-Managed Inventories

Reliable information regarding inventories up and down the supply chain, facilitated by technologies such as cloud computing and blockchains, allows firms to collaborate on effective ways to improve material flows. A tactic that requires a reliable information exchange process is **vendor-managed inventories (VMI)**, a system in which the supplier has access to the customer's inventory data and is responsible for maintaining the inventory level required by the customer. The inventory is on the customer's site, and often the supplier retains possession of the inventory until it is used by the customer. Companies such as Walmart and Dell leverage their market position to mandate VMI. Vendor-managed inventories have several key elements.

vendor-managed inventories (VMI)
A system in which the supplier has access to the customer's inventory data and is responsible for maintaining the inventory on the customer's site.

- *Collaborative Effort.* For VMI to succeed, the customers must be willing to allow the supplier access to their inventory information, which is facilitated by IoT but must be bolstered by information on forecasts, sales promotions, and other demand-related data. The implication is that the supplier assumes an important administrative role in the management of the inventory. Thus, an atmosphere of trust and accountability is required.
- *Cost Savings.* Suppliers and customers eliminate the need for excess inventory through better operational planning. VMI lowers costs by reducing administrative and inventory costs. Order placement costs are also reduced.

- *Customer Service.* The supplier is frequently on the customer's site and better understands the operations of the customer, improving response times and reducing stockouts.
- *Written Agreement.* It is important that both parties fully understand the responsibilities of each partner. Areas such as billing procedures, forecast methods, and replenishment schedules should be clearly specified. Further, the responsibility for obsolete inventory resulting from forecast revisions and changes in contract lengths should be included.

VMI can be used both by service providers and by manufacturers. AT&T, Roadway Express, Walmart, Dell, Westinghouse, and Bose are among the companies that use it.

Key Performance Measures for the Supplier Relationship Process

It is important to monitor the performance of supply chains to see where improvements can be made or to measure the impact of disruptions. Supply chain managers monitor performance by measuring costs, time, quality, and environmental impact. Here is a list of some of the commonly used performance measures for the supplier relationship process.

- Percent of suppliers' deliveries on time
- Suppliers' lead times
- Percent defects in services and purchased materials
- Cost of services and purchased materials
- Inventory levels of supplies and purchased components
- Evaluation of suppliers' collaboration on streamlining and waste conversion
- Amount of transfer of environmental technologies to suppliers

Order Fulfillment Process

The order fulfillment process produces and delivers the service or product to the firm's customers. There are four key nested processes: (1) customer demand planning, (2) supply planning, (3) production, and (4) logistics.

Customer Demand Planning

The customer demand planning (CDP) process facilitates the collaboration of a supplier and its customers for the purpose of forecasting customer requirements for a service or product. CDP is a business-planning process that enables sales teams (and customers) to develop demand forecasts as input to service-planning processes, production and inventory planning, and revenue planning. Forecasts must generally precede plans: It is not possible to make decisions on staffing levels, purchasing commitments, and inventory levels until forecasts are developed that give reasonably accurate views of demand over the forecasting time horizon. Chapter 8, "Forecasting," contains many practical tools for forecasting customer demands.

Supply Planning

The supply planning process takes the demand forecasts produced by the customer demand planning process, the customer service levels and inventory targets provided by inventory management, and the resources provided by sales and operations planning to generate a plan to meet the demand. Regardless of whether the firm is producing services or a product, this process is critical for effective execution in the supply chain. See Chapter 9, "Inventory Management"; Chapter 10, "Operations Planning and Scheduling"; and Chapter 11, "Resource Planning" for the details involving the preparation of effective supply plans at both the aggregate and detailed levels.

Production

The production process executes the supply plan to produce the service or product. Nonetheless, the production process must be integrated with the processes that supply the inputs, establish the demands, and deliver the product to the customers. For example, while customers can always shop for standardized Dell computer packages at retail stores like Best Buy and Walmart, order placement, buying, production, and logistics processes are tightly linked at Dell when a customized machine is being ordered directly from the computer manufacturer. Dell's supply chain is designed to support an assemble-to-order strategy, thereby providing speedy service with minimal inventories.

Integrating the supply-facing and customer-facing processes to the production process is as important to service firms as it is to manufacturing firms. The best firms tightly link their production process to suppliers as well as customers.

Logistics

A key aspect of order fulfillment is the logistics process, which delivers the product or service to the customer. Five important decisions determine the design and implementation of logistics processes: (1) degree of ownership, (2) facility location, (3) mode selection, (4) capacity level, and (5) amount of cross-docking.

- *Ownership.* The firm has the most control over the logistics process if it owns and operates it, thereby becoming a *private carrier*. Although this approach may help to better achieve the firm's competitive priorities, the cost of equipment, labor, facilities, and maintenance could be high. The firm could instead leave the distribution to a *third-party logistics provider* (3PL), negotiating with the carrier for specific services. Those services could involve taking over a major portion of the order fulfillment process. 3PLs typically provide integrated services, from transportation and packaging services to warehousing and inventory management, for corporate clients that need to get their products to market. They can help with the design of a client's supply chain and facilitate the flow of information up and down the supply chain.
- *Facility Location.* A critical decision affecting the effectiveness of supply chains is the location of facilities that serve as points of service, storage, or manufacture. Chapter 13, "Supply Chain Logistic Networks," provides a complete discussion of facility location choices.
- *Mode Selection.* The five basic modes of transportation are (1) truck, (2) train, (3) ship, (4) pipeline, and (5) airplane. The drivers for the selection should be the firm's competitive priorities. Trucks provide the greatest flexibility because they can go wherever roads go. Transit times are good, and rates are usually better than trains for small quantities and short distances. Rail transportation can move large quantities cheaply; however, the transit times are long and often variable. Water transportation provides high capacity and low costs and is necessary for overseas shipments of bulky items; however, the transit times are slow, and highway or rail transportation is often needed to get the product to its ultimate destination. Pipeline transportation is highly specialized and is used for liquids, gases, or solids in slurry form. Although it has limited geographical flexibility, transporting via pipeline requires no packaging, and the operating costs per mile are low. Finally, air transportation is the fastest and most costly mode per mile. Nonetheless, getting a product to the customer fast using air transportation may actually reduce total costs when the costs of inventory and warehouse handling are considered. The cost of the funds tied up in some in-transit inventories can be considerable. Firms can also use mixed modal transportation, whereby a given shipment may combine two or more different modes. For example, containers can be carried by trucks, trains, or ships over different portions of their transit and can often give the best trade-offs between cost and delivery times.
- *Capacity.* The performance of a logistics process is directly linked to its capacity. The ownership decision and the modal selection decision are often intertwined because the question of how much capacity is needed must be resolved. If ownership of the equipment and facilities is under consideration, capital costs as well as variable operating costs must be weighed against the costs of obtaining the logistics services from a supplier. Making things more difficult is the fact that the requirements for the logistics process are rarely known with certainty. In such cases, management can use the *expected value*



bkp/Shutterstock

The Trans-Alaska Pipeline System traverses 800 miles from the North Slope of Alaska to the northernmost ice-free port of Valdez, Alaska. The pipeline is 48 inches in diameter, has 11 pump stations, and has a maximum throughput of 2 million barrels per day.

decision rule to evaluate capacity alternatives. The expected value of an alternative is calculated as follows:

> *Expected value of an alternative* = (probability of demand and occurring) multiplied by (payoff for using the alternative if that level of demand materialized) summed over all possible levels of demand.

See Supplement A, "Decision Making," for details on this approach. Example 14.3 demonstrates the use of the expected value decision rule for analyzing truck capacity.

EXAMPLE 14.3 Using the Expected Value Decision Rule for Truck Capacity

Tower Distributors provides logistical services to local manufacturers. Tower picks up products from the manufacturers, takes them to its distribution center, and then assembles shipments to retailers in the region. Tower needs to build a new distribution center; consequently, it needs to make a decision on how many trucks to use. The monthly amortized capital cost of ownership is $2,100 per truck. Operating variable costs are $1 per mile for each truck owned by Tower. If capacity is exceeded in any month, Tower can rent trucks at $2 per mile. Each truck Tower owns can be used 10,000 miles per month. The requirements for the trucks, however, are uncertain. Managers have estimated the following probabilities for several possible demand levels and corresponding fleet sizes.

Requirements (miles/month)	100,000	150,000	200,000	250,000
Fleet Size (trucks)	10	15	20	25
Probability	0.2	0.3	0.4	0.1

Notice that the sum of the probabilities must equal 1.0. If Tower Distributors wants to minimize the expected cost of operations, how many trucks should it use?

SOLUTION

We use the expected value decision rule to evaluate the alternative fleet sizes where we want to minimize the expected monthly cost. To begin, the monthly cost, C, must be determined for each possible combination of fleet size and requirements. The cost will depend on whether additional capacity must be rented for the month. For example, consider the *10-truck fleet size* alternative, which represents a capacity of 100,000 miles per month.

C = monthly capital cost of ownership + variable operating cost per month + rental costs if needed:

$$C\text{ (100,000 miles/month)} = (\$2{,}100/\text{truck})(10\text{ trucks}) + (\$1/\text{mile})(100{,}000\text{ miles}) = \$121{,}000$$

$$C\text{ (150,000 miles/month)} = (\$2{,}100/\text{truck})(10\text{ trucks}) + (\$1/\text{mile})(100{,}000\text{ miles}) + (\$2\text{ rent/mile})(150{,}000\text{ miles} - 100{,}000\text{ miles}) = \$221{,}000$$

$$C\text{ (200,000 miles/month)} = (\$2{,}100/\text{truck})(10\text{ trucks}) + (\$1/\text{mile})(100{,}000\text{ miles}) + (\$2\text{ rent/mile})(200{,}000\text{ miles} - 100{,}000\text{ miles}) = \$321{,}000$$

$$C\text{ (250,000 miles/month)} = (\$2{,}100/\text{truck})(10\text{ trucks}) + (\$1/\text{mile})(100{,}000\text{ miles}) + (\$2\text{ rent/mile})(250{,}000\text{ miles} - 100{,}000\text{ miles}) = \$421{,}000$$

Next, calculate the expected value for the *10-truck fleet size* alternative as follows:

$$\textit{Expected Value}\text{ (10 trucks)} = 0.2(\$121{,}000) + 0.3(\$221{,}000) + 0.4(\$321{,}000) + 0.1(\$421{,}000) = \$261{,}000$$

Using similar logic, we can calculate the expected costs for each of the other fleet-size options:

$$\textit{Expected Value}\text{ (15 trucks)} = 0.2(\$131{,}500) + 0.3(\$181{,}500) + 0.4(\$281{,}500) + 0.1(\$381{,}500) = \$231{,}500$$

$$\textit{Expected Value}\text{ (20 trucks)} = 0.2(\$142{,}000) + 0.3(\$192{,}000) + 0.4(\$242{,}000) + 0.1(\$342{,}000) = \$217{,}000$$

$$\textit{Expected Value}\text{ (25 trucks)} = 0.2(\$152{,}500) + 0.3(\$202{,}500) + 0.4(\$252{,}500) + 0.1(\$302{,}500) = \$222{,}500$$

Using the expected value decision rule, Tower Distributors should use a fleet of 20 trucks.

DECISION POINT

The fleet size of 20 trucks means that Tower will have enough capacity to handle 90 percent of its requirements (sum of the probabilities for 100,000 miles, 150,000 miles, and 200,000 miles). Further, there will be a 50 percent chance that it will have excess capacity (sum of the probabilities for 100,000 miles and 150,000 miles). While the decision to invest in 20 trucks will minimize expected costs, it will also provide slack capacity 50 percent of the time, which is reflective of the relatively high cost for being short of capacity.

- *Cross-Docking.* Low-cost operations and delivery speed can be enhanced with a technique called **cross-docking**, which is the packing of products on incoming shipments so that they can be easily sorted at intermediate warehouses for outgoing shipments based on their final destinations; the items are carried from the incoming-vehicle docking point to the outgoing-vehicle docking point without being stored in inventory at the warehouse. The warehouse becomes a short-term staging area for organizing efficient shipments to customers. The benefits of cross-docking include reductions in inventory investment, storage space requirements, handling costs, and lead times, as well as increased inventory turnover and accelerated cash flow. Management must decide where cross-docking operations are best placed, given the overall flow of items and their destinations.

cross-docking

The packing of products on incoming shipments so that they can be easily sorted at intermediate warehouses for outgoing shipments based on their final destinations.

Key Performance Measures for the Order Fulfillment Process

Managers periodically collect data on performance measures and track them to note changes in level or direction. Currently, concerns about security and the environment are prompting supply chain managers to take a careful look at their order fulfillment operations and those of their suppliers. Here are some measures being used to monitor performance.

- Percent of incomplete orders shipped
- Percent of orders shipped on time
- Time to fulfill the order
- Percent of botched services or returned items
- Cost to produce the service or item
- Customer satisfaction with the order fulfillment process
- Inventory levels of work-in-process and finished goods
- Amount of greenhouse gases emitted into the air
- Number of security breaches

Customer Relationship Process

The customer relationship process addresses the interface between the firm and its customers downstream in the supply chain. The purpose of the customer relationship process, which supports *customer relationship management (CRM)* programs, is to identify, attract, and build relationships with customers and to facilitate the transmission and tracking of orders. Key nested processes include the marketing, order placement, and customer service processes.

Marketing

The marketing process focuses on such issues as determining the customers to target, how to target them, what services or products to offer and how to price them, and how to manage promotional campaigns. In this regard, **electronic commerce (e-commerce)**, which is the application of information and communication technology anywhere along the supply chain of business processes, has had a huge impact up and down the supply chain. Blockchain has facilitated the application of e-commerce because of its security qualities, transparency in transactions, cost efficiency, and smart contract capability. It also makes payments easier, especially if cryptocurrencies are involved. There are two e-commerce technologies that relate to the marketing process: (1) business-to-consumer (B2C) and (2) business-to-business (B2B) systems.

electronic commerce (e-commerce)

The application of information and communication technology anywhere along the supply chain of business processes.

Business-to-Consumer Systems Business-to-consumer (B2C) systems, which allow customers to transact business over the Internet, are commonplace. B2C e-commerce offers a new distribution channel for businesses, and consumers can avoid crowded department stores with long checkout lines and parking-space shortages. Many of the advantages of e-commerce were first exploited by retail "e-businesses," such as Amazon.com, E*TRADE, and Autobytel. These three companies created Internet versions of traditional bookstores, brokerage firms, and auto

dealerships. The Internet has changed operations, processes, and cost structures for even traditional retailers, and the overall growth in its usage has been dramatic. Today, anyone with an Internet connection can open a store in cyberspace. Even well-established retailers like Walmart have a Web-based shopping presence through their site-to-store program, where customers can actually shop on the Internet and pick up their order at the closest store within a few days.

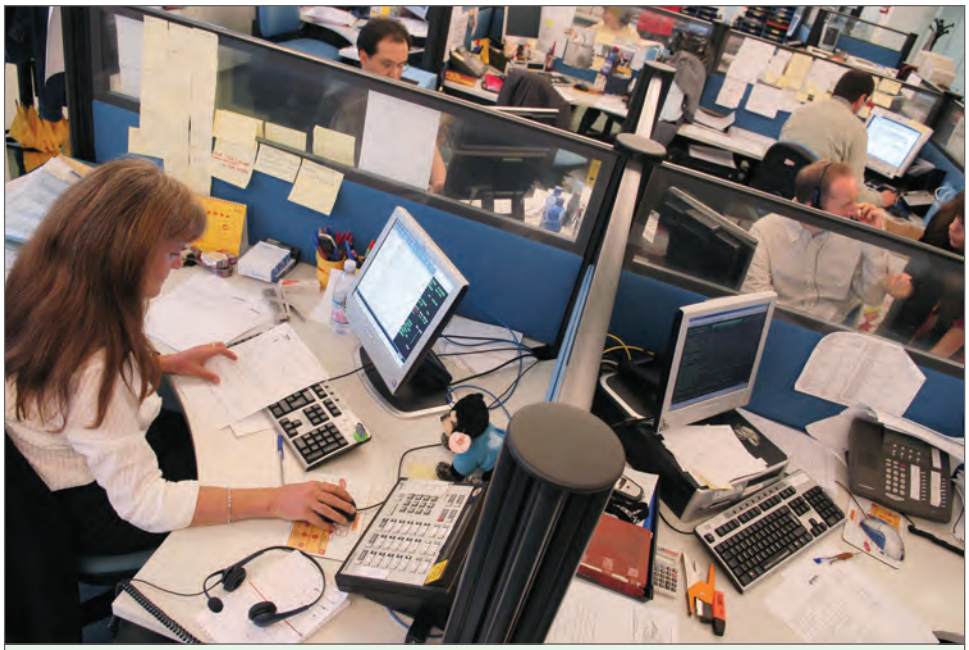
Business-to-Business Systems The biggest growth, however, has been in business-to-business (B2B) e-commerce systems, or commerce between firms. In fact, B2B e-commerce outpaces B2C transactions, with trade between businesses making up more than 70 percent of the regular economy. These systems facilitate trade up and down the supply chain, making it easier to purchase or sell services or products. B2B systems can also help manage the flow of materials. For example, if a distributor is out of stock, the firm's central warehouse can be notified to immediately ship replenishment stock directly to the customer.

Order Placement

The order placement process involves the activities required to execute a sale, register the specifics of the order request, confirm the acceptance of the order, and track the progress of the order until it is completed. Blockchain technology is a big help here.

The Internet enables firms to reengineer their order placement process to benefit both the customer and the firm. The Internet provides the following advantages for a firm's order placement process.

- *Cost Reduction.* Using the Internet can reduce the costs of processing orders because it allows for greater participation by the customer. Customers can select the services or products they want and place an order with the firm without actually talking to anyone. This approach reduces the need for call centers, which are labor intensive and often take longer to place orders.
- *Revenue Flow Increase.* A firm's Web page can allow customers to enter credit card information or purchase-order numbers as part of the order placement process. This approach reduces the time lags often associated with billing the customer or waiting for checks sent in the mail.
- *Global Access.* Another advantage the Internet provides to firms is the opportunity to accept orders 24 hours a day. Traditional brick-and-mortar firms only take orders during their normal business hours. Firms with Internet access can reduce the time it takes to satisfy customers, who can shop and purchase at any time. This access gives these firms a competitive advantage over brick-and-mortar firms.
- *Pricing Flexibility.* Firms with their services and products posted on the Web can easily change prices as the need arises, thereby avoiding the cost and delay of publishing new catalogs. Customers placing orders have current prices to consider when making their choices. From the perspective of supply chains, Dell uses this capability to control for component shortages. Because of its direct-sales approach and promotional pricing, Dell can steer customers to certain configurations of computers for which ample supplies exist.



Dino Fracchia/Alamy Stock Photo

Many firms have outsourced their customer service processes, particularly if the service can be transacted over the phone. Here Italian employees at a call center in Milan, Italy, provide service to international DHL customers.

Customer Service

The customer service process helps customers with answers to questions regarding the service or product, resolves problems, and, in general, provides information to assist customers. It is an important point of contact between the firm and its customers, who may judge the firm on the basis of their experiences with this process. The age-old trade-off between cost and quality, however, enters the picture, especially for call centers. In an effort to reduce the cost of their customer service

process, many firms have opted to replace human service agents with automated systems, which often require customers to wade through an exhausting sequence of options that sometimes only lead to frustration. Other firms are using Verbots®, or "verbal robots," which are supported by sophisticated artificial intelligence. They have personalities, ask and respond to questions, and in some cases are almost indistinguishable from humans over the phone. Nonetheless, most customers and others seeking information about a service or product prefer humans. Consequently, in consideration for the cost involved, many companies have expanded their supply chain by outsourcing the customer service process to an off-shore site where labor costs are low. In this regard, India has responded in a big way to the international need for low-cost call centers. Of course, the big risk in outsourcing the customer service process, or a part of it, is that the firm loses some control over a process that has direct interface with its customers. This consideration should be carefully weighed in the final analysis.

Key Performance Measures for the Customer Relationship Process

Because the customer relationship process is the interface between the firm and its customers, monitoring its performance is critical to identifying areas for improvement. Performance measures can be tracked over time to identify changes. Statistical process control charts can be used to determine whether the changes are statistically significant. Some of the commonly used performance measures for the customer relationship process include the following:

- Percent of orders taken accurately
- Time to complete the order placement process
- Customer satisfaction with the order placement process
- Customer's evaluation of firm's environmental stewardship
- Percent of business lost because of supply chain disruptions

Integrated supply chains are powerful tools for achieving competitiveness along many performance measures. In Chapter 15, "Supply Chain Sustainability," we take a look at the impact of environmental concerns on supply chains and how integrated supply chains can be used to relieve some of those concerns and still be profitable.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
14.1 Identify the major causes of disruptions in a supply chain.	See the section "Supply Chain Disruptions." Focus on understanding the causes for disruptions from external and internal sources and what it means to integrate the supply chain. Study Figure 14.1, which demonstrates the flows in a supply chain, and Figure 14.2, which shows how mild dynamics in consumer demand can result in wild fluctuations in supplier demand. Figure 14.3 shows the integrative model used in this text; Figure 14.4 shows the SCOR model.	
14.2 Explain how firms can mitigate the operational, financial, and security risks in a supply chain.	See the section "Supply Chain Risk Management" for the ways firms can mitigate the operational, financial, and security risks they face. Be sure to understand the practice of hedging and how exchange rate fluctuations and commodity price changes can be dealt with. Also study Figure 14.5 to understand the complexity of managing security risks in a supply chain.	
14.3 Describe how cloud computing and blockchains can be used to integrate supply chains.	See the section "Cloud Computing and Blockchains" for a description of what the cloud computing and blockchain technologies are and how they can be used to integrate supply chains. Study Figure 14.6 and Figure 14.7 for additional background on these technologies.	
14.4 Describe the four major nested processes in the new service or product development process.	The section "New Service or Product Development Process" discusses the four nested processes. Figure 14.8 shows how they are linked.	
14.5 Explain the five major nested processes in the supplier relationship process and use total cost analysis and preference matrices to identify appropriate sources of supply.	See the section "Supplier Relationship Process" for a discussion of the five nested processes. Focus on the "sourcing" process, which explains the total cost model and the preference matrix approach for finding an appropriate source of supply. Study Examples 14.1 and 14.2, along with Solved Problems 1 and 2.	**OM Explorer Tutor:** A.3: Preference Matrix **OM Explorer Solver:** Preference Matrix **POM for Windows:** Preference Matrix

Learning Objective	Guidelines for Review	Online Resources
14.6 Identify the four major nested processes in the order fulfillment process and use the expected value decision rule to determine the appropriate capacity of logistic resources.	Review the section "Order Fulfillment Process," which discusses the four key nested processes. Focus on Example 14.3, which shows how to use the expected value decision rule to choose the appropriate amount of truck capacity. Solved Problem 3 shows the setup and solution to a problem involving the expected value decision rule.	**OM Explorer Tutor:** A.5: Decisions Under Risk **OM Explorer Solver:** Decision Theory **POM for Windows:** Decision Tables
14.7 Define the three major nested processes in the customer relationship process.	The section "Customer Relationship Process" discusses the three major nested processes and how they link together.	

Key Equations

Supplier Relationship Process

1. Total Annual Cost $= pD +$ Freight costs $+ (Q/2 + \overline{d}L)H +$ Administrative costs

Order Fulfillment Process

2. *Expected value of an alternative* = (probability of a level of demand occurring) (payoff for using the alternative if that level of demand materialized) summed over all possible levels of demand.

Key Terms

auction 611
blockchain 601
bullwhip effect 594
catalog hubs 611
cloud computing 600
competitive orientation 609
concurrent engineering 605
cooperative orientation 610
cross-docking 615
early supplier involvement 609
electronic commerce (e-commerce) 615
electronic data interchange (EDI) 611
exchange 611
futures contract 598
green purchasing 608
hedging 598
ISO 28000:2007 600
presourcing 609
purchasing 606
radio frequency identification (RFID) 603
SCOR model 595
smart contracts 604
sole sourcing 610
supply chain integration 591
supply chain risk management 596
value analysis 609
vendor-managed inventories (VMI) 611

Solved Problem 1

Eagle Electric Repair is a repair facility for several major electric appliance manufacturers. Eagle wants to find a low-cost supplier for an electric relay switch used in many appliances. The annual requirements for the relay switch (D) are 100,000 units. Eagle operates 250 days a year. The following data are available for two suppliers of the part, Kramer and Sunrise:

Supplier	Freight Costs Shipping Quantity (Q)		Price/Unit (p)	Carrying Cost/Unit (H)	Lead Time (L) (days)	Administrative Costs
	2,000	10,000				
Kramer	$30,000	$20,000	$5.00	$1.00	5	$10,000
Sunrise	$28,000	$18,000	$4.90	$0.98	9	$11,000

Which supplier will provide the lowest annual total costs?

SOLUTION

The daily requirements for the relay switch are:

$$\overline{d} = 100{,}000/250 = 400 \text{ units}$$

We must calculate the total annual costs for each alternative:

Total annual cost = Material costs + Freight costs + Inventory costs + Administrative costs

$= pD +$ Freight costs $+ (Q/2 + \overline{d}L)H +$ Administrative costs

Kramer

$Q = 2{,}000$: ($5.00)(100,000) + $30,000 + (2,000/2 + 400(5))($1) + $10,000 = $543,000

$Q = 10{,}000$: ($5.00)(100,000) + $20,000 + (10,000/2 + 400(5))($1) + $10,000 = $537,000

Sunrise

$Q = 2{,}000$: ($4.90)(100,000) + $28,000 + (2,000/2 + 400(9))($0.98) + $11,000 = $533,508

$Q = 10{,}000$: ($4.90)(100,000) + $18,000 + (10,000/2 + 400(9))($0.98) + $11,000 = $527,428

The analysis reveals that using Sunrise and a shipping quantity of 10,000 units will yield the lowest annual total costs.

Solved Problem 2

Eagle Electric Repair wants to select a supplier based on total annual cost, consistent quality, and delivery speed. The following table shows the weights management assigned to each criterion (total of 100 points) and the scores assigned to each supplier (Excellent = 5, Poor = 1).

Criterion	Weight	Scores	
		Kramer	Sunrise
Total annual cost	30	4	5
Consistent quality	40	3	4
Delivery speed	30	5	3

Which supplier should Eagle select, given these criteria and scores?

SOLUTION

Using the preference matrix approach, the weighted scores for each supplier are:

Kramer: $WS = (30 \times 4) + (40 \times 3) + (30 \times 5) = 390$

Sunrise: $WS = (30 \times 5) + (40 \times 4) + (30 \times 3) = 400$

Based on the weighted scores, Eagle should select Sunrise even though delivery speed performance would be better with Kramer.

Solved Problem 3

Schneider Logistics Company has built a new warehouse in Columbus, Ohio, to facilitate the consolidation of freight shipments to customers in the region. George Schneider must determine how many teams of dock workers he should hire to handle the cross-docking operations and the other warehouse activities. Each team costs $5,000 a week in wages and overhead. Extra capacity can be subcontracted at a cost of $8,000 a team per week. Each team, whether in-house or subcontracted, can satisfy 200 labor hours of work a week. The labor hour requirements for the new facility are uncertain. Management has estimated the following probabilities for the requirements:

Requirements (hours/wk)	200	400	600
Number of teams	1	2	3
Probability	0.20	0.50	0.30

How many teams should Schneider hire?

SOLUTION

We use the expected value decision rule by first computing the cost for each option for each possible level of requirements and then using the probabilities to determine the expected value for each option. The option with the lowest expected cost is the one Schneider will implement. We demonstrate the approach using the "one team" in-house option.

One Team In-House

$$C(200) = \$5{,}000$$
$$C(400) = \$5{,}000 + \$8{,}000 = \$13{,}000$$
$$C(600) = \$5{,}000 + \$8{,}000 + \$8{,}000 = \$21{,}000$$

Expected Value

$$\text{(One Team)} = 0.20(\$5{,}000) + 0.50(\$13{,}000) + 0.30(\$21{,}000) = \$13{,}800$$

A table of the complete results is provided.

In-House	Weekly Labor Requirements			Expected Value
	200 hr	400 hr	600 hr	
One team	$5,000	$13,000	$21,000	$13,800
Two teams	$10,000	$10,000	$18,000	$12,400
Three teams	$15,000	$15,000	$15,000	$15,000

Based on the expected value decision rule, Schneider should employ two teams at the warehouse.

Discussion Questions

1. Suppose you are a retailer of fashion apparel meant for young professionals working in London. To keep costs down, you design the apparel in London and get it manufactured in Bangladesh and buy in large quantities. By the time, the manufactured clothes reach the shop floor, fashion trends change and the style of your apparel becomes outdated. Due to this, you appear to be less responsive to demand fluctuations. Explain how the redesign of a supply chain can help to mitigate this problem.
2. The inclusion of a disruptive technology in a firm's supply chain puts pressure on supply chain integration and has implications for how the four core processes are managed. Explain how blockchains work and how they may affect the competitive priorities for a firm in light of the core processes.
3. Chrysler and General Motors vigorously compete with each other in many automobile and truck markets. When Jose Ignacio Lopez was vice president of purchasing for GM, he made it clear that his buyers were not to accept luncheon invitations from suppliers. Thomas Stalcamp, head of purchasing for Chrysler at the time, instructed his buyers to take suppliers to lunch. Rationalize these two directives in light of supplier relations and the impact on supply chain management.
4. Firms such as Walmart, General Electric, Chase Manhattan, and Boeing have a lot of influence in their respective supply chains because of the power they have. Explain how firms with a lot of power can influence supply chain integration.
5. We discussed the inventory and supply chain considerations such as small lot sizes, close supplier ties, and quality at the source in Chapter 4, "Lean Systems." What are the implications of these principles for supply chain integration?

Problems

The OM Explorer, POM for Windows, and Active Models software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations.

Supply Chain Risk Management

1. Eastmark Electrical Equipment Manufacturers needs to secure its supply of copper for the next year. The price of copper is extremely volatile because of huge month-to-month variation in demand. Eastmark wants to break even with a hedge against future copper prices. Currently, the market price for copper is reasonably low at $3.25 per pound or $325 (CWT). Eastmark has entered into a contract with the supplier for 500,000 pounds of copper per month starting in January at market prices. Eastmark has also entered into a futures contract with

a financial institution for 500,000 pounds per month at $3.25 per pound. *Note:* CWT (hundredweight) is equal to 100 pounds in the United States.

a. Calculate the 1-month financial and the physical results if the market price of copper has risen to $4.50 per pound.

b. Calculate the 1-month financial and the physical results if the market price of copper has fallen to $3.00 per pound.

2. Refer to Problem 1 regarding Eastmark Electrical Equipment Manufacturers. Suppose the futures contact is still in force in February.

a. However, assume the firm has just lost a key client's business and purchases only 400,000 pounds of copper.

i. Calculate the 1-month financial and the physical results if the market price of copper has risen to $4.50 per pound. Calculate only the financial impact of copper transactions and disregard the loss of revenue due to business loss.

ii. Calculate the 1-month financial and the physical results if the market price of copper has fallen to $3.00 per pound. Calculate only the financial impact of copper transactions and disregard the loss of revenue due to business loss.

b. Now assume the firm has just received a new client's business and must purchase 800,000 pounds of copper.

i. Calculate the 1-month financial and the physical results if the market price of copper has risen to $4.50 per pound. Calculate only the financial impact of copper transactions and disregard the loss of revenue due to business loss.

ii. Calculate the 1-month financial and the physical results if the market price of copper has fallen to $3.00 per pound. Calculate only the financial impact of copper transactions and disregard the loss of revenue due to business loss.

Supplier Relationship Process

3. Horizon Cellular manufactures cell phones for exclusive use in its communications network. Management must select a circuit board supplier for a new phone soon to be introduced to the market. The annual requirements are 50,000 units and Horizon's plant operates 250 days per year. The data for three suppliers are in Table 14.2.

Which supplier and shipping quantity will provide the lowest total cost for Horizon Cellular?

TABLE 14.2 | DATA FOR SUPPLIERS TO HORIZON CELLULAR

Supplier	Annual Freight Costs Shipping Quantity		Price/Unit	Annual Holding Cost/Unit	Lead Time (days)	Annual Administrative Cost
	10,000	20,000				
Abbott	$10,000	$7,000	$30	$6.00	4	$10,000
Baker	$12,000	$9,000	$28	$5.60	7	$12,000
Carpenter	$9,000	$6,500	$31	$6.20	3	$9,000

4. Eight Flags operates several amusement parks in the Midwest. The company stocks machine oil to service the machinery for the many rides at the parks. Eight Flags needs 30,000 gallons of oil annually; the parks operate 50 weeks a year. Management is unsatisfied with the current supplier of oil and has obtained two bids from other suppliers. The data are contained in Table 14.3.

Which supplier and which shipping quantity will provide the lowest costs for Eight Flags?

TABLE 14.3 | DATA FOR SUPPLIERS TO EIGHT FLAGS

Supplier	Annual Freight Costs Shipping Quantity			Price/Unit	Annual Holding Cost/Unit	Lead Time (wk)	Annual Administrative Cost
	5,000	10,000	15,000				
Sharps	$5,000	$2,600	$2,000	$4.00	$0.80	4	$4,000
Winkler	$5,500	$3,200	$2,900	$3.80	$0.76	6	$5,000

5. The Bennet Company purchases one of its essential raw materials from three suppliers. Bennet's current policy is to distribute purchases equally among the three. The owner's son, Benjamin Bennet, just graduated from a business college. He proposes that these suppliers be rated (high numbers mean a good performance) on six performance criteria weighted as shown in the table. A total score hurdle of 0.60 is proposed to screen suppliers. Purchasing policy would be revised to order raw materials from suppliers with performance scores greater than the total score hurdle, in proportion to their performance rating scores.

Performance Criterion	Weight	Rating		
		Supplier A	Supplier B	Supplier C
1. Price	0.2	0.6	0.5	0.9
2. Quality	0.2	0.6	0.4	0.8
3. Delivery	0.3	0.6	0.3	0.8
4. Production facilities	0.1	0.5	0.9	0.6
5. Environmental protection	0.1	0.7	0.8	0.6
6. Financial position	0.1	0.9	0.9	0.7

a. Use a preference matrix to calculate the total weighted score for each supplier.

b. Which supplier(s) survived the total score hurdle? Under the younger Bennet's proposed policy, what proportion of orders would each supplier receive?

c. What advantages does the proposed policy have over the current policy?

6. Beagle Clothiers uses a weighted score for the evaluation and selection of its suppliers of trendy fashion garments. Each supplier is rated on a 10-point scale (10 = highest) for four different criteria: price, quality, delivery, and flexibility (to accommodate changes in quantity and timing). Because of the volatility of the business in which Beagle operates, flexibility is given twice the weight of each of the other three criteria, which are equally weighted. The table in the right column shows the scores for three potential suppliers for the four performance criteria. Based on the highest weighted score, which supplier should be selected?

Criteria	Supplier A	Supplier B	Supplier C
Price	8	6	6
Quality	9	7	7
Delivery	7	9	6
Flexibility	5	8	9

7. **[D]** Bradley Solutions and Alexander Limited are two well-established suppliers of inexpensive tools. Weekend Projects is a national chain of retail outlets that caters to the occasional fixer-upper who would prefer to get the job done fast rather than investing in a well-appointed tool box. Weekend Projects wants to find a supplier for a particular tool set that promises to be a big seller. Expected annual sales are 100,000 units. Weekend's warehouses operate 50 weeks a year. Management collected data on the two suppliers, which are contained in the first table.

a. Which of the two suppliers would provide the lowest annual cost to Weekend Projects? What shipping quantity would you suggest?

b. Before management could make a decision, another option became available. Zelda Tools offered the tool set for only $8.00; however, the lead time is longer than the other two suppliers. Zelda is a new supplier and has not been in the industry very long. Additional data for Zelda are in the second table.

Management has begun to assess the administrative costs to manage the contract with Zelda. What is the lowest level of administrative costs at which Weekend Projects would be indifferent between using Zelda versus the option you chose in part (a)?

Supplier	Freight Costs/Shipping Quantity			Price/Unit	Annual Holding Cost/Unit	Lead Time (wk)	Annual Administrative Cost
	10,000	25,000	50,000				
Bradley	$35,000	$25,000	$18,000	$8.10	$1.62	6	$10,000
Alexander	$40,000	$28,000	$19,000	$8.10	$1.62	4	$15,000

Supplier	Freight Costs/Shipping Quantity			Price/Unit	Annual Holding Cost/Unit	Lead Time (wk)
	10,000	25,000	50,000			
Zelda	$45,000	$25,000	$17,000	$8.00	$1.60	7

8. **[D]** Wanda Lux must select a supplier for a plastic bottle and proprietary dispenser for its new hair shampoo. Three suppliers have placed bids; at Wanda's request, all bids are for a shipping quantity of 20,000 bottles with annual requirements of 40,000 units. Wanda's factory operates 250 days a year. The first table shows each supplier's price, estimated annual freight costs, and current lead times; management has added estimates for holding costs and administrative oversight costs for each supplier.

Beyond costs, however, Wanda has three other criteria considered important in the selection of a supplier. The second table shows all the criteria, their weights, and the scores for all of them except total costs, where a score of 1 indicates "poor" and 10 indicates "superior." Because all three suppliers have done business with Wanda Lux before, management will assign a score of "10" to the supplier with the lowest total annual cost, a score of "8.5" for the next lowest cost, and a score of "7.0" for the worst cost of the three.

a. Which of the three suppliers will provide the lowest annual cost to Wanda Lux?

b. Given Wanda's criteria and weighting system, which supplier should Wanda award the contract to?

[D] = Difficult Problem

Suppliers	Freight Costs	Price/Unit	Annual Holding Cost Per Unit	Lead Time (days)	Annual Administrative Costs
Dover Plastics	$3,500	$5.10	$1.02	15	$4,000
Evan & Sons	$3,000	$5.05	$1.01	12	$6,000
Farley, Inc.	$4,500	$5.00	$1.00	20	$3,000

Criterion	Weight	Score		
		Dover	Evan	Farley
Total Cost	30	?	?	?
Consistent Quality	30	9	9	7
On-Time Delivery	20	8	9	9
Environment	20	8	7	7

9. **[D]** Adelie Enterprises is exploring a new service to provide weekly delivery of grocery items to homes in the greater Greenwood area. The company's customers place Web-based orders and Adelie's team assembles and delivers the orders in specially designed cardboard boxes. Management, interested in identifying a supplier that can provide boxes cheaply and efficiently, has discovered that each potential supplier's ability to satisfy the company's requirements is influenced by the level of demand. The following table provides Adelie's vendor selection criteria, criterion weights, and rankings (1–10, with 10 being the highest) under the assumption that low, moderate, or high demand is generated for their service.

SUPPLIER RATING UNDER LOW, MODERATE, AND HIGH LEVELS OF DEMAND

	Weight	Local Supplier			National Supplier			International Supplier		
		Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Product Quality	0.35	8	6	5	7	7	7	6	6	6
Delivery Speed	0.15	9	7	3	6	6	6	4	5	7
Product Price	0.25	5	5	3	5	7	9	7	7	9
Environmental Impact	0.25	9	9	9	7	7	7	8	8	8

   a. Which supplier should be selected if there is low demand for Adelie's new service? Which supplier should be selected under moderate-demand assumptions? Under high-demand assumptions?

   b. Which supplier is selected if Adelie evaluates each alternative using a maximin decision criterion (see Supplement A, "Decision Making")?

   c. Which supplier achieves the highest expected ranking if the probability of low demand is 35 percent, moderate demand is 45 percent, and high demand is 20 percent?

10. **[D]** Adelie Enterprises (from Problem 9) has decided to drop the international supplier from consideration. Furthermore, Adelie has decided to order boxes in lots of 10,000 to optimize the use of available storage space at its distribution facility. To more completely consider the cost/volume trade-offs associated with selecting the local or national supplier, management has collected the following data. Adelie services its customers 250 days per year.

	Demand Level	Demand	Price/Unit	Freight Cost/1,000	Carrying Cost/ Unit	Lead Time (days)	Administrative Costs
Local Supplier	Low	50,000	$1.25	$20	$0.10	1	$15,000
	Moderate	100,000	$1.25	$20	$0.10	1	$15,000
	High	250,000	$1.25	$20	$0.10	1	$15,000
National Supplier	Low	50,000	$1.35	$120	$0.10	15	$12,500
	Moderate	100,000	$1.25	$120	$0.10	15	$12,500
	High	250,000	$1.00	$120	$0.10	15	$12,500

a. On purely a total cost basis, which supplier should be selected if there is low demand for Adelie's new service; which supplier should be selected under moderate-demand assumptions; and which supplier should be selected under high demand?

b. Which supplier achieves the lowest expected cost if the probability of low demand is 35 percent, moderate demand is 45 percent, and high demand is 20 percent?

Order Fulfillment Process

11. Wingman Distributing Company is expanding its supply chain to include a new distribution hub in South Bend. A key decision involves the number of trucks for the facility. The particular model of truck Wingman is considering can be used 8,000 miles a month and will cost $1,500 a month in capital costs. In addition, each mile a truck is used costs $0.90 for maintenance. A local truck rental firm will rent trucks at a cost of $1.40 per mile. Given the distribution of likely requirements for trucks, management has come up with three alternatives to consider, as shown in the table:

Monthly requirements (miles)	40,000	80,000	120,000
Probability	0.30	0.40	0.30
Fleet size (trucks)	5	10	15

Which fleet size will yield the lowest expected monthly costs for Wingman?

12. Sanchez Trucking has been experiencing delays at its warehouse operations. Management hired a consultant to find out why service deliveries to local businesses have taken longer than they should. The consultant narrowed down the problem to the number of work crews loading and unloading trucks. Each crew consists of six employees who work as a team on a variety of tasks; each employee works a full 40 hours a week. However, costs are also a concern. The consultant advised management that they could supplement work crews with short-term employees, at a higher cost, to cover unexpected needs on a weekly basis. Each work crew permanently hired by Sanchez costs $3,200 per week in wages and benefits, while a crew of short-term employees costs $5,000 per week. Complicating the decision is the fact that the weekly hourly requirements for work crews is uncertain because of the volatility in the number of deliveries to be made. Deliberating with management, the consultant arrived at the following data:

Requirements (labor hours)	720	960	1,200	1,440
Probability	0.2	0.4	0.3	0.1
Number of Crews	3	4	5	6

If the consultant wants to offer a solution that minimizes the expected weekly costs for Sanchez, how many work crews should Sanchez have on its permanent payroll?

13. Acadia Logistics anticipates that it will need more distribution center space to accommodate what it believes will be a significant increase in demand for its final-mile services. Acadia could either lease public warehouse space to cover all levels of demand or construct its own distribution center to meet a specified level of demand, and then use public warehousing to cover the rest. The yearly cost of building and operating its own facility, including the amortized cost of construction, is $12.00 per square foot. The yearly cost of leasing public warehouse space is $20.00 per square foot. The expected demand requirements follow:

Requirements (sq. ft.)	200,000	300,000	400,000	500,000
Probability	0.4	0.3	0.2	0.1

a. Calculate the expected value of leasing public warehouse space as required by demand.

b. Calculate the expected value of building a 200,000-square-foot distribution center and leasing public warehouse space as required if demand exceeds the need for 200,000 square feet of space.

c. Calculate the expected value of building a 300,000-square-foot distribution center and leasing public warehouse space as required if demand exceeds the need for 300,000 square feet of space.

d. Calculate the expected value of building a 400,000-square-foot distribution center and leasing public warehouse space as required if demand exceeds the need for 400,000 square feet of space.

e. Calculate the expected value of building a 500,000-square-foot distribution center.

f. Which of these decisions provides the minimized expected value?

14 Transworld Deliveries is expanding its contract home delivery service into the northeastern United States. The company anticipates that to accommodate this expansion it will need between 25 and 40 staffed delivery vehicles. Transworld is currently moving 25 of its own vehicles, with drivers, into the Northeast. The daily cost of operating its own fleet is $820 per vehicle, while the daily cost of leasing a vehicle and driver is expected to be $1,200 per vehicle. The expected demand requirements follow:

Requirements (in vehicles)	25	30	35	40
Probability	0.25	0.25	0.25	0.25

Using an expected value approach, should Transworld purchase additional vehicles and hire additional drivers? If so, how many would you recommend?

CASE Wolf Motors

John Wolf, president of Wolf Motors, just returned to his office after visiting the company's newly acquired automotive dealership. It was the fourth Wolf Motors dealership in a network that served a metropolitan area of 400,000 people. Beyond the metropolitan area, but within a 45-minute drive, were another 500,000 people. Each of the dealerships in the network marketed a different brand of automobile and historically had operated autonomously.

Wolf was particularly excited about this new dealership because it was the first "auto supermarket" in the network. Auto supermarkets differ from traditional auto dealerships in that they sell multiple brands of automobiles at the same location. The new dealership sold a full line of Chevrolets, Nissans, and Volkswagens.

Starting 15 years ago with the purchase of a bankrupt Dodge dealership, Wolf Motors had grown steadily in size and in reputation. Wolf attributed this success to three highly interdependent factors. The first was volume. By maintaining a high volume of sales and turning over inventory rapidly, economies of scale could be achieved, which reduced costs and provided customers with a large selection. The second factor was a marketing approach called the "hassle-free buying experience." Listed on each automobile was the "one price—lowest price." Customers came in, browsed, and compared prices without being approached by pushy salespeople. If they had questions or were ready to buy, a walk to a customer service desk produced a knowledgeable salesperson to assist them. Finally, and Wolf thought perhaps most importantly, was the after-sales service. Wolf Motors established a solid reputation for servicing, diagnosing, and repairing vehicles correctly and in a timely manner—the first time.

High-quality service after the sale depended on three essential components. First was the presence of a highly qualified, well-trained staff of service technicians. Second was the use of the latest tools and technologies to support diagnosis and repair activities. Third was the availability of the full range of parts and materials necessary to complete the service and repairs without delay. Wolf invested in training and equipment to ensure that the trained personnel and technology were provided. What he worried about, as Wolf Motors grew, was the continued availability of the right parts and materials. This concern caused him to focus on the supplier relationship process and management of the service parts and materials flows in the supply chain.

Wolf thought back to the stories in the newspaper's business pages describing the failure of companies that had not planned appropriately for growth. These companies outgrew their existing policies, procedures, and control systems. Lacking a plan to update their systems, the companies experienced myriad problems that led to inefficiencies and an inability to compete effectively. He did not want that to happen to Wolf Motors.

Each of the four dealerships purchased its own service parts and materials. Purchases were based on forecasts derived from historical demand data, which accounted for factors such as seasonality. Batteries and alternators had a high failure rate in the winter, and air-conditioner parts were in great demand during the summer. Similarly, coolant was needed in the spring to service air conditioners for the summer months, whereas antifreeze was needed in the fall to winterize automobiles. Forecasts also were adjusted for special vehicle sales and service promotions, which increased the need for materials used to prep new cars and service other cars.

One thing that made the purchase of service parts and materials so difficult was the tremendous number of different parts that had to be kept on hand. Some of these parts would be used to service customer automobiles, and others would be sold over the counter. Some had to be purchased from the automobile manufacturers or their certified wholesalers, and to support, for example, the "guaranteed GM parts" promotion. Still, other parts and materials such as oils, lubricants, and fan belts could be purchased from any number of suppliers. The purchasing department had to remember that the success of the dealership depended on (1) lowering costs to support the hassle-free, one price–lowest price concept, and (2) providing the right parts at the right time to support fast, reliable after-sales service.

As Wolf thought about the purchasing of parts and materials, two things kept going through his mind: the amount of space available for parts storage and the level of financial resources available to invest in parts and materials. The acquisition of the auto supermarket dealership put an increased strain on both finances and space, with the need to support three different automobile lines at the same facility. Investment dollars were becoming scarce, and space was at a premium. Wolf wondered what could be done in the purchasing area to address some of these concerns and alleviate some of the pressures.[13]

QUESTIONS

1. What recommendations would you make to John Wolf with respect to structuring the supplier relationship process for the Wolf Motors dealership network?
2. How might purchasing policies and procedures differ as the dealerships purchase different types of service parts and materials (for example, lubricants versus genuine GM parts)?
3. How can supply chain design and integration help John Wolf reduce investment and space requirements while maintaining adequate service levels?

[13] *Source*: This case was prepared by Dr. Brooke Saladin, Wake Forest University, as a basis for classroom discussion. Copyright © Brooke Saladin. Reprinted by permission.

VIDEO CASE Integrating the Supply Chain at Cleveland Clinic

Cleveland Clinic, a nonprofit multispecialty medical center based in Cleveland, Ohio, has a vast operational footprint that spans the globe. With an annual operating budget of nearly $11 billion, its mission integrates clinical and hospital care with academic and education excellence. The Clinic serves over 9.8 million patient visits (2.4 million patients) of all ages worldwide each year. With 18 hospitals—including locations in Ohio to locations in Florida, Nevada, Toronto, Abu Dhabi, and London—and more than 220 outpatient locations, the hospital system depends on skilled leadership and a global supply chain organization that is flexible, responsive, and integrated into daily operations at all locations.

Prior to The Coronavirus Pandemic

The current supply chain organization is highly integrated. It wasn't always so. Until recently, the various departments that supported supply chain operations had grown organically to support the ever-expanding enterprise and were organized into work silos to respond to supply chain needs within each facility. Each one had its own responsibilities, incentives, and performance metrics tied to its specific operations. For example, the *purchasing* silo might keep track of the number of orders placed that arrive within pre-determined response times, while the *sourcing* silo might have incentives centered around keeping supply costs as low as possible. That could mean that sourcing an item with a lower price from a new supplier in order to keep supply costs low, could cause a delay in procurement, thereby increasing the response time for the purchasing department. When a decision was made to replace an inventory item with a different one, departments would be told to exhaust their current supply of the old item before any new ones would be ordered. Then the new replacement item had to be integrated into all the departments using that item. The information systems in those departments had to be updated for the new item data and new labeling to occur so that the material handlers could properly track the items for replenishment. With hundreds of stocking locations spread throughout the hospitals, this was a difficult task prone to errors.

Often, the incentives worked against the overall strategic goal of a "Patient First" enterprise but were so deeply entrenched that staff simply kept executing their old incentive schemes because they thought they worked to the benefit of their departments. Instead of collaborating to ensure that the best interests of the entire organization were supported, tasks and responsibilities were simply handed off without downstream impact consideration. Further compounding the silo focus, information about supplies was maintained within the silos, with little incentive to share beyond their boundaries. Existing data and information about supplies were not routinely available across operations, making the organization's information systems difficult to use for managing the supply chain. The Supply Chain Management and Patient Services Support organization consisted of the following 10 groups:

- **Executive Leadership:** Provides strategic planning and guidance
- **Administration:** Provides overall support for all teams including system support, policies, and program management
- **Global Business Transformation:** Cleveland Clinic has invested in an Enterprise Resource Planning software platform supporting supply chain, decision support services, corporate accounting, and IT. The purpose is to create an efficient and agile operating model for the future that scales for market growth.
- **Data Analytics:** Provides analytics of key metrics and maintains information in Lawson
- **Business Development:** Supports GPO growth, new opportunities
- **Materials Management:** Supports the delivery, inventorying, and couriering of products
- **Purchasing:** Facilitates order placement and provides transactional support
- **Sourcing:** Negotiates clinical and non-clinical supply contracts
- **Support Services:** Delivers services that support a world class experience for patients and caregivers
- **Project Management Office:** Oversees Mergers and Acquisitions, New Construction, and Business Development initiatives

Each group was headed by a Senior Director, and essentially acted as an independent unit with its own goals and incentive agreements.

After the Advent of the Coronavirus Epidemic

The impact of COVID-19 on Cleveland Clinic's supply chain management really underscored the need to reorganize for greater efficiency, communication, materials flows, and information sharing across the enterprise; that is, integrate the internal and external supply chain. In May of 2020, Simrit Sandhu, Chief Supply Chain and Support Services Officer, and other senior supply chain managers took a bold and aggressive step to create a new cross-functional team to realign incentives and focus each supply chain group on the same metrics and service goals that are aligned with Cleveland Clinic's "Patient First" strategic initiative. This team is now called the Business Continuity Leadership Team within the Supply Chain Management Patient Support Services (SCM PSS) Organization. It combines Global Business Transformation, Data Analytics, Inventory Management Transformation, and the Project Management Office under the direction of the Chief Supply Chain and Support Services Officer. These units will no longer be operating independently with separate goals and incentives.

To enhance the reorganization, clinical partners (physicians, dietary, patient experience managers) were invited to directly participate to ensure quality, and patient safety considerations were included instead of assumed. This has resulted in cost savings tied to better sourcing and utilization of supplies. The new Business Continuity integrated team now consists of 30+ staff with assignments and responsibilities that cut across operations instead of remaining in vertical silos. The new Supply Chain Organization is as follows:

- **Executive Leadership:** Provides strategic planning and guidance
- **Administration:** Provides overall support for all teams including system support, policies, and program management
- **Business Continuity:**
  - **Global Business Transformation:** Manages the Enterprise Resource Planning (ERP) software platform supporting supply chain, decision support services, corporate accounting, and IT for efficient, agile, and scalable operations
  - **Project Management Office (PMO):** Oversees hospital integrations, new construction, and business development initiatives
  - **Data Maintenance:** Responsible for maintaining information integrity
  - **Inventory Management Transformation:** Supports the implementation of a system of control, used to manage supplies across the Cleveland Clinic enterprise.

- **Business Development:** Supports GPO growth, new opportunities
- **Data Analytics:** Provides analytics of key metrics and maintains information in the ERP system
- **Clinical Supply Chain:** End-to-end responsibility for clinical supplies including sourcing, contract negotiation, and operations supporting the delivery, inventorying, and couriering of products. Includes linen and laundry operations.
- **Non-Clinical Sourcing:** Negotiates non-clinical and IT supply and services contracts
- **Support Services (PSS):** Patient Support Services, Food Services, and Customer Support Services (including service express call center and purchasing)

Now there is strategic alignment of all the work groups under the Business Continuity Leadership team. To support better information sharing, the Data Analytics group now maintains the centralized Master Item File for the entire supply chain, provides analytics of key metrics, and maintains information integrity across the work streams. The new structure supports the implementation of a system of control used to manage supplies across the Cleveland Clinic enterprise in 15 locations.

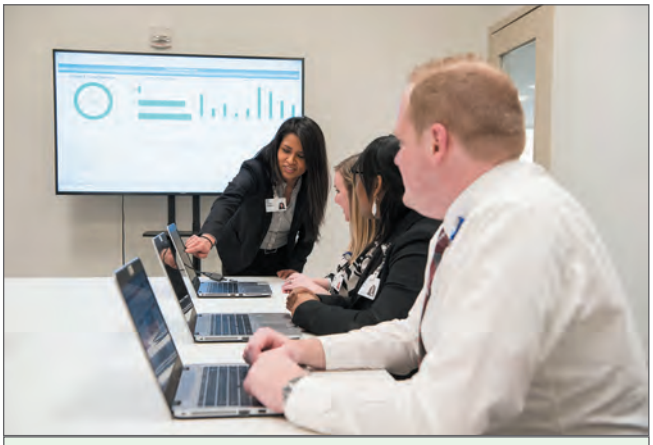


Photo courtesy of Cleveland Clinic/Don Gerda

The strategic reorganization of the Business Continuity Leadership Team allowed for improved integration and coordination of the supply chain efforts at Cleveland Clinic. Here caregivers in the IT Sourcing, Data Management, and Project Management areas work with a dashboard to coordinate their activities.

The new Business Continuity Leadership Team within the supply chain organization now has end-to-end visibility of supply and material utilization of over 192,000 individual stock-keeping units (SKUs) representing $82.4M worth of inventory. By vertically integrating into a service unit, the department is flexible and agile enough to deliver greater visibility and control over daily production and supply needs. Information flows more freely between the different enterprise areas since the silos no longer have incentives to protect their vertical interests. As a result, greater flexibility in adapting to changes in demand has improved the response capability of the Supply Chain Management and Patient Support Services Organization to support "Patient First" care and safety initiatives at the highest levels.

These changes have positively enhanced patient care. For example, during the COVID-19 outbreak in 2020, the hospital required a new type of intubation tubing that would allow a physician to insert a tube into a patient's airway at a safe distance, allowing the medical team to see what was happening with the patient's airway. The newly structured team, facing a global supply shortage, jumped into action to quickly procure the critical intubation supplies and distribute them across the organization. This was a test of the team's ability to understand the supply pipeline challenges, vendor relationships, backorder status, and coordination problems with manufacturers who could not make enough product to meet the demand. Because the newly integrated supply chain organization had reorganized its information sharing across all the former silos, improved its communications with vendors and internal departments about order status, and added information and performance metrics about new suppliers, it was much easier to keep materials flowing to the right places as needed. Such an integration across the supply chain has allowed the Supply Chain Management and Patient Support Services Organization to continue supporting Cleveland Clinic's "Patient First" strategic goal.

QUESTIONS

1. What are the key differences between the old and new supply chain organizations at Cleveland Clinic? How does the new organization promote greater integration?
2. Cleveland Clinic's goal of "Patient First" requires care that addresses every aspect of a patient's encounter with Cleveland Clinic, including the patient's physical comfort, as well as their educational, emotional, and spiritual needs. Consider the Materials Management, Purchasing, and Sourcing groups. Identify three performance measures for each one that would be consistent with the "Patient First" Goal.
3. Explain how the concept of blockchains and the Internet of Things can be useful to Cleveland Clinic with their new supply chain organization.
4. Identify three operational risks to Cleveland Clinic's supply chain and how they might be mitigated.

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SUPPLY CHAIN SUSTAINABILITY

15

LEARNING OBJECTIVES *After reading this chapter, you should be able to:*

15.1 Define the three elements of supply chain sustainability.

15.2 Explain the reverse logistics process and its implications for supply chain design.

15.3 Show how firms can improve the energy efficiency of their supply chains by using the nearest neighbor (NN) heuristic for logistics routes and determining the effects of freight density on freight rates.

15.4 Explain how supply chains can be organized and managed to support the response and recovery operations of disaster relief efforts.

15.5 Describe the ethical issues confronting supply chain managers.

15.6 Explain how a firm can manage its supply chains to ensure they are sustainable.

Coca-Cola



Dr. Juergen Bochynek/Shutterstock

Coca-Cola helped improve water quality in the United Arab Emirates by enhancing the irrigation efficiency of the falaj irrigation system. This falaj irrigation system is supplying water for a date palm plantation.

The Coca-Cola Company is a $37.3 billion company that produces the most popular soft drink in the world. Ten thousand Coke soft drinks are consumed globally per second. That makes Coke the world's largest nonalcoholic beverage manufacturer and distribution company. Its 62,600 employees produce and distribute 500 brands and 3,500 beverages in over 200 countries. Thirsty customers seek Coke products from the Arctic Circle to the tropics of Nigeria.

The geographical size of the market and the incredible volume of demand place a heavy burden on the supply chain, which consists of the manufacturing facilities, bottling partners, distribution centers, and tens of thousands of suppliers. As Coke is one of the world's top purchasers of sugar, citrus, tea, and coffee, its suppliers are largely in the agricultural sector. A company as large as Coke is keenly aware of the environmental impact of its operations. Globally, the agricultural sector consumes about 69 percent of the planet's freshwater, more than twice that of all industries (23%) and dwarfing municipal uses (8%). Creative conservation practices are needed on the part of farms to avoid consuming a region's scarce water supply. Water systems in ecoregions throughout the world are adversely affected by excessive water consumption and water quality degradation resulting from agricultural production.

As one of the biggest water consumers in the world, Coca-Cola had to do something, not only from a public relations perspective but, most importantly, from an operational perspective. In 2016 the company made a bold statement that for every drop of water it uses, it would give one back, the company's definition of being water neutral. The declaration was focused on "operational" water use. For example, it takes 0.4 liter of water in the bottling plant to make a half-liter beverage. However, according to the *water footprint*, a method of totaling the water that goes into everything we consume, if you count all the materials that go into making the beverage, it actually takes an additional 28 liters to grow the sugar beets to sweeten the beverage and seven liters to make the plastic bottle. After further study of all their products, Coca-Cola executives realized that about 85 percent of the water consumption of their products came from the agricultural ingredients. A completely different approach to water use and replenishment was needed, one that involved suppliers and the communities in the vicinity of their operations. In response, Coca-Cola initiated water replenishment projects worldwide. For example, water quality was improved in China by constructing 20 wetlands to deal with polluted water benefiting 4 million people; water availability for agricultural use in India was improved by the construction of check dams and rainwater harvesting structures to capture the seasonal monsoon rains, creating more than 13 billion liters of water replenishment potential; and the irrigation efficiency in The United Arab Emirates was enhanced by reducing water leakages, reinforcing weak structures, and improving sealings in the channels and water tanks of the falaj irrigation system at Wadi Shees, Sharjah. The falaj irrigation system is a traditional system of irrigation wherein water is extracted from underground sources without the use of machines and runs through channels dug in the earth. Globally, since 2012, Coca-Cola has replenished 1.5 trillion liters of water with about 300 projects such as these each year.

Coca-Cola has shown that being environmentally responsible, while involving substantial resources, is beneficial from an operational as well as public relations perspective.[1]

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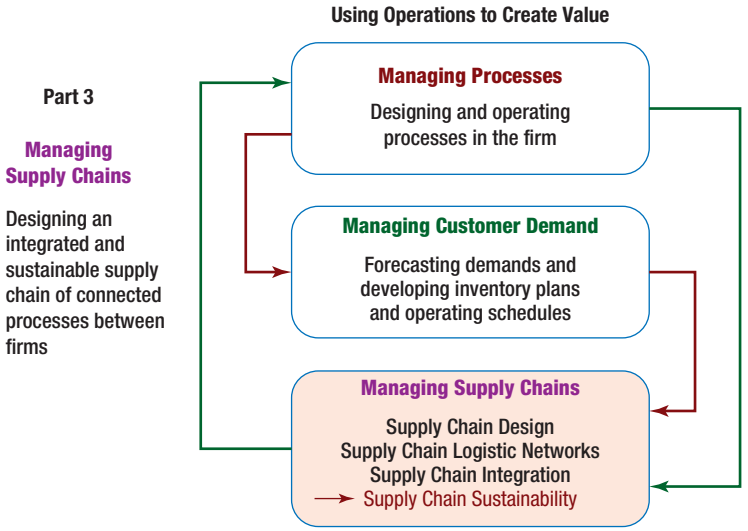
[1] *Sources:* "The Coca-Cola Company: Partnering with WWF to Promote Sustainable Agriculture," supply-chain.unglobalcompact.org/site/article/71 (January 18, 2020); "UAE Minister of Climate Change and Environment Inaugurates Regenerated Site at Wadi Shees," e.coca-colaarabia.com/sustainability (December 26, 2019); "The Coca-Cola Company/2019 Business & Sustainability Report," investors.coca-colacompany.com/financial-information/financial-results; Christine MacDonald, "Coke Claims to Give Back as It Uses: An Investigation Shows It Isn't Even Close," https://www.theverge.com/2018/5/31/17377964/coca-cola-water-sustainability-recycling-controversy-investigation (May 31, 2018).

Coca-Cola is an excellent example of how a firm can become a better corporate citizen by working with suppliers and communities to reduce the impact of its operations on scarce resources. While effective supply chain design and integration, as we have discussed thus far in Part 3 of this text, is a capability that an organization can use to be more competitive in its industry, it can also be used to become a better corporate citizen. As Coca-Cola has shown, a growing theme among many corporations is that of responsible stewardship of the capital, ecological, and human resources that they and their suppliers use in the production of their services or products. Translated into a goal, these corporations strive to have services, products, and processes with the characteristic of **sustainability**, which means that they are meeting humanity's needs without harming future generations.[2] The topic of sustainability has many implications for a firm; however, in this chapter we focus only on supply chains and how they can be used to achieve sustainability.

sustainability
A characteristic of processes that are meeting humanity's needs without harming future generations.

Integrated supply chains can facilitate the implementation of sustainable operations because of their established communication and material flows. Nonetheless, achieving sustainability throughout the supply chain is no easy task. It requires cross-functional and interfirm cooperation to address challenges such as:

- *Environmental protection*—firms should monitor their own processes and those of their suppliers to improve waste elimination methods; to reduce the pollution of the air, streams, and rivers; and to increase efforts at ecological stewardship for the protection of flora and fauna.
- *Productivity improvement*—firms should examine processes up and down the supply chain to increase material conservation, to increase energy efficiency, and to look for ways to convert waste into useful by-products.
- *Risk minimization*—as the supply chain grows, particularly on a global basis, firms should take great care to ensure that the materials going into their services, products, or processes do not pose health or safety hazards to customers.
- *Innovation*—as new services, products, or technologies are designed and developed, firms should strive to make sure they support their financial, environmental, and social responsibilities while serving the needs of customers.



A survey of 1,000 CEOs of major corporations from 21 industries and 99 countries in the UN Global Compact-Accenture Strategy 2019 CEO Study revealed that 99 percent of the CEOs believe that sustainability issues are critical to the future success of their companies, and 63 percent of them see new technology as a critical accelerator of the socioeconomic impact of their companies.[3] Further, 81 percent of the companies are taking action to achieve global sustainability goals; however, the CEOs in the study do not believe that business execution is measuring up to the challenge and previous levels of corporate ambition. Over half of the CEOs say that they face the pressure of operating under extreme cost-consciousness while seeking to invest in longer-term strategic objectives. While intuitively appealing, sustainability is not the easiest strategy for which approval can be gained from most boards of directors. Directors often need some sort of demonstrable return on investment to justify the costs. For sustainability efforts, however, managers must have a long-term view that accepts lower returns in the near future to improve the chances of survival and better returns in the future.

financial responsibility
An element of sustainability that addresses the financial needs of the shareholders, employees, customers, business partners, financial institutions, and any other entity that supplies the capital for the production of services or products or relies on the firm for wages or reimbursements.

The Three Elements of Supply Chain Sustainability

As Figure 15.1 shows, supply chain sustainability has three elements. First is **financial responsibility**, which addresses the financial needs of the shareholders, employees, customers, business partners, financial institutions, and any



▲ **FIGURE 15.1**
Supply Chains and Sustainability

[2]For a more complete discussion of sustainability and what major corporations are doing, see Pete Engardio, "Beyond the Green Corporation," *Business Week* (January 29, 2007), 50–64.

[3]"Business Contribution to the 2030 Agenda for Sustainable Development Not On Track, United Nations Global Compact and Accenture Study Finds," https://www.unglobalcompact.org/news/4481-09-24-2019, (September 24, 2019).

environmental responsibility
An element of sustainability that addresses the ecological needs of the planet and the firm's stewardship of the natural resources used in the production of services and products.

social responsibility
An element of sustainability that addresses the moral, ethical, and philanthropic expectations that society has of an organization.

humanitarian logistics
The process of planning, implementing, and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people.

other entity that supplies the capital for the production of services or products or relies on the firm for wages or reimbursements. Supply chains, for their part, support the financial responsibility of a firm by influencing elements that contribute to the return on assets, as explained in Chapter 12, "Supply Chain Design." Furthermore, because supply chains are essentially linked processes, any improvement to processes or their management, as explained in Parts 1 and 2 of this text, improves the financial well-being of the firm and increases its chances of survival in a competitive world. Second, **environmental responsibility** addresses the ecological needs of the planet and the firm's stewardship of the natural resources used in the production of services and products. The goal is to leave as small an environmental footprint as possible so that future generations can make use of abundant natural resources. The design and integration of supply chains can play a major role in preserving resources. We shall examine how supply chains can be designed to produce products and then reprocess them at the end of their lives to yield value in the form of remanufactured products or recycled materials. We will also examine how supply routes can be planned to reduce the amount of energy consumed in delivering materials or products to customers.

Finally, **social responsibility** addresses the moral, ethical, and philanthropic expectations that society has of an organization. While this responsibility covers a broad range of activities, supply chains can be used to meet such expectations. Firms can engage in **humanitarian logistics**, which is the process of planning, implementing, and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people. As such, firms can use their expertise in supply chain management to design supply chains that provide disaster relief, or to supply much needed drugs and food to underdeveloped areas of the world. Ethical considerations also arise in the choice of suppliers regarding their practices in the use of labor and natural resources, the relationship between buyers and sellers, the location of facilities, and inventory management. Table 15.1 provides some examples of well-known firms addressing sustainability.

As we have already devoted most of the text to the financial implications of processes, supply chains, and their management, we now turn to the role of supply chains in achieving a firm's environmental and social responsibilities.

TABLE 15.1 | EXAMPLES OF SUPPLY CHAIN SUSTAINABILITY EFFORTS

Financial Responsibility		Example
		***NCR*:** In moving from a country-centric model to a global low-cost manufacturing model, where the majority of product is produced in Asia, import duties, tariffs, distances, fuel, and lack of capacity in the logistical carrier base must be considered along with the occasional need to create the logistics infrastructure to move the product.
		***Nike*:** In analyzing the trade-off in the costs of manufacturing products onshore versus offshore, Nike has found that for plants in Europe it could pay 13 percent more in price for local sourcing and still be as well off as when sourcing the production from offshore manufacturers.
Environmental Responsibility		
	Reverse Logistics	***Caterpillar*:** Its remanufacturing facilities recycle over 2 million pieces and 140 million pounds of materials annually in state-of-the-art factories worldwide.
		***IBM*:** Its Global Asset Recovery division in 1 year collected over 1 million units of used information technology equipment that was converted to billions of dollars in revenues on the secondhand equipment, parts, and materials markets.
	Efficiency	***RR Donnelley*:** Proactively worked with suppliers to find ways to use less packaging and to reuse or recycle what cannot be eliminated.
		***UPS*:** Added 48 heavy-duty trucks, powered by liquefied natural gas (LPG), to cut diesel use by 95 percent while emitting 25 percent fewer greenhouse gasses.
Social Responsibility		
	Disaster Relief Supply Chains	***Intel and Solectron*:** In collaboration with the International Rescue Committee, these firms use their corporate expertise on disaster relief to significantly streamline procurement and create processes to substantially reduce response times.
		***DHL*:** Uses its comprehensive logistic networks and worldwide presence to help people and communities affected by major sudden-onset natural disasters.
	Ethics	***Airbus*:** Places its highest priority on environmental performance, and supports green economy and technology transfers in developing countries.
		***The Body Shop*:** Produces environmentally and ethically focused cosmetics and requires all suppliers to sign on to its corporate code of conduct before trading with them.

Reverse Logistics

Environmental concerns regarding business are voiced every day in the popular media. Service providers are examining ways to increase efficiency and reduce the impact of their operations on the environment. Manufacturers are feeling pressure to take responsibility for their products from birth to death. To address environmental concerns and to manage their products throughout their life cycles, firms such as Coors Brewing Company, Dell, and Caterpillar are turning to **reverse logistics**, which is the process of planning, implementing, and controlling the efficient, cost-effective flow of products, materials, and information from the point of consumption back to the point of origin for returns, repair, remanufacture, or recycling.

reverse logistics

The process of planning, implementing, and controlling the efficient, cost-effective flow of products, materials, and information from the point of consumption back to the point of origin for returns, repair, remanufacture, or recycling.

Supply Chain Design for Reverse Logistics

How are supply chains designed to be environmentally responsible for the entire life cycle of a product? A supply chain that integrates forward logistics with reverse logistics is called a **closed-loop supply chain**, because it focuses on the complete chain of operations from the birth to the death of a product. Figure 15.2 shows how a product starts its journey at the new service/product development process, makes its way to the customer, and then enters the reverse logistics chain that attempts to maximize the value of the item at the end of its useful life.

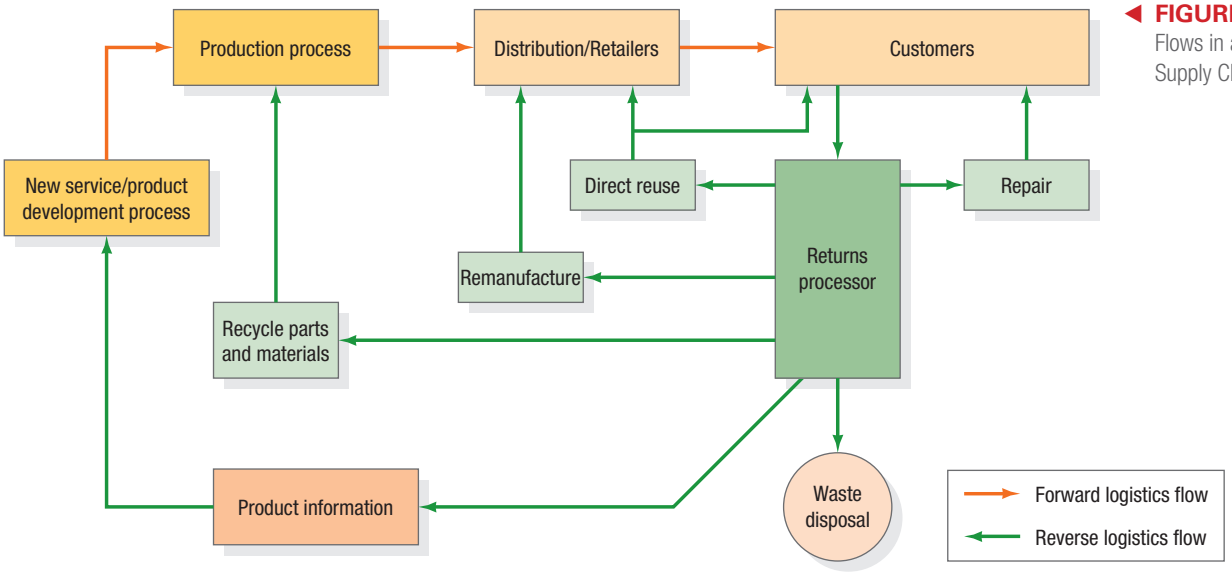
closed-loop supply chain

A supply chain that integrates forward logistics with reverse logistics, thereby focusing on the complete chain of operations from the birth to the death of a product.

It is clear that the reverse logistics operations are considerably different from the forward logistics flows, and several times more expensive. A firm must establish convenient collection points to receive the used goods from the final customer and transport the goods to a *returns processor*, which is a facility owned by the manufacturer or outsourced to a supplier that is proficient at disassembling products and gleaning any remaining value from them. Several options exist. If the item is inoperable, it could be repaired and returned to the customer. Another option is that it could be cleaned and refurbished for direct use and returned either to the distribution channel, which is the case with leased products, or back to customers, which is the case with a maintenance warranty. The product could be remanufactured by tearing it down, rebuilding it with new parts as needed, and returning it to the distribution channel. Finally, the product could be completely disassembled and the usable parts and materials cleaned, tested, and returned to the production process. There are two important by-products of the reverse logistics process: waste, which must be properly disposed of, and product information, which is transmitted to the new service/product development process so that improvements can be made to future generations of the product.

Reverse logistics processes can be particularly important in the electronics industry. Have you ever wondered what happens to your old computer after you purchase a new one? You may have given it to the store where you purchased your new one, or merely slipped it into the household trash. More retired computers in the United States are dumped in landfills than are recycled. Old computers contain electronics components with materials that can be recycled. However, they also have toxins that leach into the soil if these components are left unprocessed: lead and cadmium in computer circuit boards, lead oxide and barium in computer monitors and cathode-ray tubes (CRT), mercury in switches and flat screens, and fire retardant on printed circuit boards and plastic casings.

Many recycling processors are located in developing countries and are typically low tech. Recyclable material is collected and processed. Workers, who usually do not wear protective gear, often toss the chemicals that come out during the processing into nearby streams and rivers.



◀ **FIGURE 15.2**
Flows in a Closed-Loop Supply Chain



ISAAC LAWRENCE/AFP/Getty Images

Electronic waste is rising sharply across Asia as higher incomes allow millions of people to buy sophisticated communications gadgetry. Here a worker in Sheung Shui in the New Territories in Hong Kong goes through items at a sorting facility for electronic appliances, where some items will be refurbished and resold and others will be transferred to a processing plant for recycling.



Tom Uhlman/AP Images

A Walmart employee throws used packaging boxes into a compactor as a first step in building a super sandwich bale at a Cincinnati-area Walmart. The giant retailer is urging its suppliers to reduce greenhouse gas emissions on top of its own moves to build more energy-efficient stores, use alternative fuels for its truck fleet, and reduce packaging.

Other materials not processed often are left in the dumps, allowing the toxins to leak out. This disregard for the environment prompted a backlash against the improper disposal of electronic equipment in developed countries. The European Union (EU) passed a law requiring electronics manufacturers to take back and recycle 75 percent of the products they sell in the EU. Some U.S. states banned *e-waste*, electronic components and the chemical by-products of the recycling process, from landfills and are considering making electronics manufacturers responsible for managing e-waste.

Financial Implications Some firms participate in reverse supply chains by owning and operating processes such as remanufacturing, recycling, or repairing the used products and materials. These firms benefit from reclaiming usable parts for their manufacturing operations or by selling remanufactured products at competitive prices. If an original equipment manufacturer (OEM) participates in remanufacturing, however, there is a fear that the remanufactured products will cannibalize the sales of the firm's new products. Often these fears give rise to restrictions such as floors on the price that can be charged for remanufactured products, limits on the markets where they can be sold, limits on the distribution channels the products can be sold through, and reduced warranties that can be offered on them. Of course, not remanufacturing also has opportunity costs. There is the danger that environmentally irresponsible product disposal practices on the part of the firm's customers may result in the firm facing costly regulatory restrictions in the future. Also, third-party manufacturers may participate in the reverse logistics supply chain by collecting or purchasing the unclaimed old products, remanufacturing them, and then selling them in competition with the firm's new products. That is the case with refilled laser printer and inkjet cartridges, which erode profit margins for original printer manufacturers like Hewlett-Packard, Dell, and Epson.

Other firms, as well as individuals, participate in the reverse logistics supply chain by supplying their used products and materials for processing. A continuous supply of these used products and materials is needed to make the reverse supply chain financially viable. Various incentives may be used to influence the quantity, the quality (condition), and the timing of supply. Examples of incentives include:

- *Fee.* A fee is paid to the user when a used product or recyclable material is delivered for recovery. Usually the fee depends on the condition of the product or material, because this may determine the possibilities for its reuse. Of course, we have seen how some firms such as Walmart can garner substantial revenues from the recycling of useful materials they previously discarded.
- *Deposit fee.* Such fees provide incentive for the user to return the product or containers of the product to get the reimbursement of the deposit fee. This fee may relate to the product itself, such as a rental trailer, which must be refurbished (cleaned, maintained) before allowing the next customer to use it. Alternatively, the fee may apply to the distribution of the product, such as the deposit fee on beer bottles in some states.
- *Take back.* A company may offer to collect its products from its customers for no charge when those customers want to dispose of them. Dell, for example, charges no fees to recycle old computers from customers. Dell has designed its computers to make them easier to disassemble and recycle.
- *Trade-in.* One can get a new copy of a product if another copy is returned. For example, purchasing a refurbished engine for an automobile often requires the owner to turn in the old one, which might be disassembled for its parts or refurbished for sale to another customer.

- *Community programs.* Often communities or groups will set aside special days for the disposal of various items that are difficult to dispose of, such as automobile tires, paint, metal, and other things that the trash collectors do not normally pick up.

Many firms and individuals submit their used products and materials to be recycled for no other reason than it is the environmentally correct thing to do. Nonetheless, without the incentives, many reverse logistics supply chains would dry up.

Reverse logistics is one way to be more environmentally responsible. Another way is to reduce the firm's carbon footprint, as the following Managerial Challenge shows.

MANAGERIAL CHALLENGE Operations and Logistics

Eagle Trucking Company is a $23 million per year transportation company serving the oil and gas, health care, government, and food industries. Located in Fort Wayne, Indiana, its services include truckload (TL) and less-than-truckload (LTL) shipments, flatbed heavy hauls, and distribution network design. Todd Baker, CEO of Eagle Trucking, recently attended a conference of the Midwest Trucker's Association and learned of an initiative called SmartWay, established by the Environmental Protection Agency (EPA) in response to the fact that shippers, carriers, and consumers are increasingly becoming concerned about sustainability. Carriers submit data about their fleets, such as how many miles their trucks drive per year, their average payload, and what fuel they use. The data determine the carrier's amount of greenhouse gas emissions and ranks them in comparison to other carriers. The rankings are made public, allowing shippers to see how the carriers stack up regarding sustainability and use it to make decisions on which carrier to use. While the program is voluntary, Todd realized that in reality his company would have to participate and achieve a good ranking. Immediately upon returning to his office, Todd called an executive meeting.

Kimberly Durham, VP of customer experience; Zachary Maris, VP of operations and logistics; and Kara Priebe, VP of strategy and projects were at the conference table when Todd walked in. After explaining the SmartWay program to the group, Todd asked for thoughts from the group. Zachary reminded the group that the shipping volume in the industry has gone down due to plants reducing their hours because of coronavirus restrictions. This has caused more LTL shipments, which are not efficient. The standard routing for an LTL truck takes it to several pickup locations, transfer hubs, and drop-off locations. Perhaps there are better routes or more favorable freight rates to promote larger shipments. He also suggested partnering with rail providers on the long hauls or shifting to more lightweight trucks. Kara, who is responsible for implementing new technology, offered to explore the new electric trucks for short hauls. Kimberly was happy because she would have some good environmentally responsible messages to use in her marketing campaigns. Todd asked each of them to come back with specific plans to reduce the carbon footprint of Eagle Trucking. The remainder of this chapter will be helpful for formulating such a plan.

Energy Efficiency

Supply chains involve the flow of materials and services from their origination to their ultimate destination. As such, supply chains consume energy. Energy consumption not only is expensive from a business perspective but also can have negative effects on the environment. Increasingly more firms are measuring their **carbon footprint**, which is the total amount of greenhouse gases produced to support their operations, usually expressed in equivalent tons of carbon dioxide (CO_2). Major contributors to carbon footprints are fossil fuels—in particular, oil, diesel, and gasoline, which are used extensively in supply chain logistical operations. Therefore, it behooves firms to be efficient with respect to energy consumption throughout their supply chain. In this section, we will discuss three levers supply chain managers can use to increase the energy efficiency of their operations: (1) transportation distance, (2) freight density, and (3) transportation mode.

carbon footprint

The total amount of greenhouse gases produced to support operations, usually expressed in equivalent tons of carbon dioxide (CO_2).

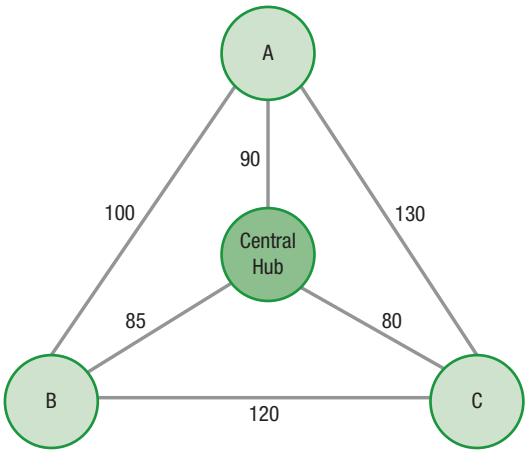
Transportation Distance

Supply chain managers can decrease the amount of energy consumed in moving materials or supplying services by reducing the distance traveled. This can be accomplished in two ways. The first involves the design of the supply chain itself. Locating service facilities or manufacturing plants in close proximity to customer populations reduces the distance required to supply the service or product. Furthermore, selecting suppliers that are in close proximity to the service facilities or manufacturing plants reduces the amount of fuel needed to procure those materials. Of course,

these suppliers must meet the firm's quality and performance needs. See Chapter 13, "Supply Chain Logistic Networks" and Chapter 14, "Supply Chain Integration," for details.

route planning
An activity that seeks to find the shortest route to deliver a service or product.

A second way to improve energy efficiency involving transportation distances is **route planning**, which seeks to find the shortest route to deliver a service or product. Once the design of the supply chain has been determined, attention turns to minimizing the distance traveled to supply the service or product to customers on a daily basis. There are two traditional versions of this problem. The first is the **shortest route problem**, which seeks to find the shortest distance between two cities in a network or map. Although elegant mathematical methods have been developed for solving this problem, today we are fortunate to have GPS systems for vehicles and websites such as Mapquest™ or apps such as Waze™, where very good, energy-efficient routes can be obtained quickly. Manufacturers with their own delivery fleets or third-party logistics providers (3PLs) can use these routes to minimize their costs of making the deliveries.



▲ **FIGURE 15.3**
Four-City Traveling Salesperson Problem

The second version is known as the **traveling salesperson problem**, which seeks to find the shortest possible route that visits each location or city exactly once and returns to the starting location. This problem is a much more difficult one to solve, yet one that delivery services face every day. Starting from a central location, such as a warehouse, distribution center, or hub, orders headed for multiple destinations are loaded into a truck that must make the deliveries, or alternatively pick up supplies, and return to the central location. The problem is to find the sequence of cities the truck must visit so that the total miles traveled is minimized. Figure 15.3 shows a four-city traveling salesperson problem with the driving miles between each city shown on the arc connecting them. How many different routes are there in the figure? Because we are dealing with driving distances between the cities, and there are no anomalies such as one-way streets or road blockages, the route Central Hub–A–C–B–Central Hub, for example, has the same total distance as the reverse of that route, Central Hub–B–C–A–Central Hub. Consequently, there are only three different routes:

shortest route problem
A problem whose objective is to find the shortest distance between two cities in a network or map.

traveling salesperson problem
A problem whose objective is to find the shortest possible route that visits each city exactly once and returns to the starting city.

Central Hub–A–B–C–Central Hub, which is 90 + 100 + 120 + 80 = 390 miles.

Central Hub–B–C–A–Central Hub, which is 85 + 120 + 130 + 90 = 425 miles.

Central Hub–C–A–B–Central Hub, which is 80 + 130 + 100 + 85 = 395 miles.

The optimal route for the example is Central Hub–A–B–C–Central Hub.

It may look easy to find the best route; simply evaluate each possible route as we just did. However, if the truck must visit n cities there are $(n - 1)!/2$ different routes to consider. For example, if there are only eight cities to visit, there are 2,520 possible routes to consider.[4] While complete enumeration of all the feasible routes is one way to solve this problem, the computational effort becomes onerous. If you were faced with the problem in Figure 15.3, how might you proceed to solve it in the absence of a brute force approach? You might do the following: Start with the Central Hub and go to the closest unvisited city; from that city find the next closest unvisited city, and repeat until you get back to the Central Hub. This approach is called the **nearest neighbor (NN) heuristic**, and has the following steps:

nearest neighbor (NN) heuristic
A technique that creates a route by deciding the next city to visit on the basis of its proximity.

1. Start with the city that is designated as the central location. Call this city the *start* city. Place all other cities in an *unvisited* set.
2. Choose the city in the unvisited set that is closest to the start city. Remove that city from the unvisited set.
3. Repeat the procedure with the latest visited city as the start city.
4. Conclude when all the cities have been visited, and return back to the central location.
5. Compute the total distance traveled along the selected route.

Using the NN heuristic for the problem in Figure 15.3 yields the following route: Central Hub–C–B–A–Central Hub, for a total distance of 390 miles. Notice that this is the optimal solution to the problem. The NN heuristic does not always yield the optimal solution; however, its main advantages are that it is fast and that it generally provides reasonable solutions to a very complex problem. Example 15.1 shows the application of the NN heuristic for the delivery of natural food products.

[4]We assume that there are roads connecting each pair of cities. The factorial is divided by 2, because the sequence of cities visited in one tour is assumed to have the same distance as a tour with the cities in reverse sequence.

EXAMPLE 15.1 Finding an Energy-Efficient Route Using the Nearest Neighbor Heuristic

Hillary and Adams, Inc., is a privately owned firm located in Atlanta that serves as the regional distributor of natural food products for Georgia, Kentucky, North Carolina, South Carolina, and Tennessee. They are particularly well known for their unique blend of fiery hot Habanera sauces. Every week, a truck leaves the large distribution center in Atlanta to stock local warehouses located in Charlotte, North Carolina; Charleston, South Carolina; Columbia, South Carolina; Knoxville, Tennessee; Lexington, Kentucky; and Raleigh, North Carolina. The truck visits each local warehouse only once and returns to Atlanta after all the deliveries have been completed. The distance between any two cities in miles is given in the table.

From/To	Atlanta	Charleston	Charlotte	Columbia	Knoxville	Lexington	Raleigh
Atlanta	–	319	244	225	214	375	435
Charleston	319	–	209	116	373	540	279
Charlotte	244	209	–	93	231	398	169
Columbia	225	116	93	–	264	430	225
Knoxville	214	373	231	264	–	170	351
Lexington	375	540	398	430	170	–	498
Raleigh	435	279	169	225	351	498	–

John Jensen, vice president of logistics at Hillary and Adams, Inc., is worried about the rising fuel costs. With a reduction in operating budgets, he is interested in finding a route that would minimize the distance traveled by the truck.

Use the NN heuristic to identify a route for the truck and compute the total distance traveled.

SOLUTION

The application of the NN heuristic results in the following steps:

1. Start with Atlanta and place all other cities in the unvisited set: Charleston, Charlotte, Columbia, Knoxville, Lexington, Raleigh.
2. Select the closest city to Atlanta in the unvisited set, which is Knoxville. Remove Knoxville from the unvisited set. The partial route is now Atlanta–Knoxville, which is 214 miles.
3. Scan the unvisited set for the city closest to Knoxville, which is Lexington. Remove Lexington from the unvisited set. The partial route is now Atlanta–Knoxville–Lexington, which is 214 + 170 = 384 miles.
4. Repeat the procedure until all cities have been removed from the unvisited city set. Connect the last city to Atlanta to complete the route.
5. Compute the total distance traveled along the selected route. The route using the NN heuristic is Atlanta–Knoxville–Lexington–Charlotte–Columbia–Charleston–Raleigh–Atlanta. The total distance traveled is (214 + 170 + 398 + 93 + 116 + 279 + 435) = 1,705 miles.

Note that using the same sequence of cities we could start the route at any one of them and travel the same total distance. For example, the route Lexington–Charlotte–Columbia–Charleston–Raleigh–Atlanta–Knoxville–Lexington will also be 1,705 miles. This fact allows us to use the NN heuristic again to see if a better solution exists; we repeat the heuristic six more times using each city as the starting point. This approach results in the following routes:

- Charleston–Columbia–Charlotte–Raleigh–Knoxville–Lexington–Atlanta–Charleston
  (116 + 93 + 169 + 351 + 170 + 375 + 319) = 1,593 miles.
- Charlotte–Columbia–Charleston–Raleigh–Knoxville–Lexington–Atlanta–Charlotte
  (93 + 116 + 279 + 351 + 170 + 375 + 244) = 1,628 miles.
- Columbia–Charlotte–Raleigh–Charleston–Atlanta–Knoxville–Lexington–Columbia
  (93 + 169 + 279 + 319 + 214 + 170 + 430) = 1,674 miles.
- Knoxville–Lexington–Atlanta–Columbia–Charlotte–Raleigh–Charleston–Knoxville
  (170 + 375 + 225 + 93 + 169 + 279 + 373) = 1,684 miles.
- Lexington–Knoxville–Atlanta–Columbia–Charlotte–Raleigh–Charleston–Lexington
  (170 + 214 + 225 + 93 + 169 + 279 + 540) = 1,690 miles.

- Raleigh–Charlotte–Columbia–Charleston–Atlanta–Knoxville–Lexington–Raleigh
  (169 + 93 + 116 + 319 + 214 + 170 + 498) = 1,579 miles.

Of the seven routes produced with the NN heuristic, the best is the last one with a travel distance of 1,579 miles.

DECISION POINT

Minimizing the number of miles to complete a route reduces the amount of fuel consumed by Hillary and Adams for the delivery process. Since each route is a loop, the truck driver would be instructed to go from Atlanta to Knoxville to Lexington to Raleigh to Charlotte to Columbia to Charleston and back to Atlanta. Alternatively, the reverse sequence could be taken; go to Charleston first, and so on. The sequence of cities dictates how the truck is loaded. The travel distances would still be 1,579 miles. While the NN heuristic cannot guarantee an optimal solution, it can help John Jensen avoid a costly mistake. For example, the route Atlanta–Raleigh–Lexington–Charleston–Knoxville–Columbia–Charlotte–Atlanta is 2,447 miles, a 55 percent increase in mileage over the best NN solution. Consequently, in addition to being environmentally responsible, the NN solution supports the competitive priority of low-cost operations. Minimizing the distance traveled to complete the route also shortens the time required to make the deliveries, which supports the competitive priority of delivery speed.



Juice Images/Alamy Stock Photo

The shipper of these pallets of items will be charged a freight rate based on six factors, including density, weight, and distance.

Freight Density

Truck vans, containers, and railcars all have limits with respect to cargo volume and weight. By reducing the volume that a product displaces while staying within the weight limits of the conveyance, the firm can use fewer trucks, containers, or railcars to ship the same number of units. Freight density, measured in pounds per cubic foot, determines the freight class and the cost a shipper must pay. The lower the freight density, the higher the freight class because the volume of the conveyance will be maxed out before the weight limit is reached. For example, 1,000 pounds of Ping-Pong balls occupy much more room in a trailer than 1,000 pounds of bowling balls. Firms can increase the freight density by reducing the volume of packaging, redesigning the product to take less volume, or postponing the assembly of the product until the customer takes possession.

Firms using 3PLs to get their materials or products to their customers must pay a freight rate based on six factors:

1. The freight density
2. The shipment's weight
3. The distance the shipment is moving
4. The commodity's susceptibility to damage
5. The value of the commodity
6. The commodity's loadability and handling characteristics (Loadability refers to how efficiently the items being shipped fit into a standard container or truck van. Also, in some cases special care must be taken in handling during the loading and unloading processes.)

Table 15.2 shows example freight rates and weight breaks based on various freight classifications for a shipment scheduled between two specific zip codes. The rates are given in dollars per hundredweight (CWT). The freight classification for a shipment is determined by the National Motor Freight Classification (NMFC) tariff and is based upon the last four factors in the previous list. There are 18 possible freight classes ranging from 50 to 500. The tariffs in the table are based on the distance to be traveled and are modified by the weight and freight class. Notice how the rates increase as the class goes up and decrease as the weight goes up.

Using Table 15.2, a shipment weighing 2,000 pounds and freight class 85 would cost 20(34.87) = $697.40. A 5,000-pound shipment of the same commodity would cost 50(26.60) = $1,330, which is more costly than the 2,000-pound shipment as we would expect. What rate will be charged if the shipper has a 4,000-pound shipment? Because the shipping weight falls between two weight breaks, we must see which of the two rates applies. Using the 2,000-pound rate, the total charge would be 40(34.87) = $1,394.80. At the 5,000-pound rate, the total charge is 40(26.60) = $1,064.00. In this case, the shipper would only be charged $1,064.00 even though the actual shipment does not meet the minimum for that rate. To

TABLE 15.2 | EXAMPLE MATRIX OF WEIGHT BREAKS AND FREIGHT CLASS ($/CWT)

Class	< 500 (lb)	500 (lb)	1,000 (lb)	2,000 (lb)	5,000 (lb)	10,000 (lb)	≥ 20,000 (lb)
50	34.30	28.32	24.25	23.04	17.58	15.74	10.47
55	36.94	30.50	26.12	24.82	18.93	17.41	11.58
60	39.59	32.69	27.99	26.60	20.29	19.08	12.69
65	41.94	34.64	29.66	28.18	21.49	20.27	13.48
70	44.64	36.86	31.56	29.99	22.88	21.94	14.59
77.5	48.10	39.72	34.01	32.32	24.65	23.85	15.86
85	51.90	42.86	36.70	34.87	26.60	26.24	17.45
92.5	55.89	46.15	39.52	37.56	28.64	28.38	18.87
100	60.27	49.77	42.61	40.50	30.89	30.77	20.46

determine the break-even weight between two adjacent weight breaks, we define the following variables:

x = break-even weight
A = lower weight bracket
B = next highest weight bracket
C = freight rate relative to A
D = freight rate relative to B

The break-even weight is given by

$$x = (BD)/C$$

In our example, the break-even weight is (50)(26.60)/(34.87) = 38.14, or 3,814 pounds. Any shipment greater than 3,814 pounds would enjoy the lower freight rate. Example 15.2 shows how a firm can find out if increasing freight density is in its best interests.

EXAMPLE 15.2 Evaluating an Increase in Freight Density

One of the products produced by Kitchen Tidy is Squeaky Kleen, a tile cleaner used by restaurants and hospitals. Squeaky Kleen comes in 5-gallon containers, each weighing 48 pounds. Currently, Kitchen Tidy ships four pallets of 25 units each week to a distribution center. The freight classification for this commodity is 100. Table 15.2 shows the freight rates governing this shipment.

In an effort to be more environmentally responsible, Kitchen Tidy asked their product engineers to evaluate a plan to convert Squeaky Kleen into a concentrated liquid by removing some water from the product. The product would be essentially the same; however, the customer would have to add water to the concentrate before using it. This would allow engineers to design a smaller container so that 50 units can be loaded on each pallet. Each container of Squeaky Kleen would weigh only 42 pounds. The product redesign would increase the product's freight density and therefore reduce the freight class, which now would be 92.5.

Use Table 15.2 to determine the savings in freight costs Kitchen Tidy might expect from the new product design.

SOLUTION

Current product design

- The weekly shipment in pounds is (number of pallets)(units per pallet)(pounds per unit) = (4)(25)(48) = 4,800 pounds.
- The freight class is 100. The shipping weight falls between two weight break brackets. The break-even weight between these two weight breaks is (50)(30.89)/(40.50) = 38.14, or 3,814 pounds. Therefore, the shipment qualifies for the lower freight rate.
- The total weekly shipping cost is 48(30.89) = $1,482.72.

New product design

- The weekly shipment in pounds is (number of pallets)(units per pallet)(pounds per unit) = (2)(50)(42) = 4,200 pounds.

- The freight class is 92.5. The shipping weight falls between two weight break brackets. The break-even weight between these two weight breaks is (50)(28.64)/(37.56) = 38.126, or 3,813 pounds. The shipment of 4,200 pounds will get the lower rate.
- The total weekly shipping cost is 42(28.64) = $1,202.88.

The new product design will save Kitchen Tidy $1,482.72 − $1,202.88 = $279.84 each week.

DECISION POINT

The decision to move forward on the new product design has other potential benefits. The smaller container for the product means less expensive packaging, which increases the profit margin of Kitchen Tidy. A smaller cubic volume also implies less warehouse space that must be devoted to this product. The environmental impact of this effort could be used to raise the image of Kitchen Tidy in the industry. Of course, care must be taken to educate the customers of Squeaky Kleen about the new product design so that they do not think they are getting less value for their money due to the smaller containers.

Transportation Mode

The four major modes of transportation are (1) air freight, (2) trucking, (3) shipping by water, and (4) rail. From an energy perspective, air freight and trucking are much less efficient than shipping or rail. According to the Association of American Railroads, on average, railroads are three times more fuel efficient than trucks, capable of moving a ton of freight 436 miles per gallon of fuel. The EPA also considers railroads best when it comes to noxious emissions per ton-mile. Further, freight railroads help relieve congestion on the highways; a typical train takes the freight equivalent of several hundred trucks. Trucks, nonetheless, are more flexible and can make deliveries right to the customer's door. Shippers can have the door-to-door convenience of trucks with the long-haul economy of railroads or ocean containers by employing **intermodal shipments**, which involves mixing the modes of transportation for a given shipment, such as moving shipping containers or truck trailers on railcars. The EPA reports that for shipments over 1,000 miles, using intermodal transport can cut fuel use and greenhouse gas emissions by as much as 65%, relative to truck transport alone. A truck transporting 40,000 lb from Boston to Los Angeles produces approximately 4.35 tons of carbon emissions, compared to only 1.75 tons for intermodal rail.[5] A huge range of consumer goods, from bicycles and lawn mowers to greeting cards and clothing, and an increasing amount of industrial and agricultural products, are being transported by intermodal shipments. All of these factors should be considered when designing an environmentally responsible supply chain.



Trains and Planes/Alamy Stock Photo

Truck trailers, often referred to as "piggy back" trailers, catch a ride on a BNSF intermodal freight train near Wellington, Kansas, for a cross-country journey.

intermodal shipments

Mixing the modes of transportation for a given shipment, such as moving shipping containers or truck trailers on railcars.

Other considerations, however, enter the mode selection. Air freight is the fastest, but costly. Trucks, being the most flexible, can reach destinations where air freight, shipping by water along rivers or oceans, or rail is not economical or feasible. Shipping by water, a preferred mode for intercontinental shipments, typically can handle containers of greater weight, thereby minimizing the number of necessary shipments. In addition, each of the transportation modes offers opportunities for energy efficiency through their designs. Design factors include:

- Relative drag—the energy needed for propulsion of a vehicle of a given size at a given speed
- Payload ratio—the cargo-carrying capacity of the vehicle relative to the vehicle's weight when fully loaded
- Propulsion systems—the technology used to move the vehicle

Electric Trucks Although first used in the early years of the 20th century, electric trucks, or eTrucks, are making a high-tech second appearance. Soon, fleet managers will have three classes to choose from: Heavy Duty Trucks (HDT) for the long-haul routes, Medium Duty Trucks (MDT) for the regional routes, and Light Duty Trucks (LDT) for urban uses. Three factors lie behind this renewed interest. First, based on the total cost of ownership (TCO), these trucks could be on a par with diesels in the relative short term. Second, electronic vehicle technology and infrastructure are becoming increasingly cost competitive. Finally, adoption of the new technology is driven by the regulatory environment, such as potential carbon dioxide fleet targets at the national level or emission-free zones at the local level. For example, in the United States, national regulations will

[5]Stephen Hamilton, "Intermodal Offers a Greener Way of Shipping," https://www.mhlnews.com/transportation-distribution/article/22037196/intermodal-offers-a-greener-way-of-shipping (April 29, 2010).

require up to 25 percent reduction in carbon dioxide emissions by 2027, which alone may not drive eTruck adoption because other technologies, such as aerodynamic improvements, low rolling-resistance tires, or improved engine efficiency, could also achieve these targets. Of course, there are barriers to the adoption of eTruck technology. The reliability of the new trucks must be proven. Also, the charging infrastructure needs to be developed. The MDT and LDT classes might be able to use the existing passenger-car charging infrastructure. However, major technology upgrades would be necessary to charge HDTs efficiently, which at present for a long-haul truck would take about 8 hours for a battery close to 1,000 kilowatt-hours and a commonly used supercharger with an average 120 kilowatts charging capacity. Finally, training up and down the supply chain for repair and maintenance would be required.[6]



Marijan Murat/dpa picture alliance/Alamy Stock Photo

An employee of Daimler AG inserts a charging plug into an electrically driven Mercedes-Benz eActros, which has a 240kWh battery pack and a range of up to 125 miles. The time it takes for a full charge depends on the power of the charging station. At 80 kW it takes 3 hours, while at 20 kW it takes at least 11 hours.

Businesses across the globe are using energy-efficient technology to reduce their greenhouse gas emissions. Walmart, for example, purchased diesel-electric and refrigerated trucks with a power unit that could keep cargo cold without the engine running, saving nearly $75 million in fuel costs and eliminating an estimated 400,000 tons of CO_2 pollution in 1 year alone. Transportation services companies such as FedEx, UPS, and DHL actively replace old equipment with newer, energy-efficient equipment and greatly reduce their carbon footprints. In New Delhi, India, there is a push to use liquefied natural gas (LNG), compressed natural gas (CNG), or electric vehicles for all commercial vehicles to reduce the air pollution levels in the capital city. Designing a supply chain that addresses environmental concerns, while meeting a firm's competitive priorities, can be a challenging task.

Disaster Relief Supply Chains

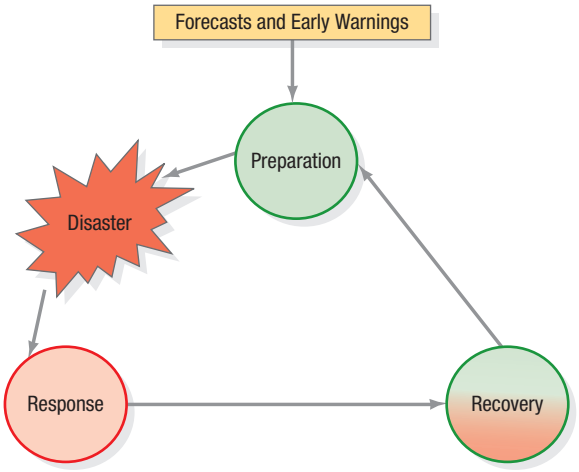
Beyond the financial and environmental responsibilities, firms and organizations are acknowledging that if they are to be considered good corporate citizens, they must also recognize social responsibilities. Supply chain managers are in a unique position to be catalysts for social responsibility activities because they are boundary spanners: They interact internally with other key functional areas of the organization as well as externally with suppliers and customers. Nonetheless, supply chain managers cannot do it alone. Social responsibility should be the focus of the entire organization, including the top management.

Organizing for Disaster Relief

According to the United Nations (UN), a *disaster* is a serious disruption of the functioning of society, causing widespread human, material, or environmental losses that exceed the ability of the affected people to cope using only their own resources. Disasters can be human related (epidemic, war, genocide, insurgency, arson, or terrorism) or natural (earthquake, tsunami, hurricane, tornado, flood, or volcanic activity). Some disasters allow more planning time than others; all disasters put pressure on relief operations. Recent disasters, such as the earthquakes in Haiti and Chile in 2010, the earthquake and tsunami in Japan in 2011, and typhoon Haiyan in the Philippines in 2013, are cases in point. Between 400 and 500 natural disasters strike per year, affecting more than 250 million people, and 80 percent of all relief operations for all types of disasters require supply chains of some sort. Needless to say, supply chain managers play a vital role.

Disaster relief operations for major disasters often involve many organizations, typically led by the United Nations. Agencies such as the International Federation of Red Cross and Red Crescent Societies and many other philanthropic and faith-based organizations assist in the relief efforts under the leadership of the United Nations through programs such as the World Food Program or the UN Development Program. In addition, private third-party logistics providers, such as Agility, TNT, and UPS, have partnered with the UN to provide additional transportation capacity in the event of large-scale international disasters and to provide warehousing services in Italy, United Arab Emirates, Panama, and Ghana. The warehouses, referred to as strategic hubs, stockpile vital supplies in anticipation of major disasters in that area of the world. In a similar vein, FedEx has partnered with Heart to Heart International, a global humanitarian

[6]Bernd Heid, Russell Hensley, Stefan Knupfer, and Andreas Tschiesner, "What's Sparking Electric-Vehicle Adoption in the Truck Industry?" mckinsey.com/industries/automotive-and-assembly/our-insights/what's-sparking-electric-vehicle-adoption-in-the-truck-industry? (September 2017).



▲ **FIGURE 15.4**
Humanitarian Supply Chain Operations

organization that works to improve health and to respond to the needs of disaster victims worldwide. Together, they have established four Forward Response Centers located in Kansas City, and internationally in Mexico, the Philippines, and the United Arab Emirates. Each center is stocked with 60 to 80 pallets containing basic relief supplies, which are ready to be moved to the affected area on a moment's notice. As these examples show, private corporations can be socially responsible by transferring, acquiring, and sharing their expertise and access to needed resources through formalized collaborations such as these.

Figure 15.4 shows the three major humanitarian supply chain operations relating to disaster relief—preparation, response, and recovery—and the temporal relationship between them.

- *Preparation.* Forecasts and early warning systems can sometimes provide enough lead time to assemble the resources and organize the relief efforts. Often, however, disasters happen with little or no warning. Nonetheless, relief agencies can do some advance planning to reduce the response time. Communication protocols and the information technology infrastructure can be prepared. Strategic partnerships with other agencies and private companies can be formalized, and training of agency personnel can be undertaken before the next disaster. Kits of standardized, nonperishable items can be preassembled and stocked, and some items can be placed in strategic hubs to reduce the delivery time when the need arises.
- *Response.* After the disaster strikes, the resources are mobilized and sent to the disaster location as soon as possible. The initial procurement of food, water, materials, and medicines are made; and personnel to provide assistance and humanitarian aid are dispatched to the region. A preliminary needs assessment is made by small multidisciplinary teams of experienced humanitarian workers and logisticians. Communication lines often are lacking. Coordination between international suppliers of needed items and the local authorities is often difficult because ports of entry are inaccessible, or the authorities are overtaken by events and inexperienced in events of this magnitude, or lacking in resources.
- *Recovery.* As time progresses, the crisis mode of "response" gives way to a focus on rebuilding the information and logistical infrastructure and rehabilitating the affected population. Supplies, food, and medicines can be ordered with more normal lead times as quantities can be better estimated. More focus is placed on the cost of these items. Collaboration and cooperation improves; however, supplies from all over the world sent during the response phase, often without consultation with teams on location, cause oversupply of some commodities.

Managing Disaster Relief Operations

Regarding the structure of supply chains and disaster relief operations, a firm's main supply chain processes of supplier relationship, order fulfillment, and customer relationship remain essentially intact. The difference when it comes to disaster relief is that the timetable and ultimate customer for a supplier changes rapidly. Nonetheless, supply chain managers can provide the glue between the disaster relief operations. From the perspective of the disaster relief agencies, which oversee the relief operations relative to their organizations, supply chains must be designed to link the preparation activities to the initial response activities and ultimately the recovery operations. The procurement of materials, food, and medicines must be matched with their distribution to the affected areas, often involving trade-offs in delivery speed, cost, and consistent quality with regard to the type of goods and their quantities. Supply chain managers can do this; they can also link disaster relief headquarters with the operations in the field, whether those operations are response or recovery operations. For this reason, disaster relief organizations need supply chain managers on their staffs, something that few of them have.

In disaster relief operations, suppliers must understand that the morphology of supply chains changes over time. The life cycle of disaster relief supply chains has five stages: (1) brief needs assessment; (2) development of the initial supply chains for flexibility; (3) speedy distribution of the supplies to the affected region based on forecasted needs; (4) increased structuring of the supply chain as time progresses, whereby supplies arrive by a fixed schedule or on request; and (5) dismantling or turning over of the supply chain to local agencies. Suppliers, and their suppliers, need to be on the same page as this life cycle plays out; the time frame and requirements can be different for each disaster. Supply chain managers who understand the implications of the disaster relief life cycle can mitigate its effects on their firm's operations while doing their best to support the relief agency's goals.

The unpredictability and severity of disasters pose unique challenges to supply chain managers, as follows:

- *Design implications.* Many disaster relief supply chains exist for only short times. At the onset of a disaster, the supply chain could require a new design from scratch that features quick response capabilities involving innovative suppliers. Response operations are all about speed and agility in the supply of needed items. Risk-taking is encouraged because the priority is quick access. Recovery operations, however, require a more scheduled program, favoring an efficient supply chain design.
- *Command and control.* In major international disasters, the United Nations typically has the leadership role. Disaster relief agencies work to supply the items and services they have access to. However, the national and local government of the affected region must be recognized and included. Sometimes the national government will not grant access to the area until it can ensure its security, or it will not allow access to relief agencies from some countries because of political reasons. In other words, critical supplies may not be deployed as soon as they are available because of national or local roadblocks.
- *Cargo security.* Shipping containers of goods in some developing countries may experience theft or extra delays. Delays can be due to numerous police checks or weight checks. Sometimes, bribes are needed to move the cargo through the checkpoints, all of which cause delays when speed is of the essence.
- *Donor independence.* There are many disaster relief agencies, all of which have the best of intentions to help relieve pain and suffering at the point of the disaster. If they are not coordinated with a list of required supplies, each sends what it thinks is needed. The result can be confusion, congestion, overstocking of some items, and understocking of other items.
- *Change in work flow.* During the response operations, supplies are sent without waiting for demand to be accurately determined. Supplies are provided according to forecasts, however imperfect, using a *push flow* from suppliers. Once relief efforts reach the recovery operations, actual needs should dictate the required volume of supplies and the supply chains should switch to a *pull flow*.
- *Local infrastructure.* Because disasters often cause major damage to the infrastructure, roads, ports, railways, and airports may be compromised, thereby limiting the logistical movement of needed supplies. Local transportation capability may be limited. Often novel approaches must be used, such as helicopters moving supplies from ships at sea or drones to find where ground delivery of supplies is possible.
- *High employee turnover.* The needs of the disaster relief and the availability of qualified local labor are highly unpredictable. The manual processes often needed in disasters are poorly defined. Coupled with the uncertainty of funding from the relief agency, employee turnover tends to be high in disaster relief operations.
- *Poor communication.* Information technology is fragmented: Telephone lines are disrupted, cell service is limited, and Internet access is unreliable.

Consequently, each disaster requires a unique supply chain solution. The flexibility to change and adapt to evolving conditions is a key attribute of disaster relief supply chains. Managerial Practice 15.1 shows how new technology can be innovatively used to get supplies to needy victims in devastated homelands.

MANAGERIAL PRACTICE 15.1 Using Drones in Disaster Relief

Most of us have not had the experience of walking through the rubble and devastation immediately after a major disaster, such as in Nepal after the earthquake in 2015 or in Haiti after Hurricane Matthew in 2016. Villages, homes, roads, bridges, airports, and hospitals were destroyed or severely damaged. First responders responsible for providing food, water, and medicine to those in need were faced with the "4W challenge": Who wants what where? Organized refugee camps, or just groups of injured people trying to find shelter can be spread over a large region and the extent of their hardships is difficult to assess. Even with answers to the four questions, you still have the remaining question, *How can supplies get to those in need?* Tens of thousands of pounds of relief supplies arriving at the operational airports or docks are useless without the last leg of the supply chain that goes from the docks to the people in need.

Satellite imagery of a devastated area can be useful; however, disaster relief requires a quicker response. In an attempt to improve the delivery of supplies and medicine, unmanned aerial vehicles (UAV), or drones, are being used to survey the damaged areas and find the people in need. Launched from the roof of a 4x4 vehicle and fitted with either a video or still camera that can operate in daylight or nighttime using infrared imagery, drones can be controlled via a satellite link by a crew of three: pilot, camera operator, and

maintainer. With a range of over 600 miles, they consume less than 2 gallons of fuel. They can fly over isolated areas to identify the extent of infrastructure damage, particularly roads, bridges, railways, and villages, and the locations of people in need, and swiftly provide pictures to the first responders. Using autonomous flight and coordination capability, multiple drones can fan out in a grid formation to image the entire affected area and upload the images in real time to logistics planning software that can coordinate relief delivery. In mid-August 2017, Sierra Leone experienced its worst flooding in over two decades as torrential downpours sparked a mudslide, killing and injuring hundreds of people. The UN utilized satellite data, radar imagery, and drone mapping in an effort to protect residents from a second mudslide. Three weeks later, Hurricane Harvey battered the United States. Drones played a critical part in surveying flooded areas, assisting with power restoration, and aiding in search and rescue operations.

Drones can be equipped with thermal imagery to identify trapped civilians, or sensors to detect hazards like natural gas or chemical leaks. Beyond the potential to survey the devastated area after a natural disaster, drones can be used to actually deliver needed medicines and supplies to areas that are otherwise difficult to reach. For example, in Rwanda, infrastructure challenges have caused critical health products to spoil or fail to reach the individuals who urgently need them, even without a natural disaster. To assist in the humanitarian effort, UPS announced a partnership with Gavi, the Vaccine Alliance, and Zipline, a California-based robotics company, to use drones to actually deliver lifesaving blood and vaccines to remote facilities in the western half of the country.



STEPHANIE AGLIETTI/AFP/Getty Images

A technician of California-based robotics company Zipline launches a drone in Muhanga, 50 kilometers (31 miles) west of the capital of Rwanda, Kigali. Rwanda inaugurated a drone operation that its backers hope will kick start a revolution in the supply of medical care in rural parts of Africa.

By making use of the capabilities of UAV technology, response teams are able to obtain a swift understanding of the impact of a disaster and organize the final stages of a disaster relief supply chain.[7]

Supply Chain Ethics

Supply chains, by virtue of their interconnectedness with other firms and their intense internal and external human interactions, often pose ethical issues for their managers. In this section, we will explore some of the ethical issues associated with buyer–supplier relationships, location of facilities, and inventory management.

Buyer–Supplier Relationships

When an ethical issue arises, even when the firm is not completely at fault, customers often blame the firm that sold them the service or product when, in fact, a supplier further upstream was at fault. Selecting suppliers that adhere to ethical codes of conduct is a critical aspect of designing a supply chain. This is a difficult task; however, socially responsible firms have some guidance for selecting ethical suppliers. Social Accountability International, an organization dedicated to defining and verifying the implementation of ethical workplaces, has compiled **SA8000:2014**, which is a list of standards covering nine dimensions of ethical workforce management:

SA8000:2014
A list of standards covering nine dimensions of ethical workforce management.

1. *Child Labor:* Employ no underage workers, usually taken to be under 15 years of age.
2. *Forced or Compulsory Labor:* Prohibit the use of forced or compulsory labor, including prison or debt bondage labor.
3. *Health and Safety:* Provide a safe and healthy work environment.
4. *Freedom of Association and Right to Collective Bargaining:* Respect the right to form and join trade unions and bargain collectively.
5. *Discrimination:* Do not engage in or support discrimination based on race, caste, origin, religion, disability, gender, sexual orientation, union or political affiliation, or age; no sexual harassment.
6. *Disciplinary Practices:* Use no corporal punishment, mental or physical coercion, or verbal abuse.
7. *Working Hours:* Require no more than 48 hours per week with at least 1 day off for every 7-day period with overtime hours and pay subject to the collective bargaining agreement.

[7] *Sources:* Jared McKiernan, "How Drones Are Changing the Disaster Relief Industry," https://caringmagazine.org/authors/jared-mckiernan/ (July 16, 2019); Kalev Leetaru, "How Drones Are Changing Humanitarian Disaster Response," https://www.forbes.com/sites/kalevleetaru/2015/11/09/how-drones-are-changing-humanitarian-disaster-response/ (November 9, 2015); (May 22, 2016); https://pressroom.ups.com/pressroom/ContentDetailsViewer.page?ConceptType=PressReleases&id=1556027218757-179 (04/24/2019).

8. *Remuneration:* Pay wages for a standard workweek such that they meet the legal and industry standards and be sufficient to meet the basic need of workers and their families.
9. *Management Systems:* There are 10 elements to this dimension that require actions on the part of management to meet and comply with the SA8000:2014 standards. Facilities seeking to gain and maintain certification must go beyond simple compliance to integrate the standard into their management systems and practices.

Once certified, firms need to be recertified every 3 years. As of November 17, 2020, there were 4,645 certified facilities involving 2,201,024 workers in 59 countries and 57 industries. Standards such as SA8000:2014 go a long way toward building a supply chain that is socially responsible.

Beyond identifying suppliers with ethical workforce practices, firms should strive to select suppliers impartially, guided strictly by market criteria and competitive priorities. Preferential treatment of suppliers because of friendships, family ties, or investment in the supplier should be avoided. Buyers should be candid when negotiating contracts and have respect for the supplier's cost structure and any special efforts for performance improvements. Gratuities to the buyer, beyond tokens of appreciation, should be excluded. Other unethical activities include:

- Revealing confidential bids and allowing certain suppliers to rebid
- Making reciprocal arrangements whereby the firm purchases from a supplier who in turn purchases from the firm
- Exaggerating situations to get better deals
- Using company resources for personal gain

Suppliers also bear an ethical responsibility with respect to accuracy in product labeling. The consequences for cheating can be significant. For example, Walmart and Target have stopped selling cotton sheets from Welspun India, one of the world's largest textile manufacturers. Welspun claimed the sheets were made from 100 percent Egyptian cotton, which is perceived to be softer and more durable than other cotton. In reality, because of lower production of Egyptian cotton, Welspun used a cheaper substitute, as verified by DNA analysis. In August 2016, Target recalled 750,000 fake Egyptian cotton sheets and pillowcases from Welspun, while Walmart offered customer refunds on the same products. After the announcement by Target, shares of Welspun dropped 20 percent before trading was halted.

One final buyer–supplier relationship deserves special mention. In almost every supply chain, purchasing power plays a role in the relationship between a buyer and supplier. Buyers who represent a large portion of the revenue for a supplier can exact concessions from the supplier that may not be in its best interests. For example, should a powerful buyer force suppliers to take a loss, even for only the short term, on the premise that they, and everyone else, will benefit in the long run? Some would say that was the case when Walmart required all suppliers to invest in radio frequency identification (RFID) technology to track inventories and shipments. Some suppliers, especially those selling commodities with small profit margins, were forced to take a loss to remain a supplier to Walmart. Others would say that in the long run everyone in the supply chain will be better off than before the switch to RFID. Nonetheless, the initial attempts at establishing RFID in Walmart were not well received by suppliers, and their pushback caused the program to falter. Today, Walmart shares in the supplier costs and focuses more on RFID at the item level, especially in apparel, where benefits can be more clearly defined. Privacy watchers, however, are still concerned over the use of RFID because they think the privacy of individual consumers may be compromised as they take products home with the tags attached.

It should be pointed out that ethical issues such as this also confront powerful suppliers, particularly in their contracts with retailers in regard to the exclusivity of their products or control over the ordering policy.

Facility Location

We have already discussed in Chapter 13, "Supply Chain Logistic Networks," the cost implications of the decision to locate facilities. However, major decisions such as facility location have ethical considerations as well. The construction and operation of new facilities may affect the natural environment by disrupting ecosystems, primarily through habitat destruction and increased air, water, and noise pollution. Energy efficiency is also a concern. These considerations raise an ethical dilemma: Should a location based on traditional construction and logistical costs be changed to a more environmentally responsible location if it will increase costs? The location of a facility to avoid the disruption of natural habitats or taking steps to include noise-abatement and air pollution reduction technologies because of local ordinances may increase both startup and operating costs. A balancing act between financial responsibility and environmental responsibility takes place. Locating a facility in a developing country to avoid some of the environmental laws in place in more developed countries may be less costly, but is it ethical? However, in some ways, identifying the least costly location may also help the environment. For example, minimizing the total material and personnel travel distances to and from a facility reduces operating costs and increases energy efficiency.



Pitu Cau/Alamy Stock Photo

Rush-hour traffic jams in Tokyo, Japan, are common, as in most large cities. A high proportion of delivery vehicles exacerbates the problem.

Inventory Management

Inventory policies for independent demand inventories are discussed in Chapter 9, "Inventory Management."Reducing the order quantity for an item reduces the cycle inventory held in storage while increasing the number of orders per year. The ultimate is a *just-in-time* (JIT) system, discussed in Chapter 4, "Lean Systems," where orders of small quantities are placed as they are needed. Imagine a large metropolitan area where most businesses are using JIT systems and the traffic congestion that results from delivery trucks carrying the small order quantities. For example, much of the congestion in Tokyo is attributed to JIT deliveries. While the cost of the inventory system for a given company is minimized in the traditional sense, noise pollution, energy consumption, air pollution, and travel time have increased for the community at large. Once again, there is a balancing act between financial responsibility and environmental responsibility. What can a firm do? Steps can be taken to minimize the material movement to and from the firm by (1) consolidating shipments of items using *a periodic review system* (*P*-system with the same review period for a group of items from the same supplier), or (2) increasing inventory levels by either adjusting the timing of deliveries to avoid rush hours or reducing the total number of shipments. Of course, these remedies increase inventory costs to the firm.

Managing Sustainable Supply Chains

ISO 14001:2004
A series of environmental standards developed and published by the International Organization for Standardization.

To help firms build and manage sustainable supply chains, the International Organization for Standardization has devised ISO 14000 standards for environmental management systems, and ISO 26000 for guidance on social responsibility. The **ISO 14001:2004** standards require documentation of a firm's environmental program. The ISO 14001:2004 family addresses *environmental management* by specifying what the firm does to minimize harmful effects on the environment caused by its activities, and to achieve continual improvement of its environmental performance. The documentation standards require participating companies to keep track of their raw materials use and their generation, treatment, and disposal of hazardous wastes. Although not specifying what each company is allowed to emit, the standards require companies to prepare a plan for ongoing improvement in their environmental performance. ISO 14001:2004 covers a number of areas, including the following:

- *Environmental Management System:* Requires a plan to improve performance in resource use and pollutant output.
- *Environmental Performance Evaluation:* Specifies guidelines for the certification of companies.
- *Environmental Labeling:* Defines terms such as *recyclable*, *energy efficient*, and *safe for the ozone layer*.
- *Life-Cycle Assessment:* Evaluates the lifetime environmental impact from the manufacture, use, and disposal of a product.

To maintain their certification, companies must be inspected by outside, private auditors on a regular basis. Apart from large U.S.-based companies such as Ford, General Motors, IBM, Honda of America, and Xerox, approximately 10,000 firms worldwide have registered for ISO 14001:2004.

ISO 26000:2010
A series of international guidelines to help organizations effectively assess those social responsibilities that are relevant and significant to their mission and vision.

The **ISO 26000:2010** guidelines provide a structure for addressing the seven key underlying principles of social responsibility: accountability, transparency, ethical behavior, respect for stakeholder interests, respect for the rule of law, respect for international norms of behavior, and respect for human rights. More than 400 experts and 200 observers from 99 countries and 42 international organizations contributed to the development effort. While there is no formal certification process, organizations in the public, private, and nonprofit sectors, whether large or small, and whether operating in developed or developing countries, use ISO 26000 to guide their social responsibility efforts.

In addition to documenting and complying with ISO 14001:2004 and ISO 26000, how can a firm manage its supply chains to ensure that they are sustainable? Firms might consider the following steps:

1. Develop a *sustainable supply chain framework*. Define what "sustainability" means for the firm in clear terms. Use SA8000:2014 as a guideline for workplace issues.
2. Gather data on the performance of current suppliers and use the same questionnaire to screen potential new suppliers. Use the supply chain sustainability framework as a foundation.

3. Require compliance with the sustainable supply chain framework across all business units, including their dealings with current suppliers and the selection of future suppliers.
4. Engage in active supplier management and utilize all available ethical means to influence their behavior.
5. Provide periodic reports on the impact the supply chains have on sustainability.

Designing and managing a sustainable supply chain is not an easy task. Nonetheless, many firms are making sustainability a major goal of their operations.

LEARNING OBJECTIVES IN REVIEW

Learning Objective	Guidelines for Review	Online Resources
15.1 Define the three elements of supply chain sustainability.	See the opening paragraphs of this chapter for the challenges managers face to achieve sustainability. See the section "The Three Elements of Supply Chain Sustainability," Figure 15.1, and Table 15.1, which contain examples of financial, environmental, and social responsibility involving major companies.	
15.2 Explain the reverse logistics process and its implications for supply chain design.	See the section "Reverse Logistics" and study Figure 15.2.	
15.3 Show how firms can improve the energy efficiency of their supply chains by using the nearest neighbor (NN) heuristic for logistics routes and determining the effects of freight density on freight rates.	See the section "Energy Efficiency." Be sure you understand the NN heuristic, Example 15.1, and Solved Problem 1. Study the break-even approach to identifying break-even weights for the shipment of goods, Table 15.2, Example 15.2, and Solved Problem 2.	
15.4 Explain how supply chains can be organized and managed to support the response and recovery operations of disaster relief efforts.	The section "Disaster Relief Supply Chains" contains a discussion of the organization of disaster relief supply chains and the role of supply chain managers in disaster relief efforts. Figure 15.4 shows the three major disaster relief operations that supply chains must support. Managerial Practice 15.1 shows how drones can be used to assist first responders in the last link of a disaster relief supply chain.	
15.5 Describe the ethical issues confronting supply chain managers.	The section "Supply Chain Ethics" discusses the nature of the ethical issues that supply chain managers face and how they can deal with them.	
15.6 Explain how a firm can manage its supply chains to ensure they are sustainable.	See the section "Managing Sustainable Supply Chains" for a description of ISO 14000 standards for environmental management systems and ISO 26000 for guidance on social responsibility. Pay attention to the five steps managers can take to ensure that their supply chains are sustainable.	

Key Equation

Energy Efficiency

Break-even weight:

A = lower weight bracket
B = next highest weight bracket
C = freight rate relative to A
D = freight rate relative to B

$$x = (BD)/C$$

Key Terms

carbon footprint 635
closed-loop supply chain 633
environmental responsibility 632
financial responsibility 631
humanitarian logistics 632
intermodal shipments 640
ISO 14001:2004 646
ISO 26000:2010 646
nearest neighbor (NN) heuristic 636
reverse logistics 633
route planning 636
SA8000:2014 644
shortest route problem 636
social responsibility 632
sustainability 631
traveling salesperson problem 636

Solved Problem 1

Greenstreets Recycling, Inc., collects used motor oil from several collection sites around the Greater Stanford area. To minimize the use, and thereby the cost, of its labor, vehicle, and energy resources, the company is interested in locating the shortest route that will allow its collection vehicle to visit each collection site exactly once. The following table provides the travel distances in miles between each site. Note that the company's recycling facility is located at site A.

From/To	A	B	C	D	E	F
A (depot)	–	25	50	48	41	60
B	25	–	35	22	23	43
C	50	35	–	25	47	65
D	48	22	25	–	24	40
E	41	23	47	24	–	21
F	60	43	65	40	21	–

Provide an efficient route for the collection vehicle.

SOLUTION

a. Begin at the recycling facility (site A) and proceed to its nearest neighbor (site B), which is 25 miles away.
b. From site B proceed to its nearest unvisited neighbor. Proceed from B to D—distance 22 miles.
c. From site D proceed to site E—distance 24 miles.
d. From site E proceed to site F—distance 21 miles.
e. From site F proceed to site C (the only remaining unvisited site)—distance 65 miles.
f. From site C return to A—distance 50 miles.

The completed route is A–B–D–E–F–C–A with a total distance traveled of 207 miles (25 + 22 + 24 + 21 + 65 + 50).

To see if a better solution exists, the nearest neighbor heuristic should be repeated using each city in turn as the starting point.

City B: B–D–E–F–A–C–B with a total distance of (22 + 24 + 21 + 60 + 50 + 35) = 212 miles

City C: C–D–B–E–F–A–C with a total distance of (25 + 22 + 23 + 21 + 60 + 50) = 201 miles

City D: D–B–E–F–A–C–D with a total distance of (22 + 23 + 21 + 60 + 50 + 25) = 201 miles

City E: E–F–D–B–A–C–E with a total distance of (21 + 40 + 22 + 25 + 50 + 47) = 205 miles

City F: F–E–B–D–C–A–F with a total distance of (21 + 23 + 22 + 25 + 50 + 60) = 201 miles

Note that the solutions using cities C, D, and F as the starting point all provide the shortest total distance. Thus, with the recycling facility at site A, the collection vehicle should proceed to F then E then B then D then C and finally back to A with a total distance traveled of 201 miles. It should also be noted that since the distances are symmetric, a route of reverse order, A–C–D–B–E–F–A, provides the same total distance traveled.

Solved Problem 2

Kayco Stamping in Fort Worth, Texas, ships sheet metal components to a switch box assembly plant in Waterford, Virginia. Each component weighs approximately 25 pounds, and 50 components fit on a standard pallet. A complete pallet ships as freight class classification 92.5. Use Table 15.2 to calculate the shipment cost for the following demand quantities and calculate the shipping cost per component.

a. 3 pallets
b. 13 pallets

SOLUTION

a. At 3 pallets, or 150 pieces, the shipping weight = 150 × (25 pounds) = 3,750 pounds.
At a freight classification of 92.5, using Table 15.2, the break-even weight = 50(28.64)/37.56 = 38.13 or 3,813 pounds; thus the shipment does not qualify for the lower rate.

Total shipping cost = 37.5(37.56) = $1,408.50.
The per-component shipping charge is $1,408.50/150 = $9.39.

b. At 13 pallets, or 650 pieces, the shipping weight = 650 × (25 pounds) = 16,250 pounds.
At a freight classification of 92.5, using Table 15.2, the break-even weight = 200(18.87)/28.38 =132.98 or 13,298 pounds; thus the shipment qualifies for the lower rate.
Total shipping cost = 162.5(18.87) = $3,066.38.
The per-component shipping charge is $3,066.38/650 = $4.72.

Discussion Questions

1. In the chapter opener, we get a glimpse of how a major corporation can make a significant social contribution by assisting in a disaster relief supply chain. Disasters often occur with little warning; humanitarian aid needs to get to the affected areas very quickly. From the perspective of supply chain design, what capabilities should disaster relief supply chains have?
2. Designing supply chains that are energy efficient and environmentally responsible helps a firm achieve a competitive priority of low-cost operations, which supports the firm's financial responsibility to its shareholders. Explain how focusing on energy efficiency can pose some ethical dilemmas for supply chain managers.
3. New business and subscription models are emerging in e-commerce such as the one followed by JustFab. The company's style experts are able to handpick shoes and handbags for each customer on the basis of an online quiz that is open to all users of JustFab. This enables JustFab to design and manufacture products according to the size of its customer base and their preferences. Customers also have the option of returning the products. While this is fantastic from a customer's perspective, this can be challenging from the perspective of reverse logistics and sustainability. What potential issues can arise from this model?.
4. Traditional buyer–supplier relationships revolve around financial considerations. Buyers and suppliers both try to get the best deals for their companies; often one's gain is the other's loss. Many firms today are valuing sustainable operations, which involve financial, environmental, and social responsibility. Explain how buyer–supplier relationships are evolving in this new environment.

Problems

The OM Explorer, POM for Windows, and Active Model software is available to all students using the 13th edition of this textbook. Check with your instructor about where to go to download this software and how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations.

Energy Efficiency

1. A dairy farmer has a daily milk run from his farm to various schools in the locality and then a return journey to the farm with empty bottles from a previous delivery. The distances in kilometers between all locations may be found in Table 15.3.
   a. The farmer travels from the farm (A) to (B) to (C) to (D) to (E) and then returns to the farm (A). What is the total number of kilometers that the farmer must travel using this route?
   b. Using the farm as the beginning location, create a route using the NN heuristic. What is the total number of kilometers that the farmer must travel using this route?
   c. Using Red Brook School (E) as the beginning location, create a route using the NN heuristic. What is the total number of kilometers that the farmer must travel using this route?

TABLE 15.3 | DISTANCE DATA FOR MILKMAN

From/To	Farm (A)	Fleetwood School (B)	Field School (C)	Green Park School (D)	Red Brook School (E)
Farm (A)	–	4	4.5	5	5.1
Fleetwood School (B)	4	–	7.1	8	5.3
Field School (C)	4.5	7.1	–	5.2	4.6
Green Park School (D)	5	8	5.2	–	8.2
Red Brook School (E)	5.1	5.3	4.6	4.6	–

2. Royal Seafood delivers fresh fin fish and shellfish to specialty grocery stores in the state of Oregon. The company packs a delivery truck in Corvallis and then drives in one single route to its five customers spread throughout the state. The distances in miles between all locations may be found in the table.

From/To	Corvallis (A)	Roseburg (B)	Bend (C)	Baker (D)	Lakeview (E)	Burns (F)
Corvallis (A)	–	93	102	268	219	220
Roseburg (B)	93	–	116	296	167	216
Bend (C)	102	116	–	181	138	117
Baker (D)	268	296	181	–	223	106
Lakeview (E)	219	167	138	223	–	118
Burns (F)	220	216	117	106	118	–

a. Propose an efficient route by using the NN heuristic with Corvallis as the starting city. What is the total distance traveled?

b. Use the NN heuristic to calculate five routes, each starting from the location of one of Royal Seafood's customers. What is the best route for Royal Seafood?

3. On Thursdays, Traxis Consolidated delivers liquid oxygen to its industrial customers in northern Michigan. The table provides the driving time in minutes among all customers and the Traxis liquid oxygen depot location.

From/To	A (depot)	B	C	D	E	F	G	H
A (depot)	–	26	38	31	49	33	40	52
B	26	–	53	54	75	35	56	73
C	38	53	–	46	45	68	70	77
D	31	54	46	–	25	41	30	32
E	49	75	45	25	–	69	55	44
F	33	35	68	41	69	–	27	50
G	40	56	70	30	55	27	–	21
H	52	73	77	32	44	50	21	–

a. Currently, Traxis travels from the depot (A) to (F) to (G) to (D) to (E) to (H) to (B) to (C), then returns to (A). What is the total driving time using this route?

b. Using the depot (A) as the beginning location, create a route using the NN heuristic. What is the total driving time using this route?

c. Use the NN heuristic to calculate seven routes, each starting from the location of one of Traxis's customers. What are your conclusions?

4. Big Jim plows snow for five residential customers in northern New Hampshire. Placing a Cartesian coordinate system on a map of his service area, with his home at the origin (A), Big Jim located his five customers at the following coordinates: B (10, 40); C (22, 20); D (35, 37); E (40, 25);F (50, 40). He has two ways to measure distances between his customers: Euclidean and rectilinear (see Chapter 13, "Supply Chain Logistic Networks" and the section on load–distance method for the definitions of these measures). He is wondering if his method of measuring distances will affect the sequence of customer locations he must visit to minimize his energy costs.

a. Use the NN heuristic to locate the best route for Big Jim, assuming that he is interested in minimizing Euclidean distances.

b. Use the NN heuristic to locate the best route for Big Jim, assuming that he is interested in minimizing rectilinear distances.

5. Helping Harvest is a food bank in the Greater Miami area that collects food donations from local grocery stores and transports them back to a distribution center for sorting and transfer to local food kitchens that feed people in need. Tight budgets and environmental concerns require that both fuel and driver resources be used sparingly. Thus, Mr. Vivek, Helping Harvest's general manager, would like to ensure that collection vehicles are routed most efficiently. The table provides the driving distance in miles between the depot (the distribution center where the truck begins and ends its route) and the five stores that donate food.

From/To	Depot	Store A	Store B	Store C	Store D	Store E
Depot	–	10	24	60	40	26
Store A	10	–	34	46	35	44
Store B	24	34	–	48	20	15
Store C	60	46	48	–	15	35
Store D	40	35	20	15	–	12
Store E	26	44	15	35	12	–

Currently, the Helping Harvest truck travels the following route: Depot–Store A–Store B–Store C–Store D–Store E–Depot.

a. Use the NN heuristics to find a shorter route and calculate the savings in miles traveled per day.

b. The manager at Store B would like the Helping Harvest truck to pick up from her store as early as possible. How many miles does the constraint of visiting Store B first add to the route selected in part (a)?

6. Revisit the Helping Harvest problem in Problem 5. Assume that due to truck capacity constraints, not all stores can be visited in one route. Use the NN heuristic to develop two routes: one that picks up from Stores A and B and one that picks up from Stores C, D, and E in two separate trips. How many miles does this capacity constraint add to the truck's daily miles of travel?

7. Jucio, an orange juice manufacturer in Liverpool, UK, imports fresh oranges from Spain. Jucio imports 6,000 pounds of fresh orange every week and its freight classification is 85. The company realized that it could reduce

the weight of its shipment to 2,500 pounds and bring down its freight classification to 50 by outsourcing the activity of extracting juice to a local company in Spain and transporting the juice to Liverpool. Use Table 15.2 to calculate the break-even cost of using this service.

8. Sampson Industries is very concerned about the cost of shipping products on a daily basis to its distributor. Sampson is considering consolidating daily shipments into weekly or even monthly deliveries. Currently, every month Sampson makes 20 shipments of 1,500 pounds each. Use Table 15.2 to calculate the monthly cost of Sampson's current shipping practice and then calculate the cost of consolidating to 10, 5, 2, and then 1 shipment per month. Sampson believes that the freight classification will stay at 60 irrespective of consolidation.

9. Arts N Crafts Industries manufacturers high-end light fixtures, which it sells internationally. The company is responsible for paying for shipping its product to a distributor located in Atlanta, Georgia. Due to the high cost of shipping, the company is considering shipping its products unassembled, but will include detailed assembly instructions in each package. By shipping unassembled products, Arts N Crafts will be able to shrink the size of its cartons and thereby increase the number of products per pallet from 16 (4 rows of 4) to 25 (5 rows of 5). Note that this change will not appreciably increase each product's 8-pound shipping weight. Furthermore, since individual fixtures will be packed more tightly, they will be less susceptible to damage and easier to handle. Thus, the company expects the freight class to decrease from 85 to 70. Currently the company ships 400 units per week.

   a. Using Table 15.2, assess the impact of the proposed change in packaging on weekly shipping cost.

   b. How will your analysis change if demand for the product increases to 500 units per week?

10. Mulan sells liquid detergents to hotels, hospitals, and individual customers through a network of retailers and wholesalers. To reduce environmental impact, the company is considering selling concentrated soap that can be diluted at the place of consumption. Currently the liquid detergents are transported in packs of 10 bottles and each pack weighs 20 pounds. Mulan ships 800 packs per week. Concentrated soap can be shipped in packs of 5 and each pack would weigh 15 pounds. The company expects to ship 100 packs per week. These changes will result in a lighter but more difficult package for shippers to handle. The freight classification has worsened from 65 to 85. Calculate the difference in Mulan's weekly shipping charges.

VIDEO CASE Supply Chain Sustainability at Clif Bar & Company

When Gary Erickson started out on one of his typical long-distance bike treks in 1990, he expected to have a great ride. What he did not expect was to come home with the idea for a sports nutrition energy bar that became the genesis of Clif Bar & Company.

After consuming most of his supply of Power Bars partway through the 175-mile ride, Erickson could not face the prospect of consuming another one. Instead, he figured he could come up with something better. Something sports enthusiasts would not mind eating in quantities while out on the road or the trail. The result? The CLIF® BAR, an all-natural combination of grains, nuts, and fruit, with far more taste appeal than the standard energy bar of the time.

Today, the Berkeley, California–based company has over 100 stock-keeping units, or SKUs, in its product mix, including numerous flavorful versions of the original CLIF BAR plus brands such as LUNA®, The Whole Nutrition Bar for Women™; CLIF Kid Organic ZBaR™, The Whole Grain Energy bar for kids; CLIF Mojo™, The Sweet & Salty Trail Mix Bar; and CLIF Nectar®, an organic fruit and nut bar made with just five ingredients. CLIF BARs were originally distributed through cycling shops and other niche retail outlets but can now be found in a wide variety of retail outlets in the United States, such as Whole Foods, Trader Joe's, REI, and even your local grocery store.

From the beginning, CLIF BARs were made from wholesome ingredients. Yet as Erickson looked at the ingredients being sourced for CLIF BAR, he realized that making a healthy food product and sourcing ingredients from farmers, ranchers, and cooperatives using organic growing techniques was a "natural" fit. The company made a commitment to both sustainable growing techniques and using only organic raw ingredients back then, and by 2003, had made CLIF BAR 70 percent certified organic. Since then, six of Clif Bar & Company's CLIF and LUNA brands are now made with 70 percent organic ingredients or more.

The impact on the supply chain for sourcing organic ingredients is tremendous. First, there is a limited—but growing—number of organic growers for the ingredients Clif Bar uses. Second, growers who do not use pesticides, herbicides, and genetically modified plants are sometimes at risk of producing lower crop yields. Third, it can be more costly to store the ingredients. And fourth, as more companies commit to environmentally responsible programs and organic ingredients, competition is great for the available global supply.

The company's forecasters and planners work hard to manage both the raw ingredient inventory flows from upstream suppliers and the finished goods flows to downstream customers to be sure products are available in the right quantities and right locations. Ordering of raw materials and packaging materials is aggregated to provide efficient sourcing. Production is planned, based on both input and output forecasts, to maximize customer service and minimize inventory. Several times a year, production plans are shared with business partners at all points of the supply chain to make sure that the flow of ingredients and products is smooth, and that inventories do not accumulate at any point in the supply chain beyond planned volumes. Monthly forecasts and changes to plans also are communicated to all supply chain partners.

Clif Bar & Company managers know that consumers' tastes for products change regularly, so new flavors and brands are periodically introduced into the various brands. Likewise, flavors are sometimes retired to make room for new ones. As the company's research and development team prepares to move a new product idea from the test kitchen to the manufacturing plant, supply chain managers must get to work to ensure any new ingredients can be procured.

As a smaller and privately owned company, Clif Bar does not own its manufacturing plants and distribution centers, and relies on contractual agreements with outsourcers in the United States. These supply chain business partners are carefully chosen for their ability to manufacture and distribute Clif Bar's products, their commitment to quality, and their alignment with Clif Bar's own value system. This value system, referred to as the company's "Five

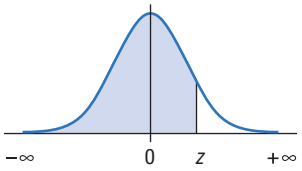
Aspirations," holds that Clif Bar & Company will work toward sustaining its people, brands, business, community, and the planet. Greg Ginsburg, Vice President of Supply Chain, wants to be sure all parts of the supply chain—owned or not—are in agreement with these aspirations. "We look at their energy sourcing, labor practices, and workplace environments. And where we source products from small cooperatives, we'll go as far back as possible to assure those tiny growers know about our expectations," says Ginsburg.

QUESTIONS

1. In what ways does Clif Bar have a sustainable supply chain?
2. Regarding financial responsibility, what business risks does Clif Bar & Company face with so many parts of its supply chain outsourced?
3. What issues or risks to sustainability could Clif Bar & Company encounter if it chose to expand to international markets?

APPENDIX

NORMAL DISTRIBUTION



z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133
.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998

Selected References

Chapter 1: Using Operations to Create Value

Bordoloi, Sanjeev, James A. Fitzimmons, and Mona Fitzsimmons. *Service Management: Operations, Strategy, Information Technology*, 9th ed. New York: McGraw-Hill, 2019.

Chase, Richard B., and Uday M. Apte. "A History of Research in Service Operations: What's the Big Idea?" *Journal of Operations Management*, vol. 25, no. 2 (2007), pp. 375–386.

Collis, David J., and Michael G. Rukstad. "Can You Say What Your Strategy Is?" *Harvard Business Review*, vol. 86, no. 4 (2008), pp. 82–90.

Frank, A.G., L.S. Dalenogare, and N.F. Ayala. Industry 4.0 Technologies: Implementation Patterns in Manufacturing Companies. *International Journal of Production Economics*, 210 (2019), pp. 15–26.

Gaimon, Cheryl. "The Management of Technology: A Production and Operations Management Perspective." *Production and Operations Management*, vol. 17, no. 1 (2008), pp. 1–11.

Hammer, Michael. "Deep Change: How Operational Innovation Can Transform Your Company." *Harvard Business Review*, vol. 82, no. 9 (2004), pp. 85–93.

Heineke, Janelle, and Mark Davis. "The Emergence of Service Operations as an Academic Discipline." *Journal of Operations Management*, vol. 25, no. 2 (2007), pp. 364–374.

Hill, Terry. *Manufacturing Strategy: Text and Cases*, 3rd ed. Homewood, IL: Irwin/McGraw-Hill, 2000.

Huckman, Robert S., and Darren E. Zinner. "Does Focus Improve Operational Performance? Lessons from the Management of Clinical Trials." *Strategic Management Journal*, vol. 29 (2008), pp. 173–193.

Jones, Daniel T., James P. Womack, and Daniel Roos. *The Machine That Changed the World: The Story of Lean Production—Toyota's Secret Weapon in the Global Car Wars That Is Now Revolutionizing World Industry*. New York: The Free Press, 2007.

Kaplan, Robert S., and David P. Norton. *Alignment: Using the Balanced Scorecard to Create Corporate Synergies*. Boston, MA: Harvard Business School Press, 2006.

Karmarkar, Uday. "Will You Survive the Services Revolution?" *Harvard Business Review*, vol. 82 (2004), pp. 100–108.

Meyer, Christopher, and Andre Schwager. "Understanding Customer Experience." *Harvard Business Review*, vol. 85 (2007), pp. 116–126.

Neilson, Gary L., Karla L. Martin, and Elizabeth Powers. "The Secrets to Successful Strategy Execution." *Harvard Business Review*, vol. 86, no. 6 (2008), pp. 60–70.

Ohno, Taiichi. *Toyota Production System: Beyond Large-Scale Production*. New York: Productivity Press, 1988.

Pande, Peter S., Robert P. Neuman, and Roland R. Cavanaugh. *The Six Sigma Way: How to Maximize the Impact of Your Change and Improvement Efforts*. New York: McGraw-Hill, 2014.

Pisano, G., and W. Shih. "Does America Really Need Manufacturing?" *Harvard Business Review*, vol. 90, no. 3 (2012), pp. 94–102.

Porter, Michael E. *Competitive Advantage*. New York: The Free Press, 1987.

Porter, Michael E., and Mark R. Kramer. "Strategy and Society: The Link Between Competitive Advantage and Corporate Social Responsibility." *Harvard Business Review*, vol. 84, no. 12 (2006), pp. 78–92.

Safizadeh, M. Hossein, Larry P. Ritzman, Deven Sharma, and Craig Wood. "An Empirical Analysis of the Product–Process Matrix." *Management Science*, vol. 42, no. 11 (1996), pp. 1576–1591.

Skinner, Wickham. "Manufacturing—Missing Link in Corporate Strategy." *Harvard Business Review* (May/June 1969), pp. 136–145.

Simchi-Levi, D., and J. Peruvankal "Is It Time to Rethink Your Manufacturing Strategy." *MIT Sloan Management Review*, vol. 53, no. 2 (2012), pp. 20–22.

Voss, Chris, Aleda Roth, and Richard Chase. "Experience, Service Operations Strategy, and Services as Destinations: Foundations and Exploratory Investigation." *Production and Operations Management*, vol. 17, no. 3 (2008), pp. 247–266.

Wiseman, Paul. "Despite China's Might, U.S. Factories Maintain Edge." http://www.cbsnews.com/news/despite-chinas-might-us-factories-maintain-edge-30-01-2011/ (January 31, 2011).

Supplement A: Decision Making

Clemen, Robert T., and Terence Reilly. *Making Hard Decisions with Decision Tools Suite*, 3rd ed. Boston, MA: Cengage, 2014.

Ragsdale, Cliff. *Spreadsheet Modeling & Decision Analysis: A Practical Introduction to Business Analytics*, 8th ed. Boston, MA: Cengage, 2018.

Velleman, J. "Deciding How to Decide." *Harvard Business Review*, vol. 91, no. 11 (2013), pp. 62–71.

Chapter 2: Process Strategy and Analysis

Andersen, Bjørn. *Business Process Improvement Toolbox*, 2nd ed. Milwaukee, WI: American Society for Quality, 2007.

Ahire, Sanjay L., and Manoj K. Malhotra. "Scripting a Holistic Rx for Process Improvement at Palmetto Health Imaging Centers." *Journal of Global Business and Organizational Excellence*, vol. 30, no. 2 (January/February 2011), pp. 23–35.

Baghai, Ramin, Edward H. Levine, and Saumya S. Sutaria. "Service-Line Strategies for U.S. Hospitals." *The McKinsey Quarterly* (July 2008), pp. 1–9.

Bhuiyan, Nadjia, Amit Baghel, and Jim Wilson. "A Sustainable Continuous Improvement Methodology at an Aerospace Company," *International Journal of Productivity and Performance Management*, vol. 55, no. 8 (2006), pp. 671–687.

Booth, Alan. "The Management of Technical Change: Automation in the UK and USA since 1950." *The Economic History Review*, vol. 62, no. 2 (May 2009), pp. 493–494.

Brink, Harold, Senthil Muthiah, and Rajan Naik. "A Better Way to Automate Service Operations." *McKinsey on Business Technology*, vol. 20 (Summer, 2010), pp. 1–10.

Carey, Susan. "Case of the Vanishing Airport Lines." *Wall Street Journal*, vol. 250, no. 33 (August 9, 2007), pp. B1–B4.

Chase, Richard B., and Uday M. Apte. "A History of Research in Service Operations: What's the Big Idea?" *Journal of Operations Management*, vol. 25 (2007), pp. 375–386.

Davenport, Thomas H. "The Coming Commoditization of Processes." *Harvard Business Review* (June 2005), pp. 101–108.

Edmondson, Amy C. "The Competitive Imperative of Learning." *Harvard Business Review*, vol. 86 (July/August, 2008), pp. 1–13.

Fleming, John H., Curt Coffman, and James K. Harter. "Manage Your Human Sigma." *Harvard Business Review* (July/August 2005), pp. 101–108.

Greasley, A. "Using Process Mapping and Business Process Simulation to Support a Process-Based Approach to Change in a Public Sector Organisation." *Technovation*, vol. 26 (2006), pp. 95–103.

Grosskopf, Alexander, Gero Decker, and Mathias Weske. *The Process: Business Process Modelling Using BPMN*. Tampa, FL: Meghan-Kiffer Press, 2009.

Hall, J. M., and M. E. Johnson. "When Should a Process Be Art, Not Science?" *Harvard Business Review*, vol. 87, no. 3 (2009), pp. 58–66.
Hammer, Michael. "Deep Change: How Operational Innovation Can Transform Your Company." *Harvard Business Review*, vol. 82, no. 4 (April 2004), pp. 85–93.
Hammer, Michael. "The Process Audit." *Harvard Business Review*, vol. 82, no. 4 (April 2007), pp. 111–123.
Hammer, Michael. "What Is Business Process Management?" *Handbook on Business Process Management*, vol. 1 (2010), pp. 3–16.
Hartvigsen, David. *SimQuick: Process Simulation with Excel*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, 2016.
Hayes, Robert. *Operations, Strategy, and Technology: Pursuing the Competitive Edge*. Hoboken, NJ: Wiley, 2005.
Hill, Terry. *Manufacturing Strategy: Text and Cases*, 3rd ed. Homewood, IL: Irwin/McGraw-Hill, 2000.
Jack, Eric, and John Collis. "Strengthen and Tone: A Flexible Approach to Operations Can Build Some Serious Muscle." *APICS Magazine* (June 2006), pp. 35–38.
Jain, Rashmi, Angappa Gunasekaran, and Anithashree Chandrasekaran. "Evolving Role of Process Reengineering: A Perspective of Employers." *Industrial and Commercial Training*, vol. 41, no. 7 (2009), pp. 382–390.
Jensen, John B., Sanjay L. Ahire, and Manoj K. Malhotra. "Trane/Ingersoll Rand Combines Lean and Operations Research Tools to Redesign Feeder Manufacturing Operations." *Interfaces*, vol. 43, no. 4 (2013), pp. 325–340.
Jeston, John, and Johan Nelis. *Management by Process: A Roadmap to Sustainable Business Process Management*. Oxford, UK: Elsevier, 2008.
Johansson, Pontus, and Jan Olhager. "Linking Product-Process Matrices for Manufacturing and Industrial Service Operations." *International Journal of Production Economics*, vol. 104 (2006), pp. 615–624.
Karmarkar, Uday. "Will You Survive the Services Revolution?" *Harvard Business Review*, vol. 82, no. 6 (June 2004), pp. 100–107.
Kulpa, Margaret K., and Kent A. Johnson. *Interpeting the CMMI: A Process Improvement Approach*, 2nd ed. Boca Raton, FL: Auerbach Publications, 2008.
Kung, Peter, and Claus Hagen. "The Fruits of Business Process Management: An Experience Report from a Swiss Bank." *Business Process Management Journal*, vol. 13, no. 4 (2007), pp. 477–487.
La Ferla, Beverly. "Mapping the Way to Process Improvement." *IEE Engineering Management* (December 2004/January 2005), pp. 16–17.
Lee, Hau L. "The Triple-A Supply Chain." *Harvard Business Review* (October 2004), pp. 102–112.
Metters, Richard, Kathryn King-Metters, and Madeleine Pullman. *Successful Service Operations Management*. Mason, OH: South-Western, 2003.
Prajogo, Daniel. "The Implementation of Operations Management Techniques in Service Organisations." *International Journal of Operations & Production Management*, vol. 26, no. 12 (2006), pp. 1374–1390.
Rummler, Geary A., and Alan P. Brache. *Improving Performance: How to Manage the White Space on the Organization Chart*, 3rd ed. San Francisco: Jossey-Bass Inc., 2012.
Safizadeh, M. Hossein, Joy M. Field, and Larry P. Ritzman. "An Empirical Analysis of Financial Services Processes with a Front-Office or Back-Office Orientation." *Journal of Operations Management*, vol. 21, no. 5 (2003), pp. 557–576.
Safizadeh, M. Hossein, Larry P. Ritzman, and Debasish Mallick. "Revisiting Alternative Theoretical Paradigms in Manufacturing." *Production and Operations Management*, vol. 9, no. 2 (2000), pp. 111–127.
Scott, Bradley, Anne E. Wilcock, and Vinay Kanetkar. "A Survey of Structured Continuous Improvement Programs in the Canadian Food Sector." *Food Control*, vol. 20 (2009), pp. 209–217.
Sehgal, Sanjay, B. S. Sahay, and S. K. Goyal. "Reengineering the Supply Chain in a Paint Company." *International Journal of Productivity and Performance Management*, vol. 55, no. 8 (2006), pp. 655–670.
Swink, Morgan, and Anand Nair. "Capturing the Competitive Advantages of AMT: Design-Manufacturing Integration as a Complementary Asset." *Journal of Operations Management*, vol. 25 (2007), pp. 736–754.
Zomerdijk, Leonieke G., and Jan de Vries. "Structuring Front Office and Back Office Work in Service Delivery Systems." *International Journal of Operations & Production Management*, vol. 27, no. 1 (2007), pp. 108–131.

Chapter 3: Quality and Performance

Babbar, Sunil. "Service Quality and Business Ethics." *International Journal of Service and Operations Management*, vol. 1, no. 3 (2005), pp. 203–219.
Besterfield, Dale. *Quality Improvement*, 9th ed. Upper Saddle River, NJ: Prentice Hall, 2012.
Cole, R. "What Really Happened to Toyota?" *MIT Sloan Management Review*, vol. 52, no. 4 (2011), pp. 29–35.
Cole, R., and M. Flynn. "Automotive Quality Reputation: Hard to Achieve, Hard to Lose, Still Harder to Win Back." *California Management Review*, vol. 52, no. 1 (2009), pp. 67–94.
Crosby, Philip B. *Quality Is Free: The Art of Making Quality Certain*. New York: McGraw-Hill, 1979.
Deming, W. Edwards. *Out of the Crisis*. Cambridge, MA: Massachusetts Institute of Technology Center for Advanced Engineering Study, 1986.
Duncan, Acheson J. *Quality Control and Industrial Statistics*, 5th ed. Homewood, IL: Irwin, 1986.
Feigenbaum, A. V. *Total Quality Control: Engineering and Management*, 3rd ed. New York: McGraw-Hill, 1983.
Hartvigsen, David. *SimQuick: Process Simulation with Excel*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, 2016.
Hoyle, David. *ISO 9000 Quality Systems Handbook-updated for the ISO 9001: 2015 standard: Increasing the Quality of an Organization's Outputs*, 7th ed. Abingdon, UK: Routledge, 2017.
Mitra, Amitava. *Fundamentals of Quality Control and Improvement*, 4th ed. Hoboken, NJ: Wiley & Sons, 2016.
Russell, J. P., and Dennis Arter. *ISO Lesson Guide to ISO 9001*, 3rd ed. Milwaukee: ASQC Quality Press, 2008.
Srinivasan, A., and B. Kurey. "Creating a Culture of Quality." *Harvard Business Review*, vol. 92, no. 4 (2014), pp. 23–25.
Yannick, Julliard. "Ethics Quality Management." *Techné Journal*, vol. 8, no. 1 (Fall 2004), pp. 117–135.

Chapter 4: Capacity Planning

Bower, J. L., and C. G. Gilbert. "How Managers' Everyday Decisions Create or Destroy Your Company's Strategy." *Harvard Business Review*, vol. 85, no. 2 (2007), pp. 72–79.
Hartvigsen, David. *SimQuick: Process Simulation with Excel*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, 2016.
Klassen, Robert D., and Larry J. Menor. "The Process Management Triangle: An Empirical Investigation of Process Trade-offs." *Journal of Operations Management*, vol. 25 (2007), pp. 1015–1034.
Tenhiala, A. "Contingency Theory of Capacity Planning: The Link Between Process Types and Planning Methods." *Journal of Operations Management*, vol. 29 (2011), pp. 65–77.

Chapter 5: Constraint Management

Brown, A. "Theory of Constraints Tapped to Accelerate BP's Gulf of Mexico Cleanup." *Industry Week* (March 18, 2011).

Corominas, Albert, Rafael Pastor, and Joan Plans. "Balancing Assembly Line with Skilled and Unskilled Workers." *Omega*, vol. 36, no. 6 (2008), pp. 1126–1132.
Goldratt, E. M., and J. Cox. *The Goal*. New York: North River Press, 2012.
McClain, John O., and L. Joseph Thomas. "Overcoming the Dark Side of Worker Flexibility." *Journal of Operations Management*, vol. 21 (2003), pp. 81–92.
Steele, Daniel C., Patrick R. Philipoom, Manoj K. Malhotra, and Timothy D. Fry. "Comparisons Between Drum-Buffer-Rope and Material Requirements Planning: A Case Study." *International Journal of Production Research*, vol. 43, no. 15 (2005), pp. 3181–3208.
Umble, M., E. Umble, and S. Murakami. "Implementing Theory of Constraints in a Traditional Japanese Manufacturing Environment: The Case of Hitachi Tool Engineering." *International Journal of Production Research*, vol. 44, no. 15 (2006), pp. 1863–1880.

Supplement B: Waiting Lines

Buell, R., and M. Norton. "Think Customers Hate Waiting? Not so Fast." *Harvard Business Review*, vol. 89, no. 5 (2011), pp. 34.
Cooper, Robert B. *Introduction to Queuing Theory*, 3rd ed. Washington, DC: George Washington University, 1990.
Hartvigsen, David. *SimQuick: Process Simulation with Excel*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, 2016.
Hillier, F. S., and G. S. Lieberman. *Introduction to Operations Research*, 11th ed. New York: McGraw-Hill, 2021.
Little, J. D. C. "A Proof for the Queuing Formula: " *Operations Research*, vol. 9 (1961), pp. 383–387.
Morse, P. M. *Queues, Inventories and Maintenance*. New York: Dover Publications, 2004.

Chapter 6: Lean Systems

Ansberry, Clare. "Hurry-Up Inventory Method Hurts Where It Once Helped." http://online.wsj.com/news/articles/SB1024952665607014520 (June 25, 2002).
Holweg, Matthias. "The Genealogy of Lean Production." *Journal of Operations Management*, vol. 25 (2007), pp. 420–437.
Immelt, J. "The CEO of General Electric on Sparking an American Manufacturing Renewal." *Harvard Business Review*, vol. 90, no. 3 (2012), pp. 43–46.
Manufacturing Engineering Inc. "5S Solutions: Train-Implement-Sustain." http://www.mfgeng.com/5S.htm (2013).
Mascitelli, Ron. "Lean Thinking: It's about Efficient Value Creation." *Target*, vol. 16, no. 2 (Second Quarter 2000), pp. 22–26.
McBride, David. "Toyota and Total Productive Maintenance." http://www.emsstrategies.com/dm050104article2.html (May 2004).
Spear, Steven J. "Learning to Lead at Toyota." *Harvard Business Review* (May 2004), pp. 78–86.
Spear, Steven J., and H. Kent Bowen. "Decoding the DNA of the Toyota Production System." *Harvard Business Review* (September–October 1999), pp. 97–106.
Staats, B., and D. Upton. "Lean Knowledge Work." *Harvard Business Review*, vol. 89, no. 12 (2011), pp. 21–22.

Chapter 7: Project Management

Dionsio, Cynthia Snyder, *Microsoft Project 2019 for Dummies*. New York: John Wiley & Sons, 2019.
Goldratt, E. M. *Critical Chain*. Great Barrington, MA: North River, 1997.
"A Guide to Project Management Body of Knowledge." Available from the Project Management Institute at www.pmi.org, 2013.
Hartvigsen, David. *SimQuick: Process Simulation with Excel*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, 2016.
Kerzner, Harold. *Advanced Project Management: Best Practices on Implementation*, 2nd ed. New York: John Wiley & Sons, 2004.
Kerzner, Harold. *Project Management: A Systems Approach to Planning, Scheduling, and Controlling*, 12th ed. New York: John Wiley & Sons, 2017.
Lewis, J. P. *Mastering Project Management*, 2nd ed. New York: McGraw-Hill, 2007.
Meredith, Jack R., Scott M. Shafer, Samuel J. Mantel Jr., and Margaret M. Sutton. *Project Management in Practice*, 6th ed. New York: John Wiley & Sons, 2017.
Meredith, Jack R., Scott M. Shafer, and Samuel J. Mantel, Jr. *Project Management: A Strategic Managerial Approach*, 8th ed. New York: John Wiley & Sons, 2017.
Nicholas, John M., and Herman Stein. *Project Management for Engineering, Business, and Technology*, 5th ed. London, U.K.: Routledge, 2017.
Srinivasan, Mandyam, Darren Jones, and Alex Miller. "CORPS Capabilities." *APICS Magazine* (March 2005), pp. 46–50.

Chapter 8: Forecasting

Armstrong, J. Scott. "Findings from Evidence-based Forecasting: Methods for Reducing Forecast Error." *International Journal of Forecasting*, vol. 22, no. 3 (2006), pp. 583–598.
Armstrong, J. Scott. (ed.). *Principles of Forecasting: A Handbook for Researchers and Practitioners*. Norwell, MA: Kluwer Academic Publishers, 2001. Also visit http://www.forecastingprinciples.com for valuable information on forecasting, including frequently asked questions, a forecasting methodology tree, and a dictionary.
Attaran, Mohsen, and Sharmin Attaran. "Collaborative Supply Chain Management." *Business Process Management Journal*, vol. 13, no. 13 (June 2007), pp. 390–404.
Bari, Anasse, Mohamed Chaouchi, and Tommy Jung. *Predictive Analytics for Dummies*, 2nd ed. New York: John Wiley & Sons, Inc. (2016).
Bresnik, Jennifer. "10 High-Value Use Cases for Predictive Analytics in Healthcare," *Health IT Analytics* (September 4, 2018).
Cederlund, Jerold P., Rajiv Kohli, Susan A. Sherer, and Yuliang Yao. "How Motorola Put CPFR into Action." *Supply Chain Management Review* (October 2007), pp. 28–35.
Fildes, Robert, Paul Goodwin, Michael Lawrence, and Konstantinos Nikolopoulos. "Effective Forecasting and Judgmental Adjustments: An Empirical Evaluation and Strategies for Improvement in Supply-Chain Planning." *International Journal of Forecasting*, vol. 25, no. 1 (2009), pp. 3–23.
Lawrence, Michael, Paul Goodwin, Marcus O'Connor, and Dilek Onkal. "Judgmental Forecasting: A Review of Progress over the Last 25 Years." *International Journal of Forecasting* (June 2006), pp. 493–518.
Makridakis, S., R. Hogarth, and A. Gaba. "Why Forecasts Fail: What to Do Instead." *MIT Sloan Management Review*, vol. 51, no. 2 (2010), pp. 83–90.
McCarthy, Teresa, Donna F. Davis, Susan L. Golicic, and John T. Mentzer. "The Evolution of Sales Forecasting Management: A 20-Year Longitudinal Study of Forecasting Practices." *Journal of Forecasting*, vol. 25 (2006), pp. 303–324.
Min, Hokey, and Wen-Bin Vincent Yu. "Collaborative Planning, Forecasting and Replenishment: Demand Planning in Supply Chain Management." *International Journal of Information Technology and Management*, vol. 7, no. 1 (2008), pp. 4–20.
Montgomery, David. "Flashpoints for Changing Your Forecasting Process." *The Journal of Business Forecasting* (Winter 2006–2007), pp. 35–42.
Saffo, Paul. "Six Rules for Effective Forecasting." *Harvard Business Review* (July–August 2007), pp. 1–30.
Smaros, Johanna. "Forecasting Collaboration in the European Grocery Sector: Observations from a Case Study." *Journal of Operations Management*, vol. 25, no. 3 (April 2007), pp. 702–716.

Smith, Larry. "West Marine: A CPFR Success Story." *Supply Chain Management Review* (March 2006), pp. 29–36.
Syntetos, Aris, Konstantinos Nikolopoulos, John Boylan, Robert Fildes, and Paul Goodwin. "The Effects of Integrating Management Judgement into Intermittent Demand Forecasts." *International Journal of Production Economics*, vol. 118, no. 1 (March 2009), pp. 72–81.
Wallers, Mathew A., and Stanley E. Faucett. "Data Science, Predictive Analytics, and Big Data: A Revolution That Will Transform Supply Chain Design and Management," *Journal of Business Logistics*, vol. 34, no. 2 (2013), pp. 77–84.
Wikipedia. "Collaborative planning, forecasting, and replenishment." http://en.wikipedia.org/wiki/Collaborative_planning_forecasting_and_replenishment (August 2020).

Chapter 9: Inventory Management

Axsäter, Sven. *Inventory Control*, 3rd ed. New York: Springer Science + Business Media, LLC, 2015.
Bastow, B. J. "Metrics in the Material World." *APICS—The Performance Advantage* (May 2005), pp. 49–52.
Benton, W. C. *Purchasing and Supply Chain Management*, 3rd ed. New York: McGraw-Hill, 2013.
Callioni, Gianpaolo, Xavier de Montgros, Regine Slagmulder, Luk N. Van Wassenhove, and Linda Wright. "Inventory-Driven Costs." *Harvard Business Review* (March 2005), pp. 135–141.
Chapman, Stephen, Tony J. R. Arnold, Ann K. Gatewood, and Lloyd M. Clive. *Introduction to Materials Management*, 8th ed. Upper Saddle River, NJ: Prentice Hall, 2017.
Gaur, V., S. Kesavan, and A. Raman. "Retail Inventory: Managing the Canary in the Coal Mine." *California Management Review*, vol. 56, no. 2 (2014), pp. 55–76.
Hartvigsen, David. *SimQuick: Process Simulation with Excel*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, 2016.
Operations Management Body of Knowledge, 3rd ed. Falls Church, VA: American Production and Inventory Control Society, 2011.
Shenoy, Dinesh, and Roberto Rosas. "Problems & Solutions in Inventory Management." London, UK: *Springer International Publishing*, 2018.
Timme, Stephen G., and Christine Williams-Timme. "The Real Cost of Holding." *Supply Chain Management Review* (July/August 2003), pp. 30–37.
Walters, Donald. *Inventory Control and Management*, 2nd ed. West Sussex, England: John Wiley and Sons, Ltd, 2013.

Supplement C: Special Inventory Models

Axsäter, Sven. *Inventory Control*, 3rd ed. New York: Springer Science + Business Media, LLC, 2015.
Bastow, B. J. "Metrics in the Material World." *APICS—The Performance Advantage* (May 2005), pp. 49–52.
Benton, W. C. *Purchasing and Supply Chain Management*, 3rd ed. New York: McGraw-Hill, 2015.
Callioni, Gianpaolo, Xavier de Montgros, Regine Slagmulder, Luk N. Van Wassenhove, and Linda Wright. "Inventory-Driven Costs." *Harvard Business Review* (March 2005), pp. 135–141.
Cannon, Alan R., and Richard E. Crandall. "The Way Things Never Were." *APICS—The Performance Advantage* (January 2004), pp. 32–35.
Chapman, Stephen, Tony J. R. Arnold, Ann K. Gatewood, and Lloyd M. Clive. *Introduction to Materials Management*, 8th ed. Upper Saddle River, NJ: Prentice Hall, 2017.
Hartvigsen, David. *SimQuick: Process Simulation with Excel*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, 2016.
Manikas, Andrew. "Fighting Pests with the EOQ." *APICS Magazine* (April 2007), pp. 34–37.
Operations Management Body of Knowledge, 3rd ed. Falls Church, VA: American Production and Inventory Control Society, 2011.
Shenoy, Dinesh, and Roberto Rosas. "Problems & Solutions in Inventory Management," *Springer International Publishing*, 2018.
Timme, Stephen G., and Christine Williams-Timme. "The Real Cost of Holding." *Supply Chain Management Review* (July/August 2003), pp. 30–37.
Walters, Donald. *Inventory Control and Management*, 2nd ed. West Sussex, England: John Wiley and Sons, Ltd, 2013.

Chapter 10: Operations Planning and Scheduling

Baker, Ken R., and Dan Trietsch. *Principles of Sequencing and Scheduling*, 2nd ed. New York: John Wiley & Sons, Inc. 2019.
Chiang, Wen-Chyuan, Jason C. H. Chen, and Xiaojing Xu. "An Overview of Research on Revenue Management: Current Issues and Future Research." *International Journal of Revenue Management*, vol. 1, no. 1 (2007), pp. 97–128.
Dougherty, John R. "Lessons from the Pros." *APICS Magazine* (November/December 2007), pp. 31–33.
Dougherty, John R., and Christopher Gray. *Sales & Operations Planning—Best Practices*. Victoria, Canada: Trafford Publishing, 2006.
Esper, Terry L., Alexander E. Ellinger, Theodore P. Stank, Daniel J. Flint, and Mark Moon. "Demand and Supply Integration: A Conceptual Framework of Value Creation through Knowledge Management." *Journal of the Academy of Marketing Science*, vol. 38 (2010), pp. 5–18.
Gray, Christopher. *Sales & Operations Planning—Standard System*. Victoria, Canada: Trafford Publishing, 2007.
Gupta, Jatinder N. D., and Edward Stafford Jr. "Flowshop Scheduling Research after Five Decades." *European Journal of Operational Research*, vol. 169 (2006), pp. 699–711.
Jacobs, F. Robert, William Berry, D. Clay Whybark, and Thomas Vollmann. *Manufacturing Planning and Control for Supply Chain Management*, 2nd ed. US: McGraw-Hill Professional, 2018.
Kelly, Erin L., and Phyllis Moen. "Rethinking the ClockWork of Work: Why Schedule Control May Pay Off at Work and at Home." *Advances in Developing Human Resources*, vol. 9, no. 4 (November 2007), pp. 487–605.
Muzumdar, Maha, and John Fontanella. "The Secrets to S&OP Success." *Supply Chain Management* (April 2006), pp. 34–41.
Nakano, Mikihisa. "Collaborative Forecasting and Planning in Supply Chains: The Impact on Performance in Japanese Manufacturers." *International Journal of Physical Distribution & Logistics Management*, vol. 39, no. 2 (2009), pp. 84–105.
Olhager, Jan, and Erik Selldin. "Manufacturing Planning and Control Approaches: Market Alignment and Performance." *International Journal of Production Research*, vol. 45, no. 6 (2007), pp. 1469–1484.
Pinedo, Michael. *Planning and Scheduling in Manufacturing and Services*, 2nd ed. New York: Springer, 2009.
Quadt, Daniel, and Heinrich Kuhn. "A Taxonomy of Flexible Flow Line Scheduling Procedures." *European Journal of Operational Research*, vol. 178 (2007), pp. 686–698.
Rennie, Elizabeth. "All Fired UP: Why Food and Beverage Professionals Must Put S&OP on the Menu." *APICS Magazine* (July/August 2006a), pp. 32–35.
Singhal, Jaya, and Kalyan Singhal. "Holt, Modigliani, Muth, and Simon's Work and Its Role in the Renaissance and Evolution of Operations Management." *Journal of Operations Management*, vol. 25, no. 2 (March 2007), pp. 300–309.
Slone, Reuben, John T. Mentzer, and J. Paul Dittmann. "Are You the Weakest Link in Your Company's Supply Chain?" *Harvard Business Review* (October 2007), pp. 1–11.
Smith, Larry, Joseph C. Andraski, and E. Fawcett. "Integrated Business Planning: A Roadmap to Linking S&OP and CPFR." *Business Forecasting*, vol. 29, no. 4 (Winter 2011), pp. 1–17.

Takey, Flavia, and Marco A. Mesquita. "Aggregate Planning for a Large Food Manufacturer with High Seasonal Demand." *Brazilian Journal of Operations & Production Management*, vol. 3, no. 1 (2006), pp. 5–20.

Trottman, Melanie. "Choices in Stormy Weather: How Airline Employees Make Hundreds of Decisions to Cancel or Reroute Flights." *Wall Street Journal* (February 14, 2006), pp. B1–B3.

Wallace, Thomas F., and Robert A. Stahl. "Sales Forecasting: Improving Cooperation Between the Demand People and the Supply People." *Foresight*, no. 12 (Winter 2009), pp. 14–20.

Wallace, Thomas F., and Robert A. Stahl. *Sales & Operations Planning: The Executive's Guide*, 7th ed. Cincinnati, OH: T. F. Wallace & Company, 2014.

Wikipedia Aggregate Planning, https://en.wikipedia.org/wiki/Aggregate_planning (2020).

Supplement D: Linear Programming

Anderson, D. R., D. J. Sweeney, T. A. Williams, J. D. Camm, and R. Kipp Martin. *An Introduction to Management Science: A Quantitative Approach to Decision Making*, 15th ed. Boston, MA: Cengage Learning, 2018.

Hillier, Fredrick S., and Mark S. Hillier. *Introduction to Management Science: A Modeling and Case Studies Approach with Spreadsheets*, 5th ed. Burr Ridge, IL: McGraw Hill, 2013.

Ragsdale, Cliff. *Spreadsheet Modeling & Decision Analysis: A Practical Introduction to Management Science*, 8th ed. Boston, MA: Cengage Learning, 2018.

Render, Barry, Ralph M. Stair, and Michael E. Hanna. *Quantitative Analysis for Management*, 13th ed. Upper Saddle River, NJ: Prentice Hall, 2018.

Winston, Wayne L., and S. Christian Albright. *Practical Management Science*, 6th ed. Boston, Ma: Cengage Learning, 2019.

Chapter 11: Resource Planning

Becker, Nathan. "iPad's Bill of Materials Close to first iPad." *Wall Street Journal Online*. http://online.wsj.com/articles/SB10001424052748704893604576200132535033172 (March 14, 2011).

Bendoly, E., and M. Cotteleer. "Understanding Behavioral Sources of Process Variation following Enterprise System Deployment." *Journal of Operations Management*, vol. 26, no. 1 (2008), pp. 23–44.

Collins, David J., and Cynthia A. Montgomery. "Competing on Resources." *Harvard Business Review*, vol. 86, no. 7 (2008), pp. 140–150.

Hendricks, Kevin B., Vinod R. Singhal, and Jeff K. Stratman. "The Impact of Enterprise Systems on Corporate Performance: A Study of ERP, SCM and CRM System Implementations." *Journal of Operations Management*, vol. 25, no. 1 (2007), pp. 65–82.

Jacobs, F. Robert, William Berry, and D. Clay Whybark. *Manufacturing Planning and Control Systems for Supply Chain Management*, 6th ed. New York: McGraw-Hill/Irwin, 2011.

Jacobs, F. Robert, and F. C. (Ted) Weston Jr. "Enterprise Resource Planning (ERP)—A Brief History." *Journal of Operations Management*, vol. 25, no. 2 (2007), pp. 357–363.

Leon, Alexis. *ERP Demystified*, 3rd ed. New York, NY: McGraw Hill Education (India) Private Limited, 2014.

Mabert, Vincent A. "The Early Road to Materials Requirements Planning." *Journal of Operations Management*, vol. 25, no. 2 (2007), pp. 346–356.

McAfee, A., and E. Brynjolfsson. "Investing in the IT That Makes a Competitive Advantage." *Harvard Business Review*, vol. 86 (July/August 2008), pp. 98–107.

Simons, Robert. "Choosing the Right Customer." *Harvard Business Review*, vol. 92, no. 3 (2014), pp. 48–55.

Wallace, Thomas F. *Sales & Operations Planning: The How-To Handbook*, 3rd ed. Cincinnati, OH: T. E. Wallace & Company, 2008.

Wallace, Thomas F., and Robert A. Stahl. *Master Scheduling in the 21st Century*. Cincinnati, OH: T. E. Wallace & Company, 2003.

Chapter 12: Supply Chain Design

Felix, Ignacio, Christoph Kuntz, Ildefonzo Silva, and Eduardo Tobias Benoliel. "The Route to No-Touch Planning: Taking the Human Error Out of Supply Chain Planning," https://www.mckinsey.com/business-functions/operations/our-insights/the-route-to-no-touch-planning (August 2018).

Fisher, Marshall L. "What Is the Right Supply Chain for Your Product?" *Harvard Business Review* (March/April 1997), pp. 105–116.

Garber, Randy, and Suman Sarkar. "Want a More Flexible Supply Chain?" *Supply Chain Management Review* (January/February 2007), pp. 28–34.

George, Katy, Sree Ramaswamy, and Lou Rassey, "Next-shoring: A CEO's Guide." *McKinsey Quarterly* (January 2014), pp. 1–8.

Gezgin, Enis, Xin Huang, Prakash Samal, and Ildefonzo Silva. "Digital Transformation: Raising Supply-Chain Performance to New Levels," https://www.mckinsey.com/business-functions/operations/our-insights/digital-transformation-raising-supply-chain-performance-to-new-levels (November 2017).

Glatzel, Christoph, Jocher Großpietsch, and Ildefonso Silva. "Is Your Top Team Undermining Your Supply Chain?" *McKinsey Quarterly* (January 2011), pp. 1–6.

Goel, Ajay K., Nazgol Moussavi, and Vats N. Srivastan. "Time to Rethink Offshoring?" *McKinsey on Business Technology: Innovations in IT Management*, no. 14 (Winter 2008), pp. 32–35.

Hartly-Urquhart, Roland. "Managing the Financial Supply Chain." *Supply Chain Management Review* (September 2006), pp. 18–25.

Hofman, Debra. "Supply Chain Measurement: Turning Data into Action." *Supply Chain Management Review* (November 2007), pp. 20–26.

Johnson, P., and M. Leenders. "Minding the Supply Savings Gaps." *MIT Sloan Management Review*, vol. 51, no. 2 (2010), pp. 25–31.

Lacity, M., and L. Willcocks. "Outsourcing Business Processes for Innovation." *MIT Sloan Management Review*, vol. 54, no. 3 (2013), pp. 63–69.

Lee, Hau L. "The Triple-A Supply Chain." *Harvard Business Review* (October 2004), pp. 102–112.

Leonards, Alexandra, "A Supply Chain Which Can Think for Itself?," https://www.raconteur.net/manufacturing/innovating-supply-chain-2019/autonomous-supply-chain (December 10, 2019).

Lindgreen, A., and J. Vanhamme. "Go Configure: The Mix of Purchasing Practices to Choose for Your Supply Base." *California Management Review*, vol. 55, no. 2 (2013), pp. 72–96.

Malik, Yogesh, Alex Niemeyer, and Brian Ruwadi. "Building the Supply Chain of the Future." *McKinsey Quarterly* (January 2011), pp. 1–6.

Melnyk, S., E. Davis, R. Spekman, and J. Sandor. "Outcome-Driven Supply Chains." *MIT Sloan Management Review*, vol. 51, no. 2 (2010), pp. 33–38.

Reeve, James M., and Mandyam M. Srinivasan. "Which Supply Chain Design Is Right for You?" *Supply Chain Management Review* (May/June 2005), pp. 50–57.

Shukla, Shreyas, Guarav Goel, and Ajai Vasudevan. "Building a Digital Supply Chain the Right Way," SCM Now Magazine, Association for Supply Chain Management (2018).

Simchi-Levi, D., A. Clayton, and B. Raven. "When One Size Does Not Fit All." *MIT Sloan Management Review*, vol. 54, no. 2 (2013), pp. 15–17.

Slone, Reuben E., John T. Mentzer, and J. Paul Dittmann. "Are You the Weakest Link in Your Supply Chain?" *Harvard Business Review* (September 2007), pp. 116–127.

Stavrulaki, Euthemia, and Mark Davis. "Aligning Products with Supply Chain Processes and Strategy." *The International Journal of Logistics Management*, vol. 21, no. 1 (2010), pp. 127–151.

Tiede, Tom, and Kay Ree Lee. "What Is an Optimal Distribution Network Strategy?" *Supply Chain Management Review* (November 2005), pp. 32–39.

Watson, Michael, Sara Lewis, Peter Cacioppi, and Jay Jayaraman. "Supply Chain Network Design: Applying Optimization and Analytics to Global Supply Chain," Pearson *FT Press* (August 22, 2012).

Zirpoli, F., and M. Becker. "What Happens When You Outsource Too Much?" *MIT Sloan Management Review*, vol. 52, no. 2 (2011), pp. 59–64.

Chapter 13: Supply Chain Logistic Networks

Agrawal, A., A. Meyer, A. De, and L. N. Van Wassenhove. "Managing Value in Supply Chains." *California Management Review*, vol. 56, no. 2 (2014), pp. 23–54.

Banker, Steve and Chris Cunnane. "Robots and the Autonomous Supply Chain," https://www.forbes.com/sites/stevebanker/2020/04/02/robots-and-the-autonomous-supply-chain/#7157053b787a (April 2, 2020).

Bowles, Ruthie. "Warehouse Robotics: Everything You Need to Know in 2019," Logiwa.com/blog/warehouse-robotics (Updated May 18, 2020).

Chittum, Ryan. "Location, Location, and Technology: Where to Put That New Store? Site-Selection Software May Be Able to Help." *Wall Street Journal* (July 18, 2005), p. R7.

Deeds, David. "Increasing the Rate of New Venture Creation: Does Location Matter?" *Academy of Management Executive*, vol. 18, no. 2 (2004), pp. 152–154.

Gavet, M. "How We Did It . . . The CEO of Ozon on Building an E-commerce Giant in a Cash-only Economy." *Harvard Business Review*, vol. 92, no. 7 (2014), pp. 38–41.

Hahn, E. D., and K. Bunyaratavej. "Services Cultural Alignment in Offshoring: The Impact of Cultural Dimensions on Offshoring Location Decisions." *Journal of Operations Management*, vol. 28, no. 3 (2010), pp. 186–193.

"How the Amazon Supply Chain Works," https://amzadvisers.com/amazon-supply-chain-works/ (May 7, 2019).

Melo, M. T., S. Nickel, and F. Saldanha-da-Gama. "Facility Location and Supply Chain Management—A Review." *European Journal of Operational Research*, vol. 196, no. 2 (2009), pp. 401–412.

Michel, Roberto. "Mobile Robotics Descend on Warehouse Operations," https://www.logisticsmgmt.com/article/mobile_robotics_descend_on_warehouse_operations (July 10, 2019).

Chapter 14: Supply Chain Integration

Altug, M. S., and G. van Ryzin. "Is Revenue Sharing Right for Your Supply Chain?" *California Management Review*, vol. 56, no. 4 (2014), pp. 53–81.

Amadeo, Kimberly. "What Are Commodities Futures?" https://www.thebalance.com/what-is-a-futures-contract-3305930 (June 5, 2020).

Anderson, J., J. Narus, and M. Wouters. "Tiebreaker Selling." *Harvard Business Review*, vol. 92, no. 3 (2014), pp. 90–96.

Anderson, J., J. Narus, and M. Wouters. "What You Can Learn from Your Customer's Customer." *MIT Sloan Management Review*, vol. 54, no. 2 (2013), pp. 75–82.

Bowersox, Donald, David Closs, and M. Bixby Cooper. *Supply Chain Logistics Management*, 4th ed. New York: McGraw-Hill, 2013.

Brody, Paul. "How Blockchain Revolutionizes Supply Chain Management," http://www.digitalistmag.com/tag/blockchain-and-supply-chain (August 23, 2017–September 6, 2017).

Chick, S. "Europe's Solution Factories." *Harvard Business Review*, vol. 92, no. 4 (2014), pp. 111–115.

Choi, T., and T. Linton. "Don't Let Your Supply Chain Control Your Business." *Harvard Business Review*, vol. 89, no. 12 (2011), pp. 112–117.

Chopra, Sunil, and ManMohan S. Sodhi. "Looking for the Bang from the RFID Buck." *Supply Chain Management Review* (May/June 2007), pp. 34–41.

Chopra, Sunil, and Peter Meindl. *Supply Chain Management: Strategy, Planning, and Operations*, 6th ed. Upper Saddle River, NJ: Prentice Hall, 2016.

Columbus, Louis. "How Blockchain Can Improve Manufacturing In 2019," https://www.forbes.com/sites/louiscolumbus/2018/10/28/how-blockchain-can-improve-manufacturing-in-2019/#2ef065125db6 (October 28, 2018).

Doheny, Mike, Venu Nagali, and Florian Weig. "Agile Operations for Volatile Times." https://www.mckinsey.com/business-functions/operations/our-insights/agile-operations-for-volatile-times (May 2012).

Fleck, Thomas. "Supplier Collaboration in Action at IBM." *Supply Chain Management Review* (March 2008), pp. 30–37.

Gil, N. "Developing Cooperative Project Client-Supplier Relationships: How Much to Expect from Relational Contracts." *California Management Review*, vol. 51, no. 2 (2009), pp. 144–170.

Henke Jr., John W., and C. Zhang. "Increasing Supplier-Driven Innovation." *MIT Sloan Management Review*, vol. 51, no. 2 (2010), pp. 41–46.

Keil, Jan. "How can Cloud Computing and Blockchain Reduce the Bullwhip Effect in Supply Chain?," https://www.infoplulse.com/blog/how-can-cloud-computing-and-blockchain-reduce-the-bullwhip-effect-in-supply-chain (July 30, 2019).

Lee, Hau L. "The Triple-A Supply Chain." *Harvard Business Review* (October 2004), pp. 102–112.

Liker, Jeffrey K., and Thomas Y. Choi. "Building Deep Supplier Relationships." *Harvard Business Review* (December 2004), pp. 104–113.

Malik, Yogesh, Alex Niemeyer, and Brian Ruwadi. "Building the Supply Chain of the Future." *McKinsey Quarterly* (January 2011), pp. 1–10.

Miller, Jamey. "Shared Success: Working Together to Find the Value of VMI." *APICS Magazine* (November/December 2007), pp. 37–39.

Rosic, Ameer. "What is Blockchain Technology? A Step-by-Step Guide for Beginners," https://blockgeeks.com/guides/what-is-blockchain-technology/ (2016).

Sharma, Toshendra Kumar. "Role of Blockchain in the Manufacturing Industry," https://www.blockchain-council.org/blockchain/role-of-blockchain-in-the-manufacturing-industry/ (January 27, 2019).

Simchi-Levi, David, Ioannis M. Kyratzoglou, and Constantine G. Vassiliadis. "Supply Chains and Risk Management," MIT Forum for Supply Chain Innovation 2013, Massachusetts Institute of Technology.

Thomke, S., and D. Reinertsen. "Six Myths of Product Development." *Harvard Business Review*, vol. 90, no. 5 (2012), pp. 84–94.

Wagner, Richard H. "An Interview with Dirk Brand: Hotel Manager of Queen Mary 2." Beyondships.com (December 2007), pp. 1–4.

Wallingford, Jeff. "Viewpoint: Managing Currency Risk in the Supply Chain." *Industry Week*. https://www.industryweek.com/home/contact/22031432/jeff-wallingford (June 25, 2012).

Chapter 15: Supply Chain Sustainability

Atasu, A. "So What If Remanufacturing Cannibalizes My New Product Sales." *California Management Review*, vol. 52, no. 2 (2010), pp. 56–77.

Bove, Anne-Titia, and Steven Swartz. "Starting at the Source: Sustainability in Supply Chains," *McKinsey & Company*. https://www.mckinsey.com/business-functions/sustainability/our-insights/starting-at-the-source-sustainability-in-supply-chains (November 11, 2016).

Beamon, Benita M. "Environmental and Sustainability Ethics in Supply Chain Management." *Science and Engineering Ethics*, vol. 11 (2005), pp. 221–234.

Beschorner, Thomas, and Martin Muller. "Social Standards: Toward an Active Ethical Involvement of Business in Developing Countries." *Journal of Business Ethics*, vol. 73 (2006), pp. 11–23.

Bonini, Sheila, Steven Gorner, and Alissa Jones. "How Companies Manage Sustainability." *McKinsey & Company Global Survey Results* (February 2010), pp. 1–8.

Curkovic, Sime, and Robert Sroufe. "Using ISO 14001 to Promote a Sustainable Supply Chain." *Business Strategy and the Environment*, vol. 20 (2011), pp. 71–93.

Day, J. M., I. Junglas, and L. Silva. "Information Flow Impediments in Disaster Relief Supply Chains." *Journal of the Association for Information Systems*, vol. 10, no. 8 (August 2009), pp. 637–660.

Drake, Matthew J., and John Teepen Schlachter. "A Virtue-Ethics Analysis of Supply Chain Collaboration." *Journal of Business Ethics*, vol. 82 (2007), pp. 851–864.

Ferguson, Mark. "Making Your Supply Chain More Sustainable by Closing the Loop." *The European Business Review* (November/December 2010), pp. 28–31.

"Global Responsibility," *RR Donnelley* (2010), pp. 1–21.

Golicic, S., C. Boerstler, and L. Ellram. "'Greening' Transportation in the Supply Chain." *MIT Sloan Management Review*, vol. 51, no. 2 (2010), pp. 47–55.

Handfield, Robert B., and David L. Baumer. "Managing Conflicts of Interest in Purchasing." *Journal of Supply Chain Management* (Summer 2006), pp. 41–50.

Hindo, Brian. "Everything Old Is New Again." *BusinessWeek* (September 25, 2006), pp. 64–70.

"How to Calculate the Weight Break." http://freightlogistics.wordpress.com (December 19, 2007).

Keating, B., A. Quazi, A. Kriz, and T. Coltman. "In Pursuit of a Sustainable Supply Chain: Insights from Weatpac Banking Corporation." *Research Online*. http://ro.uow.edu.au/infopapers/688 (2008).

Kulwiec, Ray. "Reverse Logistics Provides Green Benefits." *Target*, vol. 22, no. 3 (Third Issue 2006), pp. 11–20.

Lacy, Peter, Tim Cooper, Rob Hayward, and Lisa Neuberger. "A New Era of Sustainability," *UN Global Compact-Accenture CEO Study 2010* (June 2010), pp. 1–60.

Lai, K., T. Cheng, and A. Tang. "Green Retailing: Factors for Success." *California Management Review*, vol. 52, no. 2 (2010), pp. 6–32.

Maon, Francois, Adam Lindgreen, and Joelle Vanhamme. "Supply Chains in Disaster Relief Operations: Cross-Sector Socially Oriented Collaborations." *Hull University Business School*, Research Memorandum 80 (April 2009), pp. 1–35.

Melnyk, Steven, E. W. Davis, R. E. Spekman, and J. Sandor. "Outcome Driven Supply Chains." *Sloan Management Review*, vol. 51, no. 2 (2010), pp. 33–38.

Meyer, Tobias A. "Increasing the Energy Efficiency of Supply Chains." *McKinsey Quarterly* (August 2009), pp. 1–2.

Mollenkopf, Diane A., and David J. Closs. "The Hidden Value in Reverse Logistics." *Supply Chain Management Review* (July/August 2005), pp. 34–43.

New, S. "The Transparent Supply Chain." *Harvard Business Review*, vol. 88, no. 10 (2010), pp. 76–82.

Olcott, G., and N. Oliver. "Social Capital, Sensemaking, and Recovery: Japanese Companies and the 2011 Earthquake." *California Management Review*, vol. 56, no. 2 (2014), pp. 5–22.

Plambeck, Erica L. "The Greening of Walmart's Supply Chain." *Supply Chain Management Review* (July/August 2007), pp. 18–25.

Plambeck, Erica L., H. Lee, and P. Yatsko. "Improving Environmental Performance in Your Chinese Supply Chain." *MIT Sloan Management Review*, vol. 53, no. 2 (2012), pp. 43–51.

Rothenberg, S., and J. Ettlie. "Strategies to Cope with Regulatory Uncertainty in the Auto Industry." *California Management Review*, vol. 54, no. 1 (2011), pp. 126–145.

Sheffi, Y. "Driving Growth and Employment Through Logistics." *MIT Sloan Management Review*, vol. 54, no. 1 (2012), pp. 20–22.

Simchi-Levi, D., W. Schmidt, and Y. Wei. "From Superstorms to Factory Fires." *Harvard Business Review*, vol. 92, no. 1 (2014), pp. 96–101.

"Social Accountability International—SA8000." http://www.sa-intl.org (2014).

Thomas, A., and L. Kopczak. "Life-Saving Supply Chains and the Path Forward." In H. Lee and C. Y. Lee (Eds.), *Building Supply Chain Excellence in Emerging Economies*. London: Springer Science and Business Media LLC, 2007, pp. 93–110.

Van Wassenhove, L. "Humanitarian Aid Logistics: Supply Chain Management in High Gear." *Journal of the Operational Research Society*, vol. 57, no. 5 (2006), pp. 475–489.

Wagner, S. "A Strategic Framework for Spare Parts Logistics." *California Management Review*, vol. 54, no. 4 (2012), pp. 69–93.

Whybark, D. C. "Issues in Managing Disaster Relief Inventories." *International Journal of Production Economics*, vol. 108, no. 1 (July 2007), pp. 228–235.

Whybark, D. C., Steven A. Melnyk, Jamison Day, and Ed Davis. "Disaster Relief Supply Chain Management: New Realities, Management Challenges, Emerging Opportunities." *Decision Line* (May 2010), pp. 4–7.

Glossary

ABC analysis The process of dividing SKUs into three classes, according to their dollar usage, so that managers can focus on items that have the highest dollar value.

acceptable quality level (AQL) The quality level desired by the consumer.

acceptance sampling The application of statistical techniques to determine whether a quantity of material should be accepted or rejected based on the inspection or test of a sample.

action notice A computer-generated memo alerting planners about releasing new orders and adjusting the due dates of scheduled receipts.

activity The smallest unit of work effort consuming both time and resources that the project manager can schedule and control.

activity slack The maximum length of time that an activity can be delayed without delaying the entire project, calculated as $S = LS - ES$ or $S = LF - EF$.

activity-on-node (AON) network An approach used to create a network diagram, in which nodes represent activities and arcs represent the precedence relationships between them.

additive manufacturing (AM) The technologies that build 3D objects by adding layers of material such as plastic, metal, or concrete.

additive seasonal method A method in which seasonal forecasts are generated by adding a seasonal constant to, or by subtracting a seasonal constant from, the estimate of average demand per season.

advanced planning and scheduling (APS) systems Computer software systems that seek to optimize resources across the supply chain and align daily operations with strategic goals.

aggregate plan Another term for the sales and operations plan.

aggregation The act of clustering several similar services or products so that forecasts and plans can be made for whole families.

annual plan (or financial plan) A plan for financial assessment used by a nonprofit service organization.

anticipation inventory Inventory used to absorb uneven rates of demand or supply.

appraisal costs Costs incurred when the firm assesses the performance level of its processes.

artificial intelligence (AI) A constellation of technologies, from machine learning to natural language processing, that allows machines to sense, comprehend, act, and learn.

assemble-to-order strategy A strategy for producing a wide variety of products from relatively few subassemblies and components after the customer orders are received.

assignable causes of variation Any variation-causing factors that can be identified and eliminated.

attributes Service or product characteristics that can be quickly counted for acceptable performance.

auction A marketplace where firms place competitive bids to buy something.

automation A system, process, or piece of equipment that is self-acting and self-regulating.

available-to-promise (ATP) inventory The quantity of end items that marketing can promise to deliver on specified dates.

average aggregate inventory value The total average value of all items held in inventory for a firm.

back office A process with low customer contact and little service customization.

backlog An accumulation of customer orders that a manufacturer has promised for delivery at some future date.

backorder A customer order that cannot be filled when promised or demanded but is filled later.

backorder and stockout cost Additional costs to expedite past-due orders, the costs of lost sales, and the potential cost of losing a customer to a competitor (sometimes called loss of goodwill).

backward integration A firm's movement upstream toward the sources of raw materials, parts, and services through acquisitions.

balance delay The amount by which efficiency falls short of 100 percent.

Baldrige Performance Excellence Program A program named for the late secretary of commerce Malcolm Baldrige, who was a strong proponent of enhancing quality as a means of reducing the trade deficit; organizations vie for an award that promotes, recognizes, and publicizes quality strategies and achievements.

bar chart A series of bars representing the frequency of occurrence of data characteristics measured on a yes/no basis.

base case The act of doing nothing and losing orders from any demand that exceeds current capacity, or incur costs because capacity is too large.

base-stock system An inventory control system that issues a replenishment order, Q, each time a withdrawal is made, for the same amount of the withdrawal.

batch process A process that differs from the job process with respect to volume, variety, and quantity.

benchmarking A systematic procedure that measures a firm's processes, services, and products against those of industry leaders.

big data Data sets that are so large or complex that traditional data processing applications are inadequate to deal with them.

bill of materials (BOM) A record of all the components of an item, the parent–component relationships, and the usage quantities derived from engineering and process designs.

bill of resources (BOR) A record of a service firm's parent–component relationships and all of the materials, equipment time, staff, and other resources associated with them, including usage quantities.

binding constraint A constraint that helps form the optimal corner point; it limits the ability to improve the objective function.

Black Belt Employees who have reached the highest level of training in a Six Sigma program and spend all of their time teaching and leading teams involved in Six Sigma projects.

blockchain A digital record of transactions in which individual records, called blocks, are linked together in a single list, called a chain.

bottleneck A capacity constraint resource (CCR) whose available capacity limits the organization's ability to meet the product volume, product mix, or demand fluctuation required by the marketplace.

brainstorming Letting a group of people, knowledgeable about the process, propose ideas for change by saying whatever comes to mind.

break-even analysis The use of the break-even quantity; it can be used to compare processes by finding the volume at which two different processes have equal total costs.

break-even quantity The volume at which total revenues equal total costs.

bullwhip effect The phenomenon in supply chains whereby ordering patterns experience increasing variance as you proceed upstream in the chain.

business plan A projected statement of income, costs, and profits.

***c*-chart** A chart used for controlling the number of defects when more than one defect can be present in a service or product.

capacity The maximum rate of output of a process or a system.

capacity cushion The amount of reserve capacity a process uses to handle sudden increases in demand or temporary losses of production capacity; it measures the amount by which the average utilization (in terms of total capacity) falls below 100 percent.

capacity gap Positive or negative difference between projected demand and current capacity.

capacity requirement What a process's capacity should be for some future time period to meet the demand of customers (external or internal), given the firm's desired capacity cushion.

capacity requirements planning (CRP) A technique used for projecting time-phased capacity requirements for work stations; its purpose is to match the materials requirements plan with the capacity of key processes.

capital intensity The mix of equipment and human skills in a process.

carbon footprint The total amount of greenhouse gases produced to support operations, usually expressed in equivalent tons of carbon dioxide (CO_2).

cash flow The difference between the flows of funds into and out of an organization over a period of time, including revenues, costs, and changes in assets and liabilities.

catalog hubs A system whereby suppliers post their catalog of items on the Internet and buyers select what they need and purchase them electronically.

causal methods A quantitative forecasting method that uses historical data on independent variables, such as promotional campaigns, economic conditions, and competitors' actions, to predict demand.

cause-and-effect diagram A diagram that relates a key performance problem to its potential causes.

center of gravity A good starting point to evaluate locations in the target area using the load–distance model.

centralized placement Keeping all the inventory of a product at a single location such as at a firm's manufacturing plant or a warehouse and shipping directly to each of its customers.

certainty The word that is used to describe that a fact is known without doubt.

channel assembly The process of using members of the distribution channel as if they were assembly stations in the factory.

channel One or more facilities required to perform a given service.

$\bar{x}$-chart A chart used to see whether the process is generating output, on average, consistent with a target value set by management for the process or whether its current performance, with respect to the average of the performance measure, is consistent with past performance.

chase strategy A strategy that involves hiring and laying off employees to match the demand forecast.

checklist A form used to record the frequency of occurrence of certain process failures.

closed-loop supply chain A supply chain that integrates forward logistics with reverse logistics, thereby focusing on the complete chain of operations from the birth to the death of a product.

closeout An activity that includes writing final reports, completing remaining deliverables, and compiling the team's recommendations for improving the project process.

cloud computing The practice of using a network of remote servers hosted on the Internet to store, manage, and process data.

collaborative planning, forecasting, and replenishment (CPFR) A process for supply chain integration that allows a supplier and its customers to collaborate on making the forecast by using the Internet.

combination forecasts Forecasts that are produced by averaging independent forecasts based on different methods, different sources, or different data.

common causes of variation The purely random, unidentifiable sources of variation that are unavoidable with the current process.

competitive capabilities The cost, quality, time, and flexibility dimensions that a process or supply chain actually possesses and is able to deliver.

competitive orientation A supplier relation that views negotiations between buyer and seller as a zero-sum game: Whatever one side loses, the other side gains, and short-term advantages are prized over long-term commitments.

competitive priorities The critical dimensions that a process or supply chain must possess to satisfy its internal or external customers, both now and in the future.

complementary products Services or products that have similar resource requirements but different demand cycles.

component An item that goes through one or more operations to be transformed into or become part of one or more parents.

concurrent engineering A concept that brings product engineers, process engineers, marketers, buyers, information specialists, quality specialists, and suppliers together to design a product and the processes that will meet customer expectations.

constraint Any factor that limits the performance of a system and restricts its output. In linear programming, a limitation that restricts the permissible choices for the decision variables.

continuous improvement The philosophy of continually seeking ways to improve processes based on a Japanese concept called *kaizen*.

continuous review (Q) system A system designed to track the remaining inventory of a SKU each time a withdrawal is made to determine whether it is time to reorder.

continuous-flow process The extreme end of high-volume standardized production and rigid line flows, with production not starting and stopping for long time intervals.

control chart A time-ordered diagram that is used to determine whether observed variations are abnormal.

cooperative orientation A supplier relation in which the buyer and seller are partners, each helping the other as much as possible.

core competencies The unique resources and strengths that an organization's management considers when formulating strategy.

core process A set of activities that delivers value to external customers.

corner point A point that lies at the intersection of two (or possibly more) constraint lines on the boundary of the feasible region.

crash cost (CC) The activity cost associated with the crash time.

crash time (CT) The shortest possible time to complete an activity.

critical mass A situation whereby several competing firms clustered in one location attract more customers than the total number who would shop at the same stores at scattered locations.

critical path The sequence of activities between a project's start and finish that takes the longest time to complete.

critical path method (CPM) A network planning method developed in the 1950s as a means of scheduling maintenance shutdowns at chemical-processing plants.

cross-docking The packing of products on incoming shipments so that they can be easily sorted at intermediate warehouses for outgoing shipments based on their final destinations.

cumulative sum of forecast errors (CFE) A measurement of the total forecast error that assesses the bias in a forecast.

customer contact The extent to which the customer is present, is actively involved, and receives personal attention during the service process.

customer involvement The ways in which customers become part of the process and the extent of their participation.

customer population An input that generates potential customers.

customer relationship process A process that identifies, attracts, and builds relationships with external customers and facilitates the placement of orders by customers, sometimes referred to as *customer relationship management*.

cycle counting An inventory control method whereby storeroom personnel physically count a small percentage of the total number of items each day, correcting errors that they find.

cycle inventory The portion of total inventory that varies directly with lot size.

cycle time The maximum time allowed for work on a unit at each station.

cycle-service level See service level.

decision theory A general approach to decision making when the outcomes associated with alternatives are often in doubt.

decision tree A schematic model of alternatives available to the decision maker, along with their possible consequences.

decision variables Variables that represent the choices the decision maker can control.

defect Any instance when a process fails to satisfy its customer.

degeneracy A condition that occurs when the number of nonzero variables in the optimal solution is less than the number of constraints.

Delphi method A process of gaining consensus from a group of experts while maintaining their anonymity.

demand management The process of changing demand patterns using one or more demand options.

dependent demand The demand for an item that occurs because the quantity required varies with the production plans for other items held in the firm's inventory.

dependent demand items Items whose required quantity varies with the production plans for other items held in the firm's inventory.

dependent variable The variable that one wants to forecast.

design-to-order strategy A strategy that involves designing new products that do not currently exist, and then manufacturing them to meet unique customer specifications.

diseconomies of scale Occurs when the average cost per unit increases as the facility's size increases.

distribution center (DC) A warehouse or stocking point where goods are stored for subsequent distribution to manufacturers, wholesalers, retailers, and customers.

drum-buffer-rope (DBR) A planning and control system that regulates the flow of work-in-process materials at the bottleneck or the capacity constrained resource (CCR) in a productive system.

earliest due date (EDD) A priority sequencing rule that specifies that the job or customer with the earliest due date is the next job to be processed.

earliest finish time (EF) An activity's earliest start time plus its estimated duration, t, or $EF = ES + t$.

earliest start time (ES) The earliest finish time of the immediately preceding activity.

early supplier involvement A program that includes suppliers in the design phase of a service or product.

economic order quantity (EOQ) The lot size that minimizes total annual cycle-inventory holding and ordering costs.

economic production lot size (ELS) The optimal lot size in a situation in which replenishment is not instantaneous.

economies of scale A concept that states that the average unit cost of a service or good can be reduced by increasing its output rate.

economies of scope Economies that reflect the ability to produce multiple products more cheaply in combination than separately.

electronic commerce (e-commerce) The application of information and communication technology anywhere along the supply chain of business processes.

electronic data interchange (EDI) A technology that enables the transmission of routine business documents having a standard format from computer to computer.

elemental standard data A database of standards compiled by a firm's analysts for basic elements that they can draw on later to estimate the time required for a particular job, which is most appropriate when products or services are highly customized, job processes prevail, and process divergence is great.

employee empowerment An approach to teamwork that moves responsibility for decisions further down the organizational chart—to the level of the employee actually doing the job.

end item The final product sold to a customer.
enterprise process A company-wide process that cuts across functional areas, business units, geographical regions, and product lines.
enterprise resource planning (ERP) systems Large, integrated information systems that support many enterprise processes and data storage needs.
environmental responsibility An element of sustainability that addresses the ecological needs of the planet and the firm's stewardship of the natural resources used in the production of services and products.
ethical failure costs Societal and monetary costs associated with *deceptively* passing defective services or products to internal or external customers such that it jeopardizes the well-being of stockholders, customers, employees, partners, and creditors.
Euclidean distance The straight-line distance, or shortest possible path, between two points.
exchange An electronic marketplace where buying firms and selling firms come together to do business.
executive opinion A forecasting method in which the opinions, experience, and technical knowledge of one or more managers are summarized to arrive at a single forecast.
expediting The process of completing a job or finishing with a customer sooner than would otherwise be done.
exponential smoothing method A weighted moving average method that calculates the average of a time series by implicitly giving recent demands more weight than earlier demands.
external customers A customer who is either an end user or an intermediary (e.g., manufacturers, financial institutions, or retailers) buying the firm's finished services or products.
external failure costs Costs that arise when a defect is discovered after the customer receives the service or product.
external suppliers The businesses or individuals who provide the resources, services, products, and materials for the firm's short-term and long-term needs.
facility location The process of determining geographical sites for a firm's operations.
feasible region A region that represents all permissible combinations of the decision variables in a linear programming model.
financial responsibility An element of sustainability that addresses the financial needs of the shareholders, employees, customers, business partners, financial institutions, and any other entity that supplies the capital for the production of services or products or relies on the firm for wages or reimbursements.
finished goods (FG) The items in manufacturing plants, warehouses, and retail outlets that are sold to the firm's customers.
first-come, first-served (FCFS) A priority sequencing rule that specifies that the job or customer arriving at the workstation first has the highest priority.
Five S (5S) A methodology consisting of five workplace practices—sorting, straightening, shining, standardizing, and sustaining—that are conducive to visual controls and lean production.
fixed automation A manufacturing process that produces one type of part or product in a fixed sequence of simple operations.
fixed cost The portion of the total cost that remains constant regardless of changes in levels of output.
fixed order quantity (FOQ) A rule that maintains the same order quantity each time an order is issued.
fixed schedule A schedule that calls for each employee to work the same days and hours each week.
flexible (or programmable) automation A manufacturing process that can be changed easily to handle various products.
flexible flow The customers, materials, or information moves in diverse ways, with the path of one customer or job often crisscrossing the path that the next one takes.
flexible workforce A workforce whose members are capable of doing many tasks, either at their own workstations or as they move from one workstation to another.
flow time The amount of time a job spends in the service or manufacturing system.
flowchart A diagram that traces the flow of information, customers, equipment, or materials through the various steps of a process.
focus forecasting A method of forecasting that selects the best forecast from a group of forecasts generated by individual techniques.
focused factories The result of a firm's splitting large plants that produced all the company's products into several specialized smaller plants.
forecast A prediction of future events used for planning purposes.
forecast error The difference found by subtracting the forecast from actual demand for a given period.
forward integration Acquiring more channels of distribution, such as distribution centers (warehouses) and retail stores, or even business customers.
forward placement Locating stock closer to customers at a warehouse, DC, wholesaler, or retailer.
fourth industrial revolution (Industry 4.0) The ongoing automation of traditional manufacturing and industrial practices using modern smart technology.
front office A process with high customer contact where the service provider interacts directly with the internal or external customer.
futures contract A contractual agreement, generally made on the trading floor of a futures exchange, to buy or sell a particular commodity or financial instrument at a predetermined price in the future.
Gantt chart A project schedule, usually created by the project manager using computer software, that superimposes project activities, with their precedence relationships and estimated duration times, on a time line.
geographical information system (GIS) A system of computer software, hardware, and data that the firm's personnel can use to manipulate, analyze, and present information relevant to a location decision.
graphic method of linear programming A type of graphic analysis that involves the following five steps: plotting the constraints, identifying the feasible region, plotting an objective function line, finding a visual solution, and finding the algebraic solution.
graphs Representations of data in a variety of pictorial forms, such as line charts and pie charts.
Green Belt Employees who have achieved the first level of training in a Six Sigma program and spend part of their time teaching and helping teams with their projects.
green purchasing The process of identifying, assessing, and managing the flow of environmental waste and finding ways to reduce it and minimize its impact on the environment.

gross requirements The total demand derived from *all* parent production plans.

group technology (GT) An option for achieving line-flow layouts with low volume processes; this technique creates cells not limited to just one worker and has a unique way of selecting work to be done by the cell.

hedging A supply chain risk-management strategy used in limiting or offsetting the probability of loss from fluctuations in the prices of commodities or currencies.

heijunka The leveling of production load by both volume and product mix.

hiring and layoff cost Costs of advertising jobs, interviews, training programs for new employees, scrap caused by the inexperience of new employees, loss of productivity, and initial paperwork. Layoff costs include the costs of exit interviews, severance pay, retaining and retraining remaining workers and managers, and lost productivity.

histogram A summarization of data measured on a continuous scale, showing the frequency distribution of some process failure (in statistical terms, the central tendency and dispersion of the data).

holdout sample Actual demands from the more recent time periods in the time series that are set aside to test different models developed from the earlier time periods.

humanitarian logistics The process of planning, implementing, and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people.

hybrid office A process with moderate levels of customer contact and standard services with some options available.

immediate predecessors Work elements that must be done before the next element can begin.

independent demand items Items for which demand is influenced by market conditions and is not related to the inventory decisions for any other item held in stock or produced.

independent variables Variables that are assumed to affect the dependent variable and thereby "cause" the results observed in the past.

industrial robot Versatile, computer-controlled machine programmed to perform various tasks.

interarrival times The time between customer arrivals.

intermediate item An item that has at least one parent and at least one component.

intermodal shipments Mixing the modes of transportation for a given shipment, such as moving shipping containers or truck trailers on railcars.

internal customers One or more employees or processes that rely on inputs from other employees or processes to perform their work.

internal failure costs Costs resulting from defects that are discovered during the production of a service or product.

internal suppliers The employees or processes that supply important information or materials to a firm's processes.

Internet of Things (IoT) The interconnectivity of objects, embedded with software, sensors, and actuators that enable these objects to collect and exchange data over a network without requiring human intervention.

inventory A stock of materials used to satisfy customer demand or to support the production of services or goods.

inventory holding cost The sum of the cost of capital and the variable costs of keeping items on hand, such as storage and handling, taxes, insurance, and shrinkage.

inventory management The planning and controlling of inventories to meet the competitive priorities of the organization.

inventory pooling A reduction in inventory and safety stock because of the merging of variable demands from customers.

inventory position (IP) The measurement of a SKU's ability to satisfy future demand.

inventory record A record that shows an item's lot-size policy, lead time, and various time-phased data.

inventory turnover An inventory measure obtained by dividing annual sales at cost by the average aggregate inventory value maintained during the year.

ISO 14001:2004 A series of environmental standards developed and published by the International Organization for Standardization.

ISO 26000:2010 A series of international guidelines to help organizations effectively assess those social responsibilities that are relevant and significant to their mission and vision.

ISO 28000:2007 A set of requirements for a supply chain security management system that includes aspects of financing, manufacturing, information systems, and the facilities for packing, storing, and transferring goods between modes of transportation and locations.

ISO 9001:2015 A set of standards governing documentation of a quality program.

jidoka Automatically stopping the process when something is wrong and then fixing the problems on the line itself as they occur.

job process A process with the flexibility needed to produce a wide variety of products in significant quantities, with considerable divergence in the steps performed.

judgment methods A forecasting method that translates the opinions of managers, expert opinions, consumer surveys, and salesforce estimates into quantitative estimates.

just-in-time (JIT) system The JIT system is a key foundation of a lean system, and represents a collection of practices that eliminate waste, or *muda*, by cutting excess capacity or inventory and removing nonvalue-added activities.

Kanban A Japanese word meaning "card" or "visible record" that refers to cards used to control the flow of production through a factory.

latest finish time (LF) The latest start time of the activity that immediately follows.

latest start time (LS) The latest finish time minus its estimated duration t, or $LS = LF - t$.

layout The physical arrangement of operations (or departments) relative to each other.

lead time The elapsed time between the receipt of a customer order and filling it.

lean systems Operations systems that maximize the value added by each of a company's activities by removing waste and delays from them.

learning curve A line that displays the relationship between processing time and the cumulative quantity of a product or service produced.

level strategy A strategy that keeps the workforce constant, but varies its utilization via overtime, undertime, and vacation planning to match the demand forecast.

line balancing The assignment of work to stations in a line process so as to achieve the desired output rate with the smallest number of workstations.

line flow The customers, materials, or information moves linearly from one operation to the next, according to a fixed sequence.

line process A process that lies between the batch and continuous processes on the continuum; volumes are high and products are standardized, which allows resources to be organized around particular products.

linear programming A technique that is useful for allocating scarce resources among competing demands.

linear regression A causal method in which one variable (the dependent variable) is related to one or more independent variables by a linear equation.

linearity A characteristic of linear programming models that implies proportionality and additivity—there can be no products or powers of decision variables.

Little's law Relates the number of customers in a waiting-line system to the arrival rate and the waiting time of customers.

load–distance method A mathematical model used to evaluate locations based on proximity factors.

lot A quantity of items that are processed together.

lot size The quantity of an inventory item that management either buys from a supplier or manufactures using internal processes.

lot sizing The determination of how frequently and in what quantity to order inventory.

lot-for-lot (L4L) rule A rule under which the lot size ordered covers the gross requirements of a single week.

make-or-buy decision A managerial choice between whether to outsource a process or do it in-house.

make-to-order strategy A strategy used by manufacturers that make products to customer specifications in low volumes.

make-to-stock strategy A strategy that involves holding items in stock for immediate delivery, thereby minimizing customer delivery times.

manufacturing execution systems (MES) Computerized systems used in manufacturing to track and document the transformation of raw materials to finished goods and optimize their production output.

manufacturing resource planning (MRP II) A system that ties the basic MRP system to the company's financial system and to other core and supporting processes.

market research A systematic approach to determine external consumer interest in a service or product by creating and testing hypotheses through data-gathering surveys.

mass customization The strategy that uses highly divergent processes to generate a wide variety of customized products at reasonably low costs.

mass production A term sometimes used in the popular press for a line process that uses the make-to-stock strategy.

Master Black Belt Full-time teachers and mentors to several Black Belts.

master production schedule (MPS) A part of the material requirements plan that details how many end items will be produced within specified periods of time.

material requirements planning (MRP) A computerized information system developed specifically to help manufacturers manage dependent demand inventory and schedule replenishment orders.

mean absolute deviation (MAD) A measurement of the dispersion of forecast errors.

mean absolute percent error (MAPE) A measurement that relates the forecast error to the level of demand and is useful for putting forecast performance in the proper perspective.

mean squared error (MSE) A measurement of the dispersion of forecast errors.

metrics Performance measures that are established for a process and the steps within it.

minimum-cost schedule A schedule determined by starting with the normal time schedule and crashing activities along the critical path, in such a way that the costs of crashing do not exceed the savings in indirect and penalty costs.

mixed strategy A strategy that considers the full range of supply options.

mixed-model assembly A type of assembly that produces a mix of models in smaller lots.

mixed-model line A production line that produces several items belonging to the same family.

most likely time (m) The probable time required to perform an activity.

MRP explosion A process that converts the requirements of various final products into a material requirements plan that specifies the replenishment schedules of all the subassemblies, components, and raw materials needed to produce final products.

multiplicative seasonal method A method whereby seasonal factors are multiplied by an estimate of average demand to arrive at a seasonal forecast.

naïve forecast A time-series method whereby the forecast for the next period equals the demand for the current period, or Forecast $= D_t$.

nearest neighbor (NN) heuristic A technique that creates a route by deciding the next city to visit on the basis of its proximity.

nested process The concept of a process within a process.

network diagram A visual display, designed to depict the relationships between activities, that consists of nodes (circles) and arcs (arrows).

new service/product development process A process that designs and develops new services or products from inputs received from external customer specifications or from the market in general through the customer relationship process.

next-shoring A supply chain strategy that involves locating processes in close proximity to customer demand or product R&D.

nominal value A target for design specifications.

nonnegativity An assumption that the decision variables must be positive or zero.

normal cost (NC) The activity cost associated with the normal time.

normal time (NT) In the context of project management, the time necessary to complete an activity under normal conditions.

objective function An expression in linear programming models that states mathematically what is being maximized or minimized.

offshoring A supply chain strategy that involves moving processes to another country.

one-worker, multiple-machines (OWMM) cell A one-person cell in which a worker operates several different machines simultaneously to achieve a line flow.

open orders See scheduled receipts (SR).

operation A group of resources performing all or part of one or more processes.

operations management The systematic design, direction, and control of processes that transform inputs into services and products for internal, as well as external, customers.

operations planning and scheduling The process of balancing supply with demand, from the aggregate level down to the short-term scheduling level.

operations strategy The means by which operations implements the firm's corporate strategy and helps to build a customer-driven firm.

optimistic time (a) The shortest time in which an activity can be completed, if all goes exceptionally well.

optional replenishment system A system used to review the inventory position at fixed time intervals and, if the position has dropped to (or below) a predetermined level, to place a variable-sized order to cover expected needs.

order fulfillment process A process that includes the activities required to produce and deliver the service or product to the external customer.

order qualifier Minimal level required from a set of criteria for a firm to do business in a particular market segment.

order winner A criterion customers use to differentiate the services or products of one firm from those of another.

ordering cost The cost of preparing a purchase order for a supplier or a production order for manufacturing.

outsourcing Paying suppliers and distributors to perform processes and provide needed services and materials.

overtime The time that employees work that is longer than the regular workday or workweek for which they receive additional pay.

overtime cost Wages paid for work beyond the normal workweek, typically 150 percent of regular-time wages (sometimes up to 200 percent for Sundays and holidays), exclusive of fringe benefits. Overtime can help avoid the extra cost of fringe benefits that come with hiring another full-time employee.

***p*-chart** A chart used for controlling the proportion of defective services or products generated by the process.

pacing The movement of product from one station to the next as soon as the cycle time has elapsed.

parameter A value that the decision maker cannot control and that does not change when the solution is implemented.

parent Any product that is manufactured from one or more components.

Pareto chart A bar chart on which factors are plotted along the horizontal axis in decreasing order of frequency.

part commonality The degree to which a component has more than one immediate parent.

past due The amount of time by which a job missed its due date.

path The sequence of activities between a project's start and finish.

payoff table A table that shows the amount for each alternative if each possible event occurs.

periodic order quantity (POQ) A rule that allows a different order quantity for each order issued but issues the order for predetermined time intervals.

periodic review (P) system A system in which an item's inventory position is reviewed periodically rather than continuously.

perpetual inventory system A system of inventory control in which the inventory records are always current.

pessimistic time (b) The longest estimated time required to perform an activity.

phase A single step in providing a service.

pipeline inventory Inventory that is created when an order for an item is issued but not yet received.

plan-do-check-act cycle A cycle, also called the Deming wheel, used by firms actively engaged in continuous improvement to train their work teams in problem solving.

planned order release An indication of when an order for a specified quantity of an item is to be issued.

planned receipts Orders that are not yet released to the shop or the supplier.

planning horizon The set of consecutive time periods considered for planning purposes.

plants within plants (PWPs) Different operations within a facility with individualized competitive priorities, processes, and workforces under the same roof.

poka-yoke Mistake-proofing methods aimed at designing fail-safe systems that minimize human error.

postponement The strategy of delaying final activities in the provision of a product until the orders are received.

precedence diagram A diagram that allows one to visualize immediate predecessors better; work elements are denoted by circles, with the time required to perform the work shown below each circle.

precedence relationship A relationship that determines a sequence for undertaking activities; it specifies that one activity cannot start until a preceding activity has been completed.

predetermined data method A database approach that divides each work element into a series of micromotions that make up the element. The analyst then consults a published database that contains the normal times for the full array of possible micromotions.

preemptive discipline A rule that allows a customer of higher priority to interrupt the service of another customer.

preference matrix A table that allows the manager to rate an alternative according to several performance criteria.

presourcing A level of supplier involvement in which suppliers are selected early in a product's concept development stage and are given significant, if not total, responsibility for the design of certain components or systems of the product.

prevention costs Costs associated with preventing defects before they happen.

priority rule A rule that selects the next customer to be served by the service facility.

priority sequencing rule A rule that specifies the job or customer processing sequence when several jobs are waiting in line at a workstation.

process analysis The documentation and detailed understanding of how work is performed and how it can be redesigned.

process Any activity or group of activities that takes one or more inputs, transforms them, and provides one or more outputs for its customers.

process capability The ability of the process to meet the design specifications for a service or product.

process capability index, C_{pk} An index that measures the potential for a process to generate defective outputs relative to either upper or lower specifications.

process capability ratio, C_p The tolerance width divided by 6 standard deviations.

process chart An organized way of documenting all the activities performed by a person or group of people, at a workstation, with a customer, or on materials.

process choice A way of structuring the process by organizing resources around the process or organizing them around the products.

process divergence The extent to which the process is highly customized with considerable latitude as to how its tasks are performed.

process failure Any performance shortfall, such as error, delay, environmental waste, rework, and the like.

process improvement The systematic study of the activities and flows of each process to improve it.

process simulation The act of reproducing the behavior of a process, using a model that describes each step.

process strategy The pattern of decisions made in managing processes so that they will achieve their competitive priorities.

process structure The process type relative to the kinds of resources needed, how resources are partitioned between them, and their key characteristics.

product family A group of services or products that have similar demand requirements and common process, labor, and materials requirements.

product-mix problem A one-period type of planning problem, the solution of which yields optimal output quantities (or product mix) of a group of services or products subject to resource capacity and market demand constraints.

production plan A sales and operations plan for a manufacturing firm that centers on production rates and inventory holdings.

productivity The value of outputs (services and products) produced divided by the values of input resources (wages, costs of equipment, etc.).

program An interdependent set of projects that have a common strategic purpose.

program evaluation and review technique (PERT) A network planning method created for the U.S. Navy's Polaris missile project in the 1950s, which involved 3,000 separate contractors and suppliers.

project An interrelated set of activities with a definite starting and ending point, which results in a unique outcome for a specific allocation of resources.

project management A systemized, phased approach to defining, organizing, planning, monitoring, and controlling projects.

projected on-hand inventory An estimate of the amount of inventory available each week after gross requirements have been satisfied.

protection interval The period over which safety stock must protect the user from running out of stock.

pull method A method in which customer demand activates production of the service or item.

purchased item An item that has one or more parents but no components because it comes from a supplier.

purchasing The activity that decides which suppliers to use, negotiates contracts, and determines whether to buy locally.

push method A method in which production of the item begins in advance of customer needs.

quality A term used by customers to describe their general satisfaction with a service or product.

quality at the source A philosophy whereby defects are caught and corrected where they were created.

quality of life A factor that considers the availability of good schools, recreational facilities, cultural events, and an attractive lifestyle.

quantity discount A drop in the price per unit when an order is sufficiently large.

***R*-chart** A chart used to monitor process variability.

radio frequency identification (RFID) A method for identifying items through the use of radio signals from a tag attached to an item.

range of feasibility The interval (lower and upper bounds) of an objective function coefficient over which the right-hand-side parameter of a constraint can vary while its shadow price remains valid.

range of optimality The interval (lower and upper bounds) of an objective function coefficient over which the optimal values of the decision variables remain unchanged.

raw materials (RM) The inventories needed for the production of services or goods.

rectilinear distance The distance between two points with a series of 90-degree turns, as along city blocks.

reduced cost How much the objective function coefficient of a decision variable must improve (increase for maximization or decrease for minimization) before the optimal solution changes and the decision variable "enters" the solution with some positive number.

reengineering The fundamental rethinking and radical redesign of processes to improve performance dramatically in terms of cost, quality, service, and speed.

regular time cost Regular-time wages paid to employees plus contributions to benefits, such as health insurance, dental care, Social Security, retirement funds, and pay for vacations, holidays, and certain other types of absences.

reorder point (*R*) The predetermined minimum level that an inventory position must reach before a fixed quantity Q of the SKU is ordered.

reorder point (ROP) system See continuous review (Q) system.

repeatability The degree to which the same work can be done again.

resource flexibility The ease with which employees and equipment can handle a wide variety of products, output levels, duties, and functions.

resource plan An intermediate step in the planning process that lies between S&OP and scheduling. It determines requirements for materials and other resources on a more detailed level than the S&OP.

resource planning A process that takes sales and operations plans; processes information in the way of time standards, routings, and other information on how services or products are produced; and then plans the input requirements.

revenue management Varying price at the right time for different customer segments to maximize revenues yielded by existing supply capacity.

reverse logistics The process of planning, implementing, and controlling the efficient, cost-effective flow of products, materials, and information from the point of consumption back to the point of origin for returns, repair, remanufacture, or recycling.

risk-management plan A plan that identifies the key risks to a project's success and prescribes ways to circumvent them.

rotating schedule A schedule that rotates employees through a series of workdays or hours.
route planning An activity that seeks to find the shortest route to deliver a service or product.
SA8000:2014 A list of standards covering nine dimensions of ethical workforce management.
safety stock inventory Surplus inventory that a company holds to protect against uncertainties in demand, lead time, and supply changes.
sales and operations plan (S&OP) A plan of future aggregate levels so that supply is in balance with demand. It states a company's or department's production rates, workforce levels, and inventory holdings that are consistent with demand forecasts and capacity constraints. The S&OP is a time-phased plan, meaning that it is projected for several time periods (such as months or quarters) into the future.
salesforce estimates The forecasts that are compiled from estimates of future demands made periodically by members of a company's salesforce.
sample size A quantity of randomly selected observations of process outputs.
sampling plan A plan that specifies a sample size, the time between successive samples, and decision rules that determine when action should be taken.
scatter diagram A plot of two variables showing whether they are related.
schedule A detailed plan that allocates resources over shorter time horizons to accomplish specific tasks.
scheduled receipts (SR) Orders that have been placed but have not yet been received.
SCOR model A framework that focuses on a basic supply chain of plan, source, make, deliver, and return processes, repeated again and again along the supply chain.
Scrum An agile project management framework that focuses on allowing teams to respond rapidly, efficiently, and effectively to change.
sensitivity analysis A technique for systematically changing parameters in a model to determine the effects of such changes.
sequencing Determining the order in which jobs or customers are processed in the waiting line at a workstation.
service blueprint A special flowchart of a service process that shows which steps have high customer contact.
service facility A person (or crew), a machine (or group of machines), or both, necessary to perform the service for the customer.
service level The desired probability of not running out of stock in any one ordering cycle, which begins at the time an order is placed and ends when it arrives in stock.
service system The number of lines and the arrangement of the facilities.
setup cost The cost involved in changing over a machine or workspace to produce a different item.
setup time The time required to change a process or an operation from making one service or product to making another.
shadow price The marginal improvement in Z (increase for maximization and decrease for minimization) caused by relaxing the constraint by one unit.
shortest route problem A problem whose objective is to find the shortest distance between two cities in a network or map.
simple moving average method A time-series method used to estimate the average of a demand time series by averaging the demand for the n most recent time periods.
simplex method An iterative algebraic procedure for solving linear programming problems.
single-bin system A system of inventory control in which a maximum level is marked on the storage shelf or bin, and the inventory is brought up to the mark periodically.
single-digit setup The goal of having a setup time of less than 10 minutes.
Six Sigma A comprehensive and flexible system for achieving, sustaining, and maximizing business success by minimizing defects and variability in processes.
slack The amount by which the left-hand side of a linear programming constraint falls short of the right-hand side.
smart contracts Codified agreements that self-execute when the conditions are met.
social responsibility An element of sustainability that addresses the moral, ethical, and philanthropic expectations that society has of an organization.
sole sourcing The awarding of a contract for a service or item to only one supplier.
staffing plan A sales and operations plan for a service firm, which centers on staffing and on other human resource-related factors.
standard deviation of the errors (σ) A measurement of the dispersion of forecast errors.
statistical process control (SPC) The application of statistical techniques to determine whether a process is delivering what the customer wants.
stock-keeping unit (SKU) An individual item or product that has an identifying code and is held in inventory somewhere along the supply chain.
stockout An order that cannot be satisfied, resulting in a loss of the sale.
subassembly An intermediate item that is *assembled* (as opposed to being transformed by other means) from more than one component.
supplier relationship process A process that selects the suppliers of services, materials, and information and facilitates the timely and efficient flow of these items into the firm.
supply chain An interrelated series of processes within and across firms that produces a service or product to the satisfaction of customers.
supply chain design Designing a firm's supply chain to meet the competitive priorities of the firm's operations strategy.
supply chain integration The effective coordination of supply chain processes through the seamless flow of information up and down the supply chain.
supply chain management The synchronization of a firm's processes with those of its suppliers and customers to match the flow of materials, services, and information with customer demand.
supply chain processes Business processes that have external customers or suppliers.
supply chain risk management The practice of managing the risk of any factor or event that can materially disrupt a supply chain, whether within a single firm or across multiple firms.
support process A process that provides vital resources and inputs to the core processes and therefore is essential to the management of the business.

surplus The amount by which the left-hand side of a linear programming constraint exceeds the right-hand side.
sustainability A characteristic of processes that are meeting humanity's needs without harming future generations.
swim lane flowchart A visual representation that groups functional areas responsible for different subprocesses into lanes. It is most appropriate when the business process spans several department boundaries.
takt time Cycle time needed to match the rate of production to the rate of sales or consumption.
tardiness See past due.
teams Small groups of people who have a common purpose, set their own performance goals and approaches, and hold themselves accountable for success.
technological forecasting An application of executive opinion to keep abreast of the latest advances in technology.
theoretical minimum (TM) A benchmark or goal for the smallest number of stations possible, where the total time required to assemble each unit (the sum of all work-element standard times) is divided by the cycle time.
theory of constraints (TOC) A systematic management approach that focuses on actively managing those constraints that impede a firm's progress toward its goal.
throughput time Total elapsed time from the start to the finish of a job or a customer being processed at one or more work centers.
time between orders (TBO) The average elapsed time between receiving (or placing) replenishment orders of Q units for a particular lot size.
time series The repeated observations of demand for a service or product in their order of occurrence.
time study A work measurement method using a trained analyst to perform four basic steps in setting a time standard for a job or process: selecting the work elements (or nested processes) within the process to be studied, timing the elements, determining the sample size, and setting the final standard.
time-based competition A strategy that focuses on the competitive priorities of delivery speed and development speed.
time-series analysis A statistical approach that relies heavily on historical demand data to project the future size of demand and recognizes trends and seasonal patterns.
tolerance An allowance above or below the nominal value.
total quality management (TQM) A philosophy that stresses three principles for achieving high levels of process performance and quality: (1) customer satisfaction, (2) employee involvement, and (3) continuous improvement in performance.
tracking signal A measure that indicates whether a method of forecasting is accurately predicting actual changes in demand.
transportation method A more efficient solution technique than the simplex method for solving transportation problems.
transportation method for location problems A quantitative approach that can help solve multiple-facility location problems.
transportation problem A special case of linear programming that has linear constraints for capacity limitations and demand requirements.
traveling salesperson problem A problem whose objective is to find the shortest possible route that visits each city exactly once and returns to the starting city.
trend projection with regression A forecasting model that is a hybrid between a time-series technique and the causal method.
two-bin system A visual system version of the Q system in which a SKU's inventory is stored at two different locations.
type I error An error that occurs when the employee concludes that the process is out of control based on a sample result that falls outside the control limits, when in fact it was due to pure randomness.
type II error An error that occurs when the employee concludes that the process is in control and only randomness is present, when actually the process is out of statistical control.
undertime The situation that occurs when employees do not have enough work for the regular-time workday or workweek.
usage quantity The number of units of a component that are needed to make one unit of its immediate parent.
utilization The degree to which equipment, space, or the workforce is currently being used, and is measured as the ratio of average output rate to maximum capacity (expressed as a percent).
value analysis A systematic effort to reduce the cost or improve the performance of services or products, either purchased or produced.
value stream mapping (VSM) A qualitative lean tool for eliminating waste, or *muda*, that involves a current state drawing, a future state drawing, and an implementation plan.
variable cost The portion of the total cost that varies directly with volume of output.
variables Service or product characteristics, such as weight, length, volume, or time, that can be measured.
vendor-managed inventories (VMI) A system in which the supplier has access to the customer's inventory data and is responsible for maintaining the inventory on the customer's site.
visual system A system that allows employees to place orders when inventory visibly reaches a certain marker.
waiting line One or more "customers" waiting for service.
warranty A written guarantee that the producer will replace or repair defective parts or perform the service to the customer's satisfaction.
weeks of supply An inventory measure obtained by dividing the average aggregate inventory value by sales per week at cost.
weighted moving average method A time-series method in which each historical demand in the average can have its own weight; the sum of the weights equals 1.0.
work breakdown structure (WBS) A statement of all work that has to be completed.
work elements The smallest units of work that can be performed independently.
work sampling A process that estimates the proportion of time spent by people or machines on different activities, based on observations randomized over time.
work-in-process (WIP) Items, such as components or assemblies, needed to produce a final product in manufacturing or service operations.
workforce scheduling A type of scheduling that determines when employees work.

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