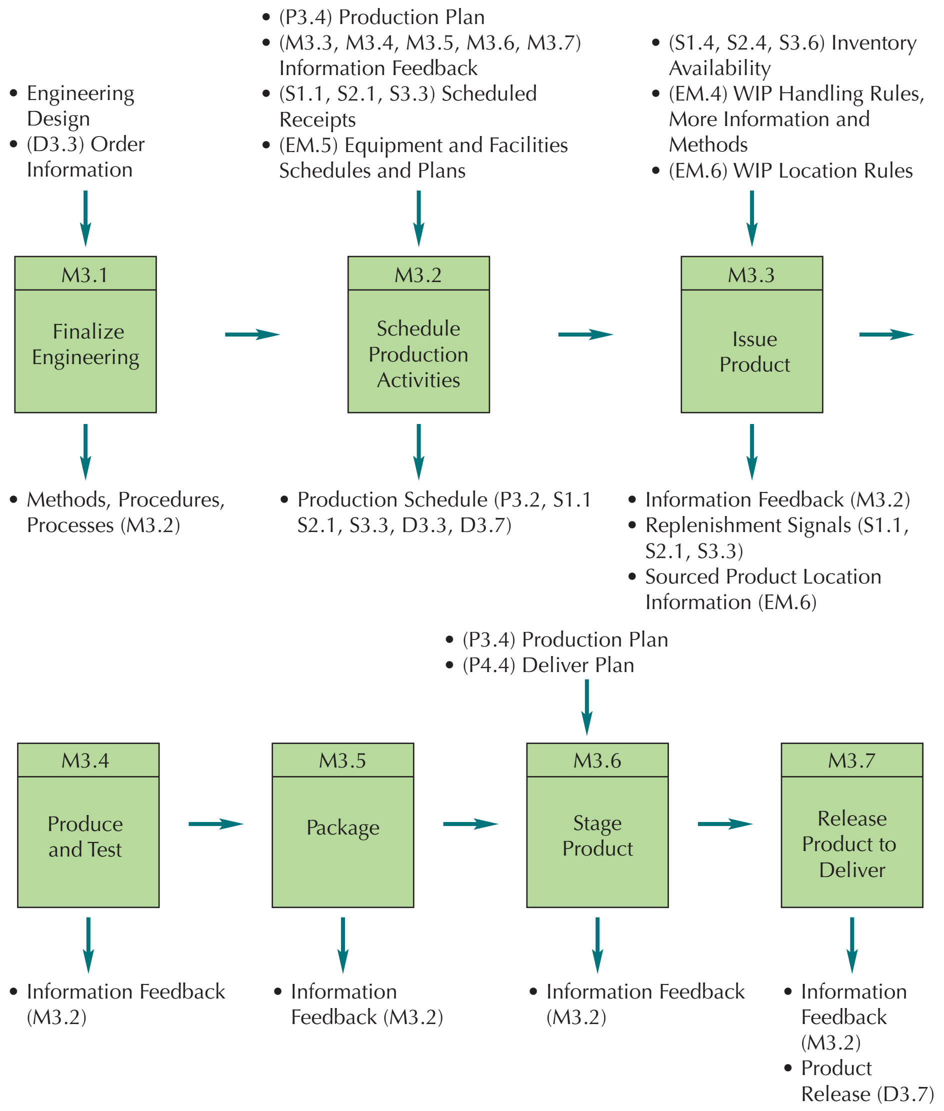
FIGURE 4.19
Detailed Process Map for SCOR's "Make Engineer-to-Order"
Source: "Phios Process Directory for SCOR," **http://repository.phios.com/SCOR/Activity.asp?ID=5394 (Phios Corporation).**



CHAPTER SUMMARY

Although the term *business processes* has been in the management lexicon for years, not all organizations clearly understand the importance of business processes and their effects on operations and supply chain performance. In this chapter, we defined the concept of business processes and showed how the business process perspective is different from the traditional, functionally oriented view of business. Business processes change the focus from "How is the business organized?" to "What does the business do?"

Fortunately, practitioners and theorists continue to develop various tools and approaches for managing business processes. In this chapter, we described two process mapping approaches and demonstrated how they can be used. We also spent considerable time talking about various approaches to managing and improving business processes, including performance measurement and benchmarking, the Six Sigma methodology, and continuous improvement tools. We concluded the chapter with a discussion of the SCOR model, which represents an attempt by industry partners to develop a comprehensive model of the various business processes that define supply chain management.

KEY FORMULAS

Productivity (page 84):

$$\text{Productivity} = \text{outputs}/\text{inputs} \quad \textbf{(4.1)}$$

Efficiency (page 86):

$$\text{Efficiency} = 100\%\,(\text{actual outputs}/\text{standard outputs}) \quad \textbf{(4.2)}$$

Percent value-added time (page 88):

$$\text{Percent value-added time} = 100\%\,(\text{value-added time})/(\text{total cycle time}) \quad \textbf{(4.3)}$$

KEY TERMS

SOLVED PROBLEM

PROBLEM

The repair process at Biosphere

Biosphere Products makes and sells environmental monitoring devices for use in industry. These devices monitor and record air quality levels and issue an alarm whenever conditions warrant.

If a monitoring device fails, Biosphere will repair the device as part of the customer's service agreement. The repair process consists of the following steps:

1. Once the device arrives at Biosphere's repair center, a work order is immediately entered into the computer system. This step takes 5 minutes.
2. A device will then wait, on average, 24 hours before a technician has a chance to run diagnostics and disassemble the device. The diagnostics procedure usually takes about 30 minutes, while disassembly takes around 1 hour.
3. Next the technician orders replacements for any broken/worn parts from the main plant. While it takes only 5 minutes to order the parts, it usually takes 48 hours for them to arrive from the main plant.
4. After the parts come in, the device will usually wait another 24 hours until a technician has time to reassemble and test the device. The reassembly and testing process takes, on average, 3 hours.
5. If the device still fails to work, the technician will repeat the process, starting with diagnostics and disassembly. The first time through, 10% of the devices aren't fixed; however, virtually all of them work by the time a second pass has been completed.
6. Once the device has been tested and passed, it is immediately boxed up (10 minutes) and a call is made to UPS, which picks up the package, usually within 1 hour.

Map Biosphere's current process. How long will it take, on average, to move a device through the system, assuming that everything "works" the first time? How long will it take if the device has to be repaired a second time? What is the percent value-added time under each scenario?

Solution

Figure 4.20 shows the process map, starting with the arrival of the device at the repair facility and ending when UPS picks it up. If the device has to be repaired only once, the total cycle time is 101 hours and 50 minutes. However, if the device has to be "repaired again," we must add another 76 hours and 35 minutes, resulting in a total cycle time of 178 hours and 25 minutes.

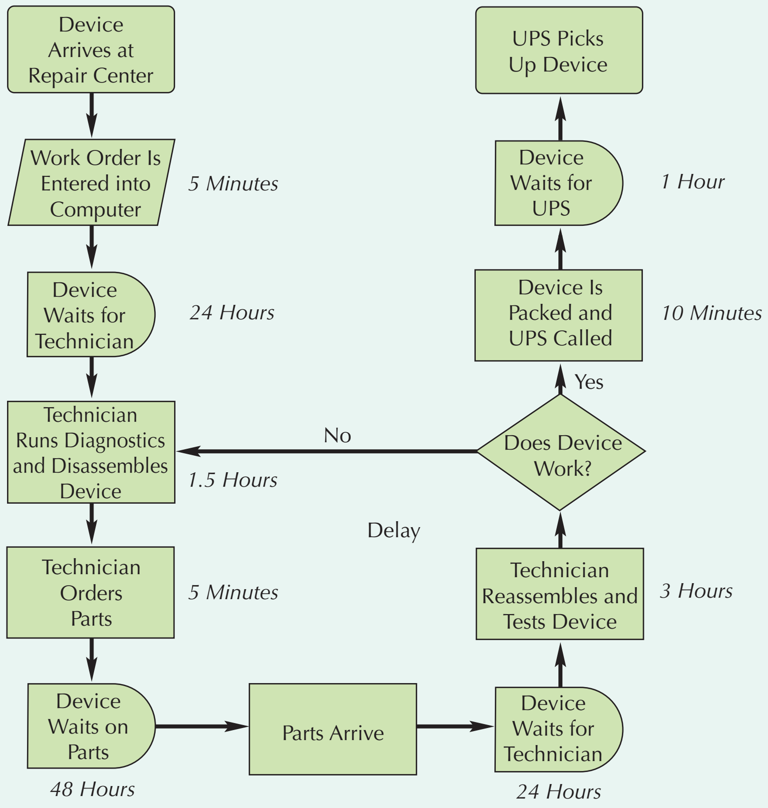


FIGURE 4.20 Process Map for Biosphere Products—Device Repair Process

It gets worse. One could argue that the only value-added activities are running the diagnostics, disassembling and reassembling the device, and testing. These activities total 4.5 hours. Therefore, if Biosphere correctly repairs the device the first time:

$$\text{Percent value-added time} = 100\%\,(4.5\text{ hours}/101.83\text{ hours}) = 4.4\%$$

If the device has to be repaired a second time:

$$\text{Percent value-added time} = 100\%\,(4.5\text{ hours}/178.42\text{ hours}) = 2.5\%$$

In other words, over 95% of the time is spent on non-value-added activities. A careful reader will notice that, in the second calculation, we didn't add in any more time for diagnostics, disassembling and reassembling the device, and testing. This was intentional: Our argument is that if these activities did not fix the device the first time, then the first pass through was *wasted* time, not value-added time.

So what should Biosphere do? Looking at the process map, it becomes clear that the vast majority of the time is spent waiting on a technician or on parts or looping through activities because a device wasn't fixed right the first time. If, for example, Biosphere could keep spare parts at the repair center, it could chop 48 hours off the cycle time. Management might also investigate why it takes technicians so long to get around to working on a device. Are they busy working on other devices, or are they involved in other activities that can wait? Management might even decide that more technicians are needed.

With regard to the relatively high failure rate of "repaired" devices, Biosphere might have to do some more detailed analysis: Are the technicians being trained properly? Are they making the same mistakes over and over again? If so, why? Clearly, Biosphere is an ideal candidate for DMAIC improvement efforts.

DISCUSSION QUESTIONS

1. Use the P&G example described in the chapter to explain the benefits to the customer of adopting a business processes perspective. Why might a traditional functional perspective have "blinded" P&G to the problems with the old system?
2. We noted that cycle time, while an important measure of process performance, is not the only measure to be considered. Give an example where focusing exclusively on reducing cycle times might hurt other, equally important, measures of process performance.
3. Consider the course registration process at your college. Is this a mass process, mass customization, artistic, or nascent/broken process? Justify your answer.
4. In the chapter, we stated that "there are countless possible measures of process performance, many of which are derived from the four core measures" quality, cost, time, and flexibility. In the following table, identify how you think the three measures we described (productivity, efficiency, and cycle time) relate to the four core measures. Specifically:
   - If you think the measure always has a positive impact on a core measure, mark the square with a "+".
   - If you think the measure always has a negative impact, mark the square with "−".
   - If you think the measure can have either a positive or a negative impact, depending on the circumstances, mark the square with "+/−".

Be ready to justify your answers. What are the implications for using performance measures to evaluate processes?

	QUALITY	COST	TIME	FLEXIBILITY
Productivity				
Efficiency				
Cycle time				

PROBLEMS

Additional homework problems are available at www.pearsonhighered.com/bozarth. These problems use Excel to generate customized problems for different class sections or even different students.

(* = easy; ** = moderate; *** = advanced)

Problems for Section 4.2: Mapping Business Processes

1. Billy's Hamburger Barn has a single drive-up window. Currently, there is one attendant at the window who takes the order (30–40 seconds), gathers up the food and bags it (30–120 seconds), and then takes the customer's money (30–40 seconds) before handing the food to the customer.
   a. (**) Map the current process. What is the minimum cycle time? The longest cycle time?
   b. (***) Suppose Billy's Hamburger Barn redesigns the process described in problem 11 so there are now two attendants. The first attendant takes the order. Once this step is finished, the first attendant then takes the money, and the second one gathers up and bags the food. If two of the process steps can now run in parallel (gathering the food and taking the money), what is the new minimum cycle time? What is the longest cycle time? What potential problems could arise by splitting the process across two individuals?
2. Faircloth Financial specializes in home equity loans, loans that customers can take out against the equity they have in their homes. ("Equity" represents the difference between the home's value and the amount a customer owns on any other loans.) The current process is as follows:
   - The customer downloads the loan application forms from the Web, fills them in, and mails them to Faircloth (3–5 days).
   - If there are any problems with the forms (and there usually are), a customer sales representative calls up the customer and reviews these problems. It may take 1 to 2 days to contact the customer. After reaching the customer, resolving the problem can take anywhere from 5 minutes to 30 minutes. If the customer needs to initial or sign some new forms, it takes 5–7 days to mail the forms to the customer and have her send them back.
   - Every Monday morning, the customer sales representatives take a batch of completed, correct application forms to the loan officers. This means that if a correct loan application comes in on Tuesday, the soonest it can get to a loan officer is the following Monday. The loan officers then take 2 to 3 days to process the batch of loans, based on information on the forms and information available from credit rating bureaus. Customers are advised by email and regular mail regarding the final decision.

   a. (***) Map out the current process. Identify any rework loops and delays in the process. What causes these? What is the impact on cycle times? How might this affect customers' willingness to do business with Faircloth?
   b. (***) What changes might you recommend to redesign this process with the needs of the customer in mind? You might start by imagining how the "perfect" process would look to the customer and base your recommendations on that.

Problems for Section 4.3: Managing and Improving Business Processes

3. Marci spends 15 hours researching and writing a 20-page report for her philosophy class. Jack brags that he has a "streamlined process" for performing the researching and writing. Jack takes just 8 hours to research and write the paper, but his report is only 15 pages long.

a. (*) Calculate Marci's and Jack's productivity. What is the output? What is the input? Is this a single-factor or multifactor productivity measure?
b. (**) What are the limitations of using productivity measures to evaluate Marci's and Jack's performance? What other performance measures might the instructor use?

4. (**) Consider the output and labor hour figures shown in the following table. Calculate the labor productivity for each week, as well as the average labor productivity for all six weeks. Do any of the weeks seem unusual to you? Explain.

WEEK	OUTPUT (IN UNITS)	LABOR HOURS
1	1,850	200
2	1,361	150
3	2,122	150
4	2,638	250
5	2,599	250
6	2,867	300

5. Smarmy Sales, Inc. (SSI) sells herbal remedies through its Web site and through phone reps. Over the past six years, SSI has started to depend more and more on its Web site to generate sales. The figures below show total sales, phone rep costs, and Web site costs for the past six years:

YEAR	TOTAL SALES	PHONE REP COSTS	WEB SITE COSTS
2012	$4,790,000	$200,000	$50,000
2013	$5,750,000	$210,000	$65,000
2014	$6,900,000	$221,000	$85,000
2015	$8,280,000	$230,000	$110,000
2016	$9,930,000	$245,000	$145,000
2016	$11,920,000	$255,000	$190,000

a. (*) Calculate productivity for the phone reps for each of the past six years. Interpret the results.
b. (*) Calculate the productivity for the Web site for each of the past six years. Interpret the results.
c. (**) Compare your results in parts a and b. What are the limitations of these single-factor productivity measures?
d. (**) Now calculate a multifactor productivity score for each year, where the "input" is the total amount spent on both the phone reps and the Web site. Interpret the results. What can you conclude?

6. (*) A customer support job requires workers to complete a particular online form in 60 seconds. Les can finish the form in 70 seconds. What is his efficiency? What other performance measures might be important here?
7. (**) Precision Machinery has set standard times for its field representatives to perform certain jobs. The standard time allowed for routine maintenance is 2 hours (i.e., "standard output" = 0.5 jobs per hour). One of Precision's field representatives records the results below. Calculate the rep's efficiency for each customer and her average efficiency. Interpret the results.

CUSTOMER	ACTUAL TIME REQUIRED TO PERFORM ROUTINE MAINTENANCE
ABC Company	1.8 hours
Preztel	2.4 hours
SCR Industries	1.9 hours
BeetleBob	1.8 hours

8. Gibson's Bodywork does automotive collision work. An insurance agency has determined that the standard time to replace a fender is 2.5 hours (i.e., "standard output" = 0.4 fenders per hour) and is willing to pay Gibson $50 per hour for labor (parts and supplies are billed separately). Gibson pays its workers $35 per hour.

a. (**) Suppose Gibson's workers take 4 hours to replace a fender. What is Gibson's labor hour efficiency? Given Gibson's labor costs, will the company make money on the job?
b. (***) What does Gibson's labor hour efficiency have to be for Gibson to break even on the job? Show your work.

9. (**) When a driver enters the license bureau to have his license renewed, he spends, on average, 45 minutes in line, 2 minutes having his eyes tested, and 3 minutes to have his photograph taken. What is the percent value-added time? Explain any assumptions you made in coming up with your answer.
10. Average waiting times and ride times for two of DizzyWorld's rides are as follows:

RIDE	AVERAGE WAITING TIME	LENGTH OF RIDE	TOTAL PROCESS TIME
Magical Mushroom	30 minutes	10 minutes	40 minutes
Haunted Roller Coaster	40 minutes	5 minutes	45 minutes

a. (*) Calculate the percent value-added time for each ride.
b. (**) Now suppose DizzyWorld puts in place a reservation system for the Haunted Roller Coaster ride. Here's how it works: The customer receives a coupon that allows him to come back in 40 minutes and immediately go to the front of the line. In the meantime, the customer can wait in line and then ride the Magical Mushroom. Under this new system, what is the customer's total time waiting? Total time riding? What is the new percent-value added time?

11. Consider Example 4.1 and the accompanying Figure 4.6 from the book chapter.

a. (**) Calculate the percent value-added time for the current process. Which activities do you consider to be value added? Why?
b. (***) Suppose management actually *does* put a system in place that lets customers enter orders electronically, with this information sent directly to the picking area. Redraw the process map to illustrate the changes. What is the new cycle time for the process? What is the new percent value-added time? What do you think the impact would be on the number of lost orders? On customer satisfaction?

CASE STUDY

Swim Lane Process Map for a Medical Procedure

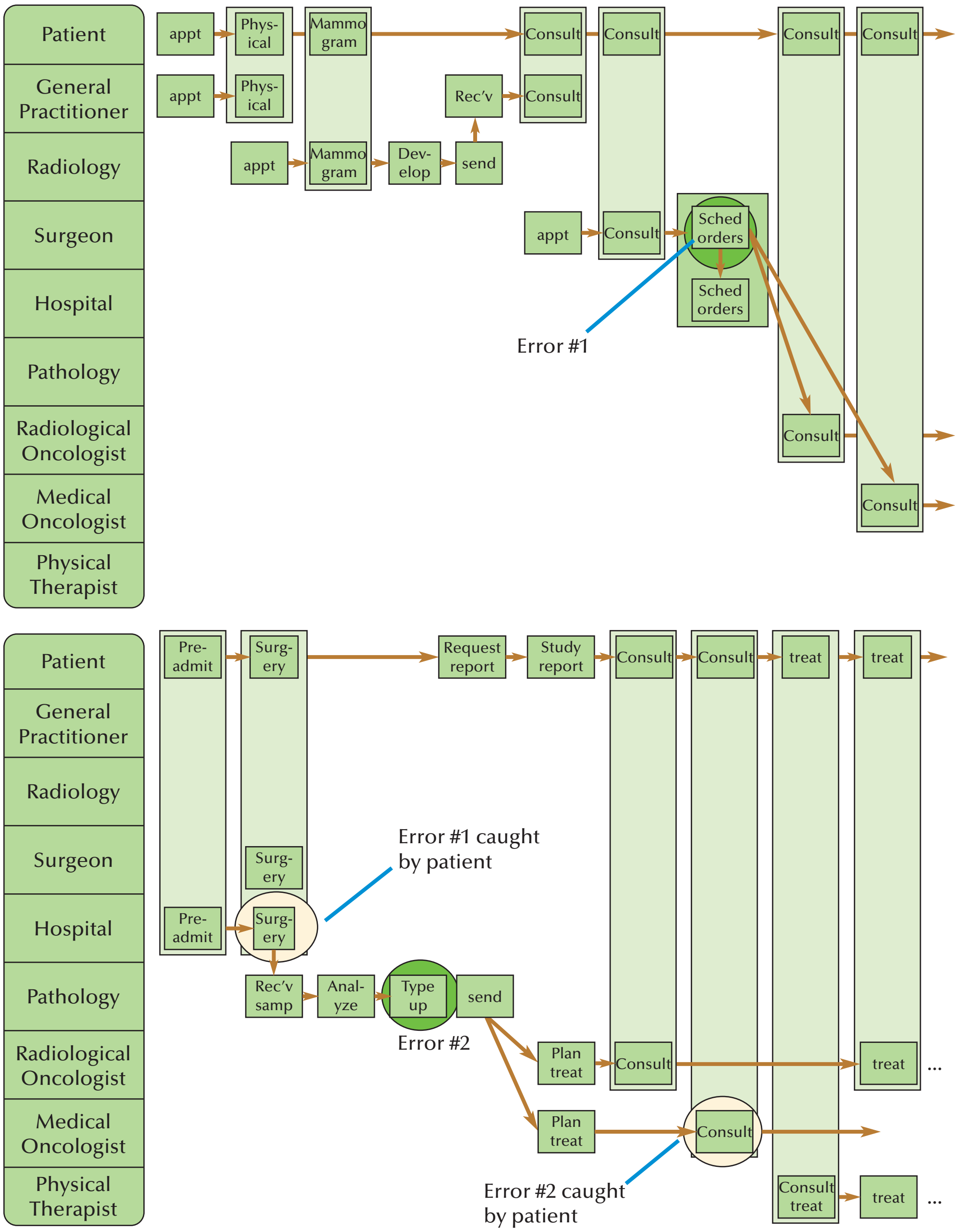
Figure 4.21 shows the swim lane process map for a patient undergoing a lumpectomy (the surgical removal of a small tumor from the breast). Nine parties, including the patient, were involved in the process. For many of the steps in Figure 4.21, a box has been drawn around multiple parties, indicating that two or more parties were involved in the step. For example, the "surgery" step involved three parties: the patient, the surgeon, and the hospital.

During the treatment process, the patient (who was a registered nurse) detected two errors. Error 1 occurred when the surgeon intended to employ a needle locator to identify the location of the tumor, but failed to forward an order to that effect to the hospital. The patient identified the omission prior to surgery. No harm occurred. Error 2 was a typographic error on the pathology report indicating that the tumor was 1.6 *millimeters* diameter when in fact it was 1.6 *centimeters*. This could have been a more serious mistake, but a phone call to confirm the correction avoided any harm.

Questions

1. Who or what organization is responsible for this process from start to finish? What are the implications for managing and improving the treatment process?
2. Which process steps should be standardized? Which process steps should be more artistic? Explain.
3. Consider the errors that occurred during the treatment process. How might you use the Six Sigma methodology and continuous improvement tools to keep these errors from reoccurring? Looking ahead, what kinds of solutions might you see coming out of such an analysis?

FIGURE 4.21
Swim Lane Process Map for a Surgical Procedure
Source: John Grout, "Swim Lane," **http://facultyweb.berry.edu/jgrout/processmapping/Swim_Lane/swim_lane.html.**



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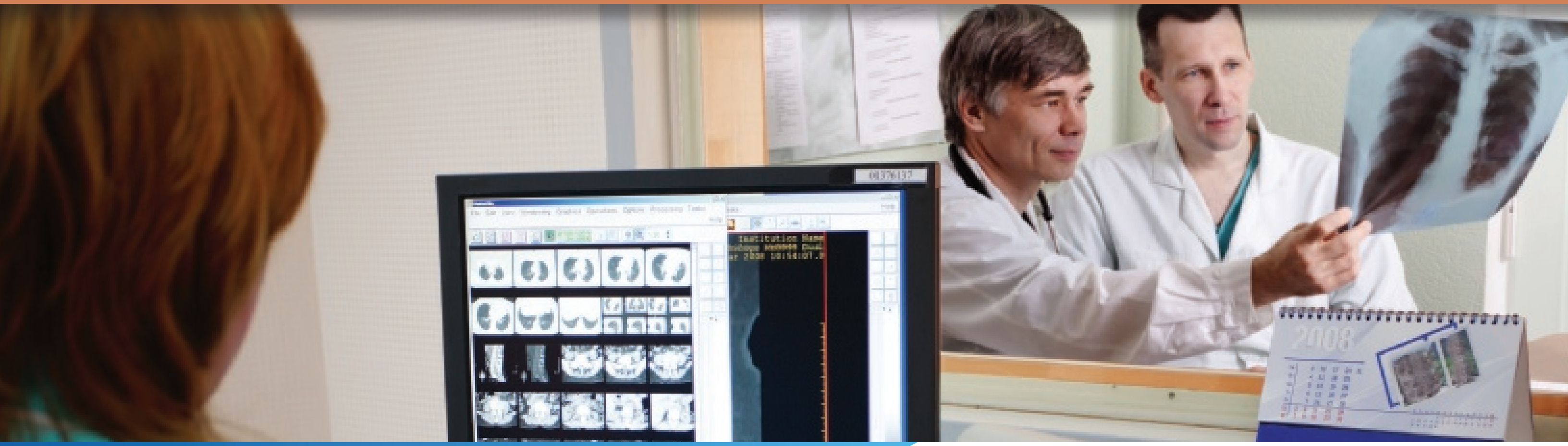

Kiselev Andrey Valerevich / Shutterstock

CHAPTER
five

Managing Quality

CHAPTER OUTLINE

CHAPTER OBJECTIVES

By the end of this chapter, you will be able to:

- Discuss the various definitions and dimensions of quality and why quality is important to operations and supply chains.
- Describe the different costs of quality, including internal and external failure, appraisal, and prevention costs.
- Describe what TQM is, along with its seven core principles.
- Calculate process capability ratios and indices and set up control charts for monitoring continuous variables and attributes.
- Describe the key issues associated with acceptance sampling, as well as the use of OC curves.
- Discuss some of the important issues associated with managing quality across the supply chain.

GETTING YOUR BAGS IS HALF THE FUN

Marvin McAbee/Alamy Stock Photo

The U.S. airline industry has experienced many changes in the past decade. Most carriers have reduced capacity in an effort to control costs, which means they're flying fewer and more crowded planes. And with many airlines tacking on extra fees to boost revenue, including charging for checked luggage, more passengers are trying to cram more of their belongings into overhead bins than ever before. In fact, some industry analysts believe nearly 60 million more bags are carried on board every year than the year before.

But plenty of bags are still being checked. How many are reaching their destinations? The U.S. Department of Transportation reported that in 2016, more than 1.7 million bags were lost or misplaced on domestic flights. That sounds like a lot, but it's actually 1.4 million *fewer* bags than were lost in 2008—just about the time most airlines adopted checked-baggage fees and inspired many passengers to start carrying their bags on board instead.

Other factors that might have helped reduce the number of lost bags are the more stringent airport security procedures being enforced by the federal government. Bags are more often scanned instead of being opened, streamlining the handling process and reducing errors. An increase in on-time arrivals has also helped, especially by reducing missed connections on multiple-leg flights. Bags checked through on connecting flights are usually the most likely to be misplaced, airlines report.

Airline executives also credit advances in technology that have helped replace labor-intensive processes with more efficient paperless ones. Bar-code scanners, long standard in the shipping industry, now help airlines track bags at several points in their journey and even let baggage workers know when they're loading something on the wrong plane. Delta Air Lines is taking it a step further, investing $50 million in radio-frequency identification (RFID) tags that will allow the airline to automatically track individual bags via 5,200 RFID readers located in 344 airports. The system will allow Delta to quickly pinpoint and resolve problems—ideally, before the customer even realizes anything is wrong.

RFID technology is just the latest investment made by Delta to improve its baggage-handling process. In 2006, Delta was near the bottom of the industry in terms of baggage-handling performance. In response, Delta made a $100 million investment in the baggage-handling systems at its largest hub, Atlanta's Hartsfield-Jackson International Airport. Conveyor belts and optical scanners, monitored from a central control room equipped with video screens, shortened the time it took bags to travel between five different terminals; what used to take 15 to 30 minutes was reduced to 10 minutes or less. A simple change to wider belts helped cut the number of conveyor jams in half, and four control-room employees were always on hand, prepared to tackle any trouble spots on the 14-mile system.

Figure 5.1 shows the impact of these changes on Delta's performance: The number of mishandled bags per 1,000 passengers fell from 9 in August 2006 to 2.11 in July 2016.

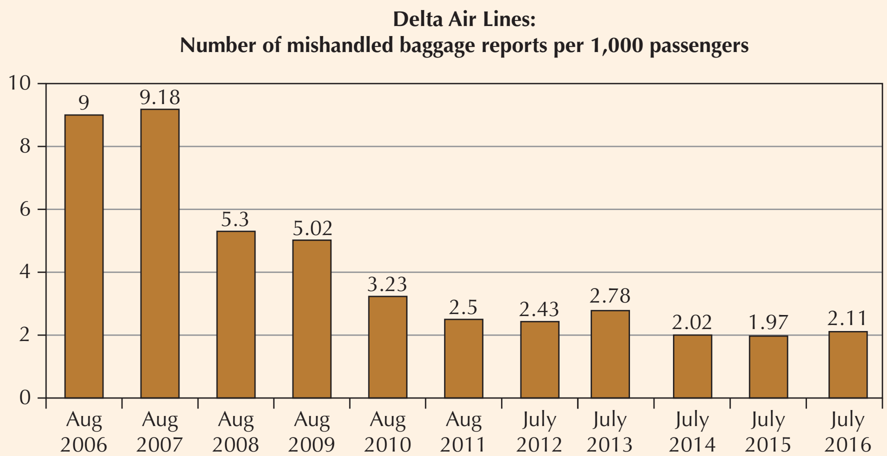

FIGURE 5.1 Decreasing the Number of Mishandled Bags at Delta Air Lines, 2006–2016

While Delta's performance is now better than the industry average of 2.72 bags, it still trails Virgin Airlines, which had the best performance at just 1.03 mishandled bags per 1,000 passengers. It's important to note that it is not just the customer who takes a hit if a bag is lost—according to the International Air Transport Association, the average lost bag generates an additional $100 in handling costs for the *airline*.

Sources: Based on "How Delta Is Trying to Fix the Problem of Lost and Delayed Luggage," *Los Angeles Times*, August 31, 2016, www.latimes.com/business/la-fi-lost-luggage-delta-20160831-snap-story.html.
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INTRODUCTION

Quality has been a mainstay of the operations and supply chain areas for nearly a century. Quality is a broad and complex topic, covering everything from companywide practices to the application of specific statistical tools. The purpose of this chapter is to give you an overview of the different perspectives on quality in today's business environment, as well as some of the tools and techniques companies use to improve and monitor quality levels.

Because the topic of quality is so broad, we have deliberately organized this chapter to flow from high-level descriptions of quality issues to more detailed tools and techniques for controlling quality. As you go through this chapter, pay attention to the flow from high-level perspectives to specific tools and techniques. Wherever you end up in an organization, you will be required to discuss and understand quality issues at *all* these levels. You may also notice that there are strong similarities between quality management and business process management, which was the focus of Chapter 4. This is no accident: Many of the perspectives, tools, and techniques used to manage business processes first appeared in the quality management area.

5.1 QUALITY DEFINED

When we talk about quality, it's important to realize that there are really two distinct, yet mutually dependent, perspectives on quality: the *value perspective* and the *conformance perspective*. The American Society for Quality recognizes this dichotomy in its two-part definition of **quality:**[1]

Quality
(a) The characteristics of a product or service that bear on its ability to satisfy stated or implied needs. (b) A product or service that is free of deficiencies.

1. The characteristics of a product or service that bear on its ability to satisfy stated or implied needs [the value perspective]
2. A product or service that is free of deficiencies [the conformance perspective]

Value perspective
A quality perspective that holds that quality must be judged, in part, by how well the characteristics of a particular product or service align with the needs of a specific user.

The **value perspective** holds that quality must be judged, in part, on how well the characteristics of a particular product or service align with the needs of a specific user. This is consistent with the views of noted quality expert Joseph Juran, who defined quality as "fitness for use."[2]

Consider how you might use the value perspective to evaluate the quality of a meal at a fast-food restaurant. You might consider such factors as the accuracy of the order-filling process (Did you get what you thought you would get?), the speed with which you were served, whether the food was fresh, and the price. On the other hand, the dimensions by which you evaluate quality will be quite different for a meal served in a four-star restaurant. What constitutes quality can differ from one situation to the next, as well as from one individual to the next.

[1]American Society for Quality, "Quality Glossary," **https://asq.org/quality-resources/quality-glossary/q.**
[2]J. DeFeo, and J. M. Juran, eds., *Juran's Quality Handbook*, 7th ed. (San Francisco: McGraw-Hill, 2016).

In an effort to provide some structure to the value perspective, David Garvin of the Harvard Business School identified eight dimensions on which users evaluate the quality of a product or service:[3]

1. *Performance*. What are the basic operating characteristics of the product or service?
2. *Features*. What extra characteristics does the product or service have, beyond the basic performance operating characteristics?
3. *Reliability*. How long can a product go between failures or the need for maintenance?
4. *Durability*. What is the useful life for a product? How will the product hold up under extended or extreme use?
5. *Conformance*. Was the product made or service performed to specifications?
6. *Aesthetics*. How well does the product or service appeal to the senses?
7. *Serviceability*. How easy is it to repair, maintain, or support the product or service?
8. *Perceived quality*. What is the reputation or image of the product or service?

Table 5.1 illustrates how these dimensions might be applied to both a manufactured good and a service.

As Table 5.1 indicates, not all of the dimensions will be relevant in all situations, and the relative importance will vary from one customer to the next. Furthermore, Garvin's list should really be viewed as a starting framework. There may be other dimensions of quality that would be unique to specific business situations.

Conformance perspective
A quality perspective that focuses on whether or not a product was made or a service was performed *as intended*.

While the value-based perspective on quality focuses on accurately capturing the end user's needs, the **conformance perspective** focuses on whether or not a product was made or a service was performed *as intended*. Conformance quality is typically evaluated by measuring the actual product or service against some preestablished standards.

Look again at Table 5.1. "Number of defects in the car" and "number of mistakes on the tax return" are two measures of conformance quality. A defect or mistake, by definition, means that the product or service failed to meet specifications. From these two perspectives on quality, we can start to see what an organization must do in order to provide high-quality products and services to users. Specifically, the organization must:

1. Understand what dimensions of quality are most important to users.
2. Develop products and services that will meet the users' requirements.
3. Put in place business processes capable of meeting the specifications driven by the users' requirements.
4. Verify that the business processes are indeed meeting the specifications.

TABLE 5.1
Dimensions of Quality for a Good and a Service

QUALITY DIMENSION	NEW CAR	TAX PREPARATION SERVICE
Performance	Tow capacity; maximum number of passengers	Cost and time to prepare taxes
Features	Accessories; extended warranty	Advance on refund check; automatic filing
Reliability	Miles between required major service visits	Not applicable
Durability	Expected useful life of the engine, transmission, body	Not applicable
Conformance	Number of defects in the car	Number of mistakes on the tax return
Aesthetics	Styling, interior appearance, look and feel of instrumentation	Neatness of the return; manner of presentation to the customer
Serviceability	Are there qualified mechanics in the area? What are the times and costs for typical maintenance procedures?	Will the tax preparation firm talk with the IRS in case of an audit?
Perceived quality	How do prices for used vehicles hold up?	What is the reputation of the firm?

[3]D. Garvin, "Competing on the Eight Dimensions of Quality," *Harvard Business Review* 65, no. 6 (November–December 1987): 101–109.

Consider Steve Walton's experiences with Decatur Trust Bank (see Example 5.1) in light of these four points. By keeping the bank open on Saturdays and offering a wide range of customer services, Decatur Trust seems to have done a fair job on the first two points—understanding the dimensions of quality important to users and developing services to meet them. However, on the other two points, Decatur Trust falls really short. No signs were in place to guide customers to the correct line or waiting area, and Decatur Trust failed to provide adequate training to the staff on hand. As a result, Steve Walton had to wait an excessively long time, and even then his IRA certificate was filled out incorrectly.

EXAMPLE 5.1

Decatur Trust Bank

Recently, the management at Decatur Trust Bank decided to keep its branch offices open on Saturday mornings. Only selected services would be offered, including withdrawals and deposits, the opening of new checking accounts, the purchase of certificates of deposit (CDs), and the establishment of individual retirement accounts (IRAs).

One Saturday morning, Steve Walton arrived at the bank. He wanted to (1) cash in a $2,000 CD that had matured; (2) withdraw $1,000 from his checking account; and (3) roll the combined $3,000 into an IRA, to be credited against his 2019 taxes. No signs were posted to indicate which employees could offer these specific services. After waiting in line for 10 minutes to see a teller, Steve learned that one of the two employees seated at desks would need to take care of his transactions. There was no formal waiting area for customers who wanted to see those employees. After two customers walked in front of Steve and obtained service, he finally spoke up and requested that he be served next.

After sitting down, Steve explained the three transactions he wanted to make to the employee, Nina Lau. Nina hesitated and then told Steve she had never opened an IRA before. When Steve suggested that someone else help him, Nina said there would not be a problem; if she made a mistake, the bank had up to seven days to correct it. Someone would call Steve about the matter.

Nina began to fill out various documents, repeatedly asking other employees for help. After she did 35 minutes of paperwork, including changes, additions, and deletions, Steve became visibly annoyed. Nina sensed his displeasure and became nervous. She apologized for the delay, explaining, "They told me to sit here today, but they never explained what I was supposed to do."

Nina finally finished the paperwork and handed it to Steve. Looking over the documents, he could not find any indication that his deposit was supposed to apply to his 2019 taxes. He asked Nina about the omission, but she didn't think it would make a difference. Steve then insisted that someone else review the document. When Jim Young, the bank manager, looked at it, he agreed that "IRA-2019" should be typed across the top of the form. As Steve got up to leave, over an hour after he had arrived, Nina assured him once again that he needn't worry about mistakes because they could be corrected within a week.

Pavel Losevsky/Fotolia

On Tuesday, Steve received an email from Nina, stating: "When you purchased the above-referenced IRA on Saturday, December 8, the certificate was inadvertently printed with both your name and your wife's. This, of course, is not permissible on an IRA. Please bring the original certificate in to the bank, and we will create a new one for you. This will not affect the account in any way."

5.2 TOTAL COST OF QUALITY

Pioneers in the quality area attempted to quantify the benefits associated with improving quality levels. One such pioneer was Joseph Juran, who edited the widely recognized *Quality Handbook*.[4] Juran argued that there are four quality-related costs: internal failure costs, external failure costs, appraisal costs, and prevention costs.

Internal failure costs
Costs caused by defects that occur prior to delivery to the customer, including money spent on repairing or reworking defective products, as well as time wasted on these activities.

Internal failure costs are costs caused by defects that occur prior to delivery to the customer, including money spent on repairing or reworking defective products (or scrapping them if they are completely ruined), as well as time wasted on these activities. As you might have guessed, this cost is not small. A *BusinessWeek* study[5] once found that the typical American factory spent 20% to 50% of its operating budget on finding and fixing mistakes. In fact, as many as one out of four factory employees didn't produce anything new that year because they were too busy reworking units not done right the first time.

External failure costs
Costs incurred by defects that are not detected until a product or service reaches the customer.

If defects are not detected until a product or service reaches the customer, the organization incurs an **external failure cost.** These costs are difficult to estimate, but they are inevitably large, for they include not only the cost of fixing the problem, but also the costs of lost future business and, in some cases, costly litigation. Consider the opening case for this chapter, which estimated the cost of mishandling a *single* bag at $100.

Appraisal costs
Costs a company incurs for assessing its quality levels.

Balanced against failure costs are appraisal and prevention costs. **Appraisal costs** are costs a company incurs for assessing its quality levels. Typical appraisal costs are the costs for inspections, the sampling of products or services, and customer surveys.

Prevention costs
The costs an organization incurs to actually prevent defects from occurring to begin with.

Note that appraising quality is *not* the same as preventing defects. For example, a manufacturer might inspect goods before they are shipped, but unless it takes steps to *improve* the production process, defect levels will not change. In contrast, **prevention costs** refer to the costs an organization incurs to actually prevent defects from occurring in the first place. Examples include the costs for employee training, supplier certification efforts, and investment in new processes, not to mention equipment maintenance expenditures. Figure 5.2 shows how these various costs behave as defect levels decrease.

According to Figure 5.2, as the level of defects is reduced from 100% to 0%, internal and external failure costs fall to zero, and prevention costs rise exponentially. The rationale behind the steeply rising prevention costs is as follows: As the defect level drops, it becomes even harder to find and resolve the remaining quality problems. You can see this effect in Figure 5.1; after making quick, significant reductions in the number of mishandled bags between 2007 and 2012, Delta Air Lines is having to spend millions of dollars more to get slight improvements in the numbers. Notice, too, that appraisal costs are flat across the various defect levels, as there is no direct relationship between appraising quality and defect levels. Therefore, while appraising quality levels may be necessary, appraisal by itself will not improve quality.

Total cost of quality curve
A curve that suggests that there is some optimal quality level, Q^*. The curve is calculated by adding costs of internal and external failures, prevention costs, and appraisal costs.

When we add internal and external failure, prevention, and appraisal costs together, we get a **total cost of quality curve.** This curve suggests that there is some optimal quality level, Q^*, that minimizes the total cost of quality. For defect levels higher than this level, exponentially increasing failure costs cause total quality costs to rise; for defect levels below Q^*, increases in prevention costs outstrip decreases in failure costs.

But as Juran continued his work, he began to notice something that contradicted the pattern shown in Figure 5.2. In particular, Juran noticed that as a business's processes improved

[4]Now in its seventh edition. See Note 2.
[5]D. Greising, "Quality: How to Make It Pay," *BusinessWeek* (August 8, 1994): 54–59.

FIGURE 5.2
Total Cost of Quality (Traditional View)

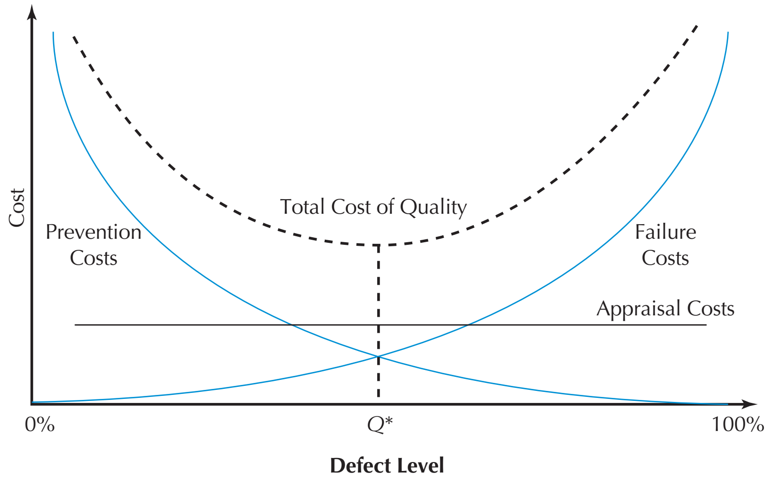
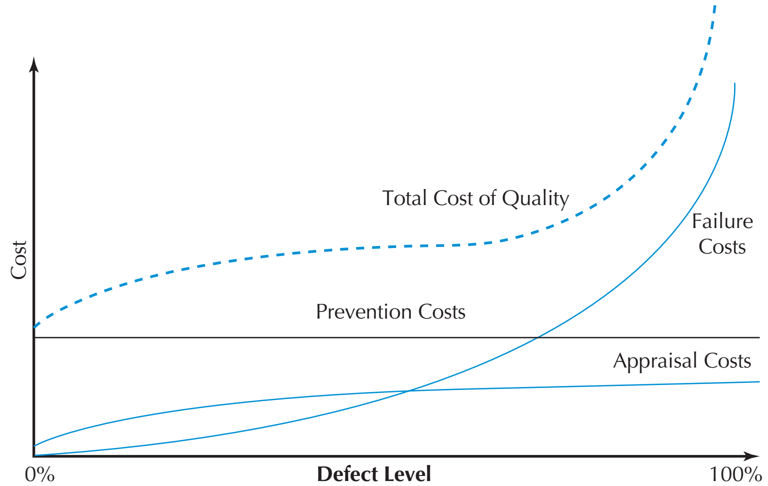


FIGURE 5.3
Total Cost of Quality (Zero Defects View)



to the point where products and services were defect-free, the cost of appraisal fell. In effect, there was no need to inspect products or services for defects. Furthermore, prevention costs held steady (or even decreased) as managers and employees became more skillful at identifying and resolving problems. With the changing appraisal and prevention cost curves, the total cost of quality curve began to look more like the one in Figure 5.3. Note that in this graph, the lowest total cost of quality occurs at the 0% defects level.

But how could this be? Let's consider an example from industry. Many companies have supplier certification programs in which they work with key suppliers to improve the quality of purchased goods. As the suppliers become better at providing high-quality goods, the purchasing companies do not need to spend as much money on appraising the quality of incoming shipments. Furthermore, good-quality practices become embedded in the supplier's business processes, and prevention costs hold steady or even decrease as quality levels improve. Moving to the left on Figure 5.3 is not always easy, but as the total cost curve suggests, it can pay off in the long term.

5.3 TOTAL QUALITY MANAGEMENT

Of course, quality management involves more than just managing to the "optimum" defect level. As we noted earlier, to fully address both the value and the conformance perspectives on quality, organizations must:

1. Understand what dimensions of quality are most important to users.
2. Develop products and services that will meet the users' requirements.

3. Put in place business processes capable of meeting the specifications driven by the users' requirements.
4. Verify that the business processes are indeed meeting the specifications.

To accomplish this, all individuals within an organization must address quality within all of an organization's business processes. From design through purchasing, manufacturing, and distribution, an organization must have processes and people capable of delivering quality products and services.

Total quality management (TQM)
A managerial approach in which an entire organization is managed so that it excels in all quality dimensions that are important to customers.

This managerial approach is often referred to as total quality management. **Total quality management (TQM)** is the management of an entire organization so that it excels in all quality dimensions that are important to customers. TQM is such a broad concept that students often have a hard time understanding what it is. Indeed, one way to think about TQM is as a business philosophy centered around seven core ideas, or *principles*:

1. Customer focus
2. Leadership involvement
3. Continuous improvement
4. Employee empowerment
5. Quality assurance
6. Supplier partnerships
7. Strategic quality plan

Customer Focus. TQM starts with employees who are willing to place themselves in the customers' shoes. If employees do not understand how customers really feel about a product or service, they risk alienating customers. In some cases, an employee might not have direct contact with an *external* customer. But every employee has a "customer" whose expectations must be met, even if that customer is *internal* to the organization.

EXHIBIT 5.1
The Malcolm Baldrige National Quality Award

The Malcolm Baldrige National Quality Award is given annually by the president of the United States to business, education, and health care organizations that apply and are judged to be outstanding in five key areas:

- Product and process outcomes
- Customer outcomes
- Workforce outcomes
- Leadership and governance outcomes
- Financial and market outcomes

Congress established the award program in 1987 to recognize U.S. organizations for their achievements in quality and performance and to raise awareness about the importance of quality and performance excellence. The U.S. Commerce Department's National Institute of Standards and Technology (NIST) manages the Baldrige National Quality Program, in close cooperation with the private sector. The Baldrige performance excellence criteria are a framework that any organization can use to improve overall performance.

Source: Based on "Baldrige Performance Excellence Program: Malcolm Baldrige National Quality Award," **www.nist.gov/baldrige/baldrige-award.**

Leadership Involvement. If companies are serious about adopting a TQM mind-set, then change must begin at the top. Managers should carry the message that quality counts to everyone in the company. To inspire and guide managers, W. Edwards Deming presented "Fourteen Points for Management," a set of guidelines for managers to follow if they are serious about improving quality:[6]

1. Demonstrate consistency of purpose toward product improvement.
2. Adopt the new philosophy [of continuous improvement].

[6]W. E. Deming, *Quality, Productivity, and Competitive Position* (Boston: MIT Center for Engineering Study, 1982).

3. Cease dependence on mass inspection; use statistical methods instead.
4. End the practice of awarding business on the basis of price tag.
5. Find and work continually on problems.
6. Institute modern methods of training.
7. Institute modern methods of supervision.
8. Drive out fear—promote a company-oriented attitude.
9. Break down barriers between departments.
10. Eliminate numerical goals asking for new levels of productivity without providing methods.
11. Eliminate standards prescribing numerical quotas.
12. Remove barriers that stand between the hourly worker and his right to pride of workmanship.
13. Institute a program of education and retraining.
14. Create a corporate and management structure that will promote the above 13 points.

In promoting his ideas, Deming stressed that managers bear the ultimate responsibility for quality problems. To succeed, they must focus on the entire organization to excel in all dimensions that are important to the customer.

Continuous improvement
A principle of TQM that assumes there will always be room for improvement, no matter how well an organization is doing.

Continuous Improvement. **Continuous improvement** means never being content with the status quo but assuming that there will always be room for improvement, no matter how well an organization is doing. Think again about the opening case: While the number of mishandled bags on U.S. domestic flights has improved dramatically over the last 10 years, there were still 1.7 million bags lost or mishandled in 2016. With failure costs at $100 per bag, that's *$170 million* in lost value to the airlines.

Employee empowerment
Giving employees the responsibility, authority, training, and tools necessary to manage quality.

Employee Empowerment. Prior to TQM, the traditional business view has been that the executives at the top of a company do the thinking, the middle managers do the supervising, and the remaining employees are paid to work, not to think. However, in a TQM organization, quality is everybody's job, from the CEO to the entry-level employees. **Employee empowerment** means giving employees the responsibility, authority, training, and tools necessary to manage quality. An excellent example of this is training employees in the Six Sigma methodology and continuous improvement tools described in Chapter 4.

Quality assurance
The specific actions firms take to ensure that their products, services, and processes meet the quality requirements of their customers.

Quality function deployment (QFD)
A technique used to translate customer requirements into technical requirements for each stage of product development and production.

Statistical quality control (SQC)
The application of statistical techniques to quality control.

Quality Assurance. **Quality assurance** refers to the specific actions a firm takes to ensure that its products, services, and processes meet the quality requirements of its customers. Quality assurance activities take place throughout the organization. For example, during the product design phase, many companies use a technique called **quality function deployment (QFD)** to translate customer requirements into technical requirements for each stage of product development and production. (See Chapter 15 for a more detailed discussion of QFD.)

Another approach that falls under the quality assurance banner is **statistical quality control (SQC),** which we will describe in detail later in the chapter. SQC uses basic statistics to help organizations measure quality levels. Other quality assurance efforts can include "error-proofing," which is the deliberate design of a process to eliminate the possibility of an error, and quality auditing of suppliers by carefully trained teams.

Supplier Partnerships. As you would expect, companies must extend their TQM efforts to include supply chain partners. If members of the supply chain do not share the same commitment to TQM, quality will suffer because suppliers' materials and services ultimately become part of the company's product or service. To ensure that suppliers are willing to meet expectations, managers must monitor their performance carefully and take steps to ensure improvement, when necessary.

Strategic quality plan
An organizational plan that provides the vision, guidance, and measurements to drive the quality effort forward and shift the organization's course when necessary.

Strategic Quality Plan. TQM cannot be achieved without significant, sustained efforts over time. A well-developed **strategic quality plan** provides the vision, guidance, and measurements to drive the quality effort forward and shift the organization's course when necessary. Such a plan generally extends several years into the future and stipulates a broad set of objectives. However, it should also establish measurable quarterly (three-month) goals for the short term.

Every quarter, executives should review the company's quality performance against its goals and take action to sustain successes and remedy failures. Cross-functional teams consisting of process owners then implement their action plans. Process owners are held responsible for achieving specific goals by certain dates, and at every team meeting, members measure their progress against preestablished measures and deadlines.

TQM and the Six Sigma Methodology

As you read through the previous section, you might have noticed a lot of overlap between TQM and the Six Sigma methodology, which we introduced in Chapter 4. Some practitioners and researchers have even gone as far as to say that TQM is passé and has been replaced by Six Sigma. But this is misleading; the fundamental principles behind TQM took decades to develop and are still valid today. The main differences are:

- TQM is a managerial approach in which the entire organization is managed so that it excels in all quality dimensions that are important to customers. The "seven core principles" of TQM and Deming's 14 points illustrate the approach.
- The Six Sigma methodology builds on TQM and makes use of both the TQM philosophy and continuous improvement tools.
- Six Sigma includes *specific* processes for guiding process improvement and new process/product development efforts. The first of these, *DMAIC (Define–Measure–Analyze–Improve–Control)*, outlines the steps that should be followed to improve *existing* business processes. The second, *DMADV (Define–Measure–Analyze–Design–Verify)*, outlines the steps needed to create *completely new* business processes or products. DMAIC is described in Chapter 4; DMADV is discussed in Chapter 15.
- Six Sigma defines specific organizational roles and career paths. We discussed five of them in Chapter 4: champions, master black belts, black belts, green belts, and team members.
- Six Sigma has an expanded tool kit that includes computer simulation, optimization modeling, data mining, and other advanced analytical techniques. Typically, master black belts and black belts provide teams with the expertise required to use these tools.

Put another way, TQM encapsulates the managerial vision behind quality management; Six Sigma builds on this to provide organizations with the processes, people, and tools required to carry out this vision.

5.4 STATISTICAL QUALITY CONTROL

At the start of the chapter, we noted that organizations must:

1. Understand what dimensions of quality are most important to users.
2. Develop products and services that will meet the users' requirements.
3. Put in place business processes capable of meeting the specifications driven by the users' requirements.
4. Verify that the business processes are indeed meeting the specifications.

Statistical quality control (SQC) is directly aimed at the fourth issue—making sure that a business's current processes are meeting the specifications. Simply put, SQC is the application of statistical techniques to quality control. In this section, we describe some popular SQC applications and illustrate how basic statistical concepts can be applied to quality issues.

Process Capability

How does an organization know whether or not its business processes are capable of meeting certain quality standards? One-way organizations do this by comparing the requirements

Process capability ratio (C_p) A mathematical determination of the capability of a process to meet certain quality standards. A $C_p \geq 1$ means the process is capable of meeting the standard being measured.

placed on a process to the actual outputs of the process. One simple measure of process capability is the **process capability ratio (C_p)**:

$$C_p = \frac{UTL - LTL}{6\sigma} \tag{5.1}$$

where:

UTL = upper tolerance limit
LTL = lower tolerance limit
σ = process standard deviation for the variable of interest

Upper tolerance limit (UTL) The highest acceptable value for some measure of interest.

Lower tolerance limit (LTL) The lowest acceptable value for some measure of interest.

The **upper tolerance limit (UTL)** and **lower tolerance limit (LTL)** (sometimes called the upper and lower specification limits) indicate the acceptable range of values for some measure of interest, such as weight, temperature, or time. Engineering, customers, or some other party typically sets UTL and LTL values. In contrast, σ is the standard deviation of the process with regard to the same measure. Because the true value of σ is rarely known, it is typically estimated from a sample of observations. This estimated value, $\hat{\sigma}$, is calculated as follows:

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^{n}(\overline{X} - X_i)^2}{n - 1}} \tag{5.2}$$

where:

$\overline{X}$ = sample mean
X_i = value for the ith observation
n = sample size

Wider tolerance limits and/or smaller values of σ will result in higher C_p values, while narrower tolerance limits and/or larger σ values will have the opposite result. Thus, higher C_p values indicate a more capable process.

To illustrate, suppose that the output values of a process are normally distributed. If this is the case, statistical theory says that individual observations should fall within $\pm 3\sigma$ of the process mean, μ, 99.7% of the time. The normal distribution given in Figure 5.4 illustrates this idea.

Now suppose that the difference between the upper and lower tolerance limits ($UTL - LTL$) just happens to equal 6σ. This suggests that the process is capable of producing within the tolerance limits 99.7% of the time and $C_p = 1$. However, if the tolerance limits are tighter than 6σ, $C_p < 1$ (Figure 5.5).

FIGURE 5.4
Normal Distribution

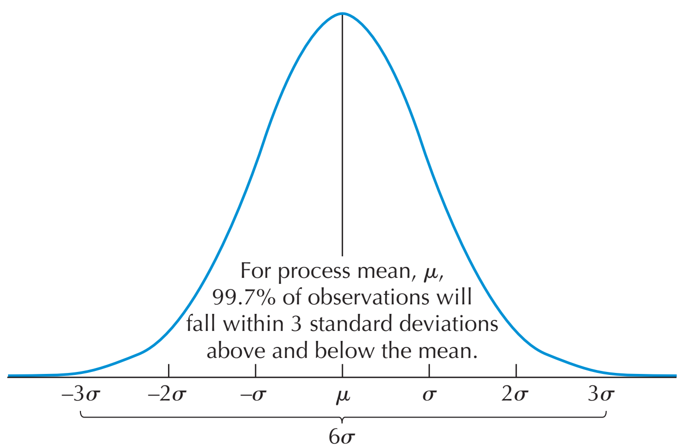
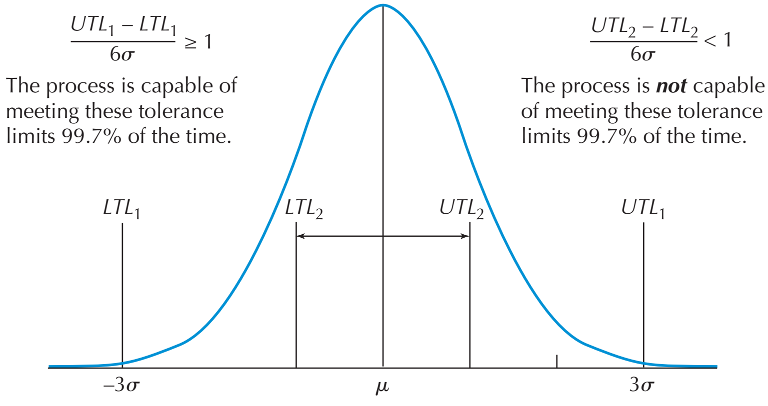


FIGURE 5.5
C_p Values for Different Tolerance Limits



MyLab Operations Management
Animation

Process capability index (C_{pk}) A mathematical determination of the capability of a process to meet certain tolerance limits.

In some cases, the process mean, μ, is not exactly centered on the target value. In this case, we use the **process capability index (C_{pk})** to determine whether the process is capable of meeting the tolerance limits 99.7% of the time:

$$C_{pk} = \min\left[\frac{\mu - LTL}{3\sigma}, \frac{UTL - \mu}{3\sigma}\right] \quad \textbf{(5.3)}$$

where:

μ = process mean
UTL = upper tolerance limit
LTL = lower tolerance limit
σ = standard deviation

EXAMPLE 5.2

Calculating and Interpreting the Process Capability Ratio at Big Bob's Axles

Big Bob's Axles has a customer that requires axles with a diameter of 25 cm $\pm$ 0.02 cm. The customer has stated that Big Bob must be able to meet these requirements 99.7% of the time in order to keep the business. Currently, Big Bob is able to make axles with a process mean of exactly 25 cm and a standard deviation of 0.005 cm. Is Big Bob capable of meeting the customer's needs?

Notice that the *UTL* and *LTL* are 25.02 cm and 24.98 cm, respectively. Therefore, the process capability ratio is:

$$C_p = \frac{UTL - LTL}{6\sigma} = \frac{25.02 - 24.98}{6(0.005)} = \frac{0.04}{0.03} = 1.33$$

Because the process capability ratio is greater than 1, Big Bob's process is more than capable of providing 99.7% defect-free axles.

EXAMPLE 5.3

Calculating and Interpreting the Process Capability Index at Milburn Textiles

Engineers at Milburn Textiles have developed the following specifications for an important dyeing process:

Target value = 140 degrees
Upper tolerance limit (UTL) = 148 degrees
Lower tolerance limit (LTL) = 132 degrees

The *UTL* and *LTL* are based on the engineers' observations that results are acceptable as long as the temperature remains between 132 and 148 degrees. Currently, the dyeing process has a mean temperature of 139.8 degrees, with a standard deviation of 2.14 degrees. Because the process mean is slightly off from the target value of 140 degrees, the quality team uses the process capability index to evaluate the capability of the process:

$$C_{pk} = \min\left(\frac{\mu - LTL}{3\sigma}, \frac{UTL - \mu}{3\sigma}\right)$$
$$= \min\left(\frac{139.8 - 132}{3(2.14)}, \frac{148 - 139.8}{3(2.14)}\right)$$
$$= \min(1.21, 1.28) = 1.21$$

Even with the process mean being off-center, the process is still capable of meeting the tolerance limits more than 99.7% of the time.

Six Sigma Quality

Six Sigma quality
A level of quality that indicates that a process is well controlled. The term is usually associated with Motorola, which named one of its key operational initiatives Six Sigma Quality.

In this book, we have already talked about the Six Sigma methodology; now we turn our attention to the quality measure of the same name. The idea behind **Six Sigma quality** is to reduce the variability of a process to such a point that the process capability ratio is greater than or equal to 2:

$$\text{Six Sigma quality } C_p = \frac{UTL - LTL}{6\sigma} \geq 2$$

Notice that this is the same as squeezing *12* or more standard deviations between the tolerance limits. For a *perfectly* centered process with normally distributed output, this translates into around *2 defects per billion* (Figure 5.6).

In reality, most processes are not perfectly centered, resulting in a higher number of observations falling outside the tolerance limits. Practitioners, therefore, use a working definition of Six Sigma quality that allows for a possible shift in the process mean of ± 1.5 standard deviations. The effect is to increase the allowable defect level to *3.4 defects per million*. Either way, you can begin to see why many firms like the term: Six Sigma quality levels serve as a quantifiable, if far-reaching, objective for many organizations.

EXAMPLE 5.4
Evaluating Six Sigma Quality at Milburn Textiles

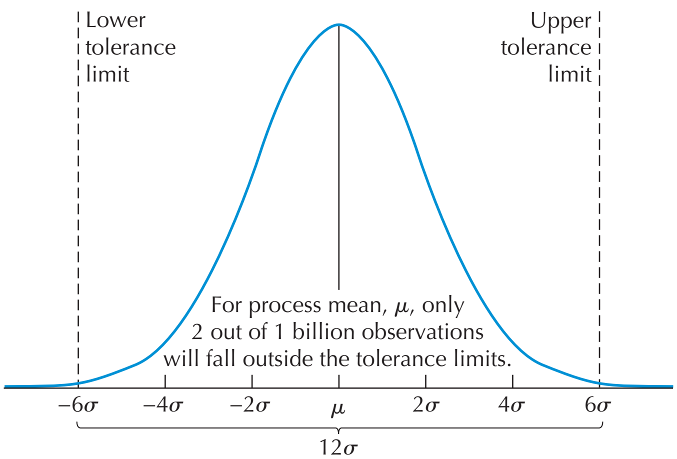
Milburn Textiles has recalibrated its dyeing process so that the process mean is now exactly 140 degrees, with a new, lower standard deviation of 1.40 degrees. Given upper and lower tolerance limits of 148 and 132 degrees, does the dyeing process provide Six Sigma quality levels?

Calculating the process capability ratio gives the following result:

$$C_p = \frac{UTL - LTL}{6\sigma} = \frac{148 - 132}{6(1.40)} = 1.90 < 2$$

Because $C_p < 2$, the process is still not capable of providing Six Sigma quality. To achieve Six Sigma quality, Milburn will have to reduce the standard deviation even further.

FIGURE 5.6
Six Sigma Quality



Control Charts

Control chart
A specialized run chart that helps an organization track changes in key measures over time.

In contrast to the process capability ratio and index, **control charts** are specialized run charts that help organizations track changes in key measures over time. By using control charts, an organization can quickly determine whether a process is "in control" and take action if it is not. Before we describe the different types of control charts in more detail, however, we must first review the concepts of sampling and variable types.

Sampling. The idea behind sampling is that businesses do not have to examine *every* process outcome to assess how well a process is doing. Instead, they can use carefully selected samples to get a fairly good idea of how well a process is working. In fact, control charts are based on samples. In general, a good sample is one in which:

- Every outcome has an equal chance of being selected into the sample. This is typically accomplished by taking a random sample from the entire population.
- The sample size is large enough to not be unduly swayed by any single observation.

Continuous variable
A variable that can be measured along a continuous scale, such as weight, length, height, and temperature.

Attribute
A characteristic of an outcome or item that is accounted for by its presence or absence, such as "defective" versus "good" or "late" versus "on-time."

Sample average ($\overline{X}$)
A key measure that represents the central tendency of a group of samples used in conjunction with range (R).

Range (R)
A key measure that represents the variation of a specific sample group, used in conjunction with sample average ($\overline{X}$).

Variable Types. Most measures of interest fall into one of two types: continuous variables or attributes. **Continuous variables** are variables that can be measured along a continuous scale, such as weight, length, height, or temperature. **Attributes,** in contrast, refer to the presence or absence of a particular characteristic. To illustrate, suppose a pizza delivery chain promises to deliver a "hot, 16-inch, thick crust pizza in 30 minutes or less." The first three variables—temperature, diameter, and thickness—can all be measured on a continuous scale and are, therefore, continuous variables. However, on-time delivery is an attribute. The pizza is either delivered within the allotted time or it isn't.

When firms take samples of a continuous variable, two key measures of interest are the sample average and the range of values. The **sample average ($\overline{X}$)** and the **range (R)** for a continuous variable are defined as follows:

$$\text{Sample average for a continous variable} = \overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \quad \textbf{(5.4)}$$

where:

n = number of observations in the sample

X_i = value of the ith observation

$$\text{Range} = R = (\text{highest value in the sample}) - (\text{lowest value in the sample}) \quad \textbf{(5.5)}$$

The sample average tells us the central tendency for the measure of interest, while the range tells us something about the variation.

Proportion
A measure that refers to the presence or absence of a particular characteristic.

Because attributes refer to the presence or absence of a particular characteristic, the variable of interest is the proportion of the sample with the characteristic. The **proportion** for a sample is calculated as:

$$p = \frac{\sum_{i=1}^{n} a_i}{n} \quad \textbf{(5.6)}$$

where:

n = number of observations in the sample

a_i = 0 if the attribute is not present for the ith observation and 1 if it is

Control limits
The upper and lower limits of a control chart. They are calculated so that if a sample falls inside the control limits, the process is considered in control.

With this background, we can begin to describe control charts in more detail. As we said earlier, control charts are specialized run charts that help organizations track changes in key measures over time. A control chart has a center line showing the expected value for a sample measure, as well as upper and lower control limits. **Control limits** are derived using statistical techniques. They are calculated so that if a sample result falls inside the control limits, the process is considered "in control." If a sample result falls outside the control limits, the process is considered "out of control."

EXAMPLE 5.5

Calculating the Sample Average and Range for a Continuous Variable at DanderNo Shampoo Company

DanderNo Shampoo Company has taken a sample of 15 shampoo bottles and measured the number of ounces in each bottle (Table 5.2).

TABLE 5.2 Sample Results at DanderNo Shampoo Company

SAMPLE OBSERVATION	OUNCES
1	16.41
2	16.12
3	16.57
4	16.88
5	16.86
6	17.02
7	15.85
8	16.43
9	16.83
10	16.17
11	16.29
12	15.99
13	15.95
14	16.21
15	16.27
Sum:	**245.85**

The sample average, $\overline{X}$, is $245.85/15 = 16.39$ ounces. The range, R, is $17.02 - 15.85 = 1.17$.

EXAMPLE 5.6

Estimating the Proportion of Dissatisfied Customers at the Estonia Hotel

The hotel manager at the Estonia Hotel has heard some rumblings that service is "not what it used to be." She would like to estimate the proportion of guests who are dissatisfied with the service they received. To accomplish this, the hotel manager asks a random sample of 100 guests if they were satisfied with their stay. Fourteen of the guests indicate that they were dissatisfied. The hotel manager then assigns a value of 1 to guests who said they were dissatisfied. Therefore, the estimated proportion of the entire population dissatisfied is:

$$p = \frac{14}{100} = 0.14, \text{ or } 14\%$$

In the following sections, we will discuss the development of three different control charts: $\overline{X}$ and R charts (for continuous variables) and p charts (for attributes). Regardless of the variable type, the process for setting up control charts is the same:

1. Take m samples of size n each while the process is in control.
2. Use the sample results to set up the control chart, using the tables or formulas provided.
3. Continue to take samples of size n and plot them against the control charts.
4. Interpret the results and take appropriate action.

We cannot overemphasize two points about control charts. First, control charts *should not* be employed until the process is capable of providing acceptable performance on a regular basis. Second, control charts, by themselves, *will not* result in improved quality levels. Rather, control charts are used to catch quality problems early, before they get out of hand. Therefore, the use of control charts falls under the appraisal activities of a firm's quality efforts (Figures 5.2 and 5.3).

***$\overline{X}$* chart**
A specific type of control chart for a continuous variable that is used to track the average value for future samples.

***R* chart**
A specific type of control chart for a continuous variable that is used to track how much the individual observations within each sample vary.

***$\overline{X}$* and *R* Charts.** For continuous variables, we need two types of control charts. An **$\overline{X}$ chart** is used to track the average value for future samples (Equation [5.5]), while an ***R* chart** is used

TABLE 5.3
Calculations for $\overline{X}$ and R Charts

CHART TYPE	CENTER LINE		CONTROL LIMITS
$\overline{X}$ chart	$\overline{\overline{X}} = \dfrac{\sum_{j=1}^{m} \overline{X}_j}{m}$	(5.7)	($A2$ values are given in Table 5.4)
	where:		
	$\overline{\overline{X}}$ = grand mean		Upper control limit $= UCL_{\overline{X}} = \overline{\overline{X}} + A2(\overline{R})$ **(5.9)**
	m = number of samples used to develop the $\overline{X}$ chart		Lower control limit $= LCL_{\overline{X}} = \overline{\overline{X}} - A2(\overline{R})$ **(5.10)**
	$\overline{X}_j$ average for the jth sample		
R chart	$\overline{R} = \dfrac{\sum_{j=1}^{m} R_j}{m}$	(5.8)	
	where:		($D3$ and $D4$ values are given in Table 5.4)
	$\overline{R}$ = average range		
	m = number of samples used to develop the R chart		Upper control limit $= UCL_R = D4(\overline{R})$ **(5.11)**
	R_j = range for the jth sample		Lower control limit $= LCL_R = D3(\overline{R})$ **(5.12)**

TABLE 5.4
A_2, D_3, and D_4 Values for Developing $\overline{X}$ and R Charts

SAMPLE SIZE *n*	*A2*	*D3*	*D4*
2	1.88	0	3.27
3	1.02	0	2.57
4	0.73	0	2.28
5	0.58	0	2.11
6	0.48	0	2.00
7	0.42	0.08	1.92
8	0.37	0.14	1.86
9	0.34	0.18	1.82
10	0.31	0.22	1.78
11	0.29	0.26	1.74
12	0.27	0.28	1.72

to track how much the individual observations within each sample vary (Equation [5.6]). Table 5.3 summarizes the calculations required to set up these control charts, while Table 5.4 includes values needed to complete the control limit calculations.

EXAMPLE 5.7

Developing and Interpreting $\overline{X}$ and R Charts at Milburn Textiles

A quality team at Milburn Textiles has been charged with setting up control charts to monitor the dyeing process first described in Examples 5.3 and 5.4. Recall that the ideal temperature for the dyeing process is 140 degrees. If the temperature is too high, the fabric will be too dark; if the temperature is too low, streaks can develop. Either condition can ruin large rolls of expensive fabric.

Because temperature is a continuous variable, the quality team decides to set up $\overline{X}$ and R charts to monitor the temperature of the dyeing process. As a first step, the quality team measures the temperature five times a day during a 10-day period. Because these samples are going to be used to set up the control charts, the team makes sure that the process is behaving normally during the 10-day period.

The resulting 10 samples ($m = 10$) of 5 observations each ($n = 5$) are shown in Table 5.5.

TABLE 5.5 Sample Temperature Results for the Dyeing Process

	OBSERVATION				
DAY	**1**	**2**	**3**	**4**	**5**
1	136	137	144	141	138
2	143	138	140	140	139
3	140	141	144	137	135
4	139	140	141	139	141
5	137	138	143	140	138
6	142	141	140	139	138
7	143	141	143	140	140
8	139	139	141	140	136
9	140	138	143	141	139
10	139	141	142	140	136

The team calculates $\overline{X}$ and R values for each of the 10 samples and then takes the average values across all samples to calculate $\overline{\overline{X}}$ and $\overline{R}$ (Table 5.6):

TABLE 5.6 Calculating $\overline{X}$, R, $\overline{\overline{X}}$, and $\overline{R}$ Values for the Dyeing Process

	OBSERVATION ($n = 5$)						
DAY	**1**	**2**	**3**	**4**	**5**	$\overline{X}$	R
1	136	137	144	141	138	139.2	8
2	143	138	140	140	139	140.0	5
3	140	141	144	137	135	139.4	9
4	139	140	141	139	141	140.0	2
5	137	138	143	140	138	139.2	6
6	142	141	140	139	138	140.0	4
7	143	141	143	140	140	141.4	3
8	139	139	141	140	136	139.0	5
9	140	138	143	141	139	140.2	5
10	139	141	142	140	136	139.6	6
					Sum	**1,398**	**53**

Note that the $A2$, $D3$, and $D4$ values have been specifically calibrated so that there is a 99.7% chance that future sample $\overline{X}$ and R values will plot within the control limits, *but only if the true mean and standard deviation have not changed*. Put another way, as long as the dyeing process temperature behaves as it has in the past, there is only a 0.3% probability that either the $\overline{X}$ or the R result for a future sample will fall outside these limits.

$$\overline{\overline{X}} = \frac{1{,}398}{10} = 139.8 \text{ degrees} \qquad \overline{R} = \frac{53}{10} = 5.3 \text{ degrees}$$

The team then calculates the upper and lower control limits for the $\overline{X}$ and R charts by selecting the $A2$, $D3$, and $D4$ values corresponding to samples of five observations each (Table 5.4). The resulting control charts are shown in Figure 5.7.

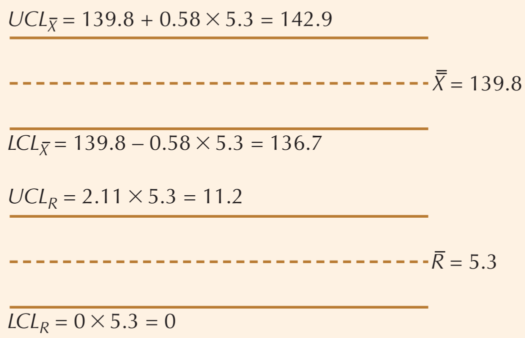


FIGURE 5.7 Blank Control Charts for the Dyeing Process

Therefore, if an $\bar{X}$ or R value *does* fall outside the control limits, the quality team can assume one of two things:

1. The process has not changed, and the result is simply a random, albeit highly unlikely outcome.
2. The process has indeed shifted.

Either way, the team should investigate further. After setting up the control charts, the quality team continues to take samples, following the same routine as before. Sample results for the next six days are shown in Figure 5.8.

Sample Results (n = 5)		
Day	$\bar{X}$	R
11	141.2	8
12	142.0	9
13	144.0	12
14	140.0	5
15	139.6	4
16	140.8	5

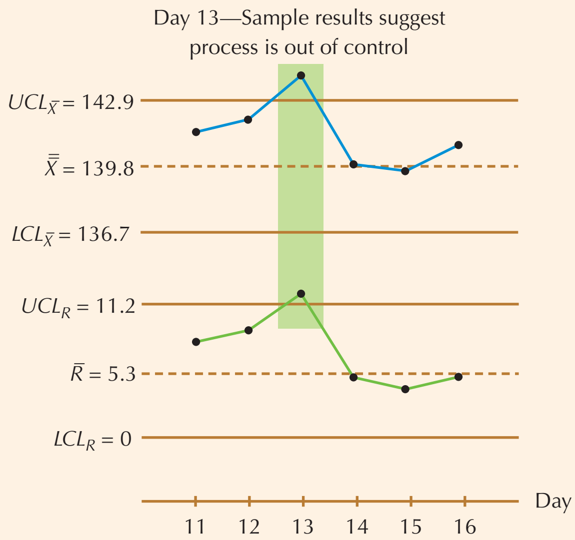


FIGURE 5.8 Control Chart Results for Days 11 through 16

MyLab Operations Management
Animation

On day 13, both the $\bar{X}$ and R values fall outside the control limits. Because it is highly unlikely that this occurred due to random chance, the quality team immediately shuts down the process to determine the cause. After replacing a faulty thermostat, the process starts back up. The results for days 14 through 16 suggest that the dyeing process is again functioning normally. By catching the temperature problem early, the quality team is able to take corrective action before the problem gets out of hand.

***p* chart**
A specific type of control chart for attributes that is used to track sample proportions.

***p* Charts.** When the measure of interest is an attribute, firms use ***p* charts** to track the sample proportions. As with $\bar{X}$ and R charts, a p chart has upper and lower control limits. If a sample p value falls outside these limits, management should immediately investigate to determine whether or not the underlying process has somehow changed. Table 5.7 describes the key calculations for developing a p chart.

TABLE 5.7 Calculations for *p* Charts

CENTER LINE	CONTROL LIMITS
Average p value across multiple samples: $$\bar{p} = \frac{\sum_{j=1}^{m} p_j}{m} \quad (5.13)$$	Upper control limit $= UCL_p = \bar{p} + 3(S_p)$ **(5.14)** Lower control limit $= LCL_p = \bar{p} - 3(S_p)$ **(5.15)**
Where $p_j = p$ for the jth sample $m =$ number of samples used to develop the control chart	where $S_p =$ standard deviation for attribute samples and $$S_p = \sqrt{\frac{(\bar{p})(1-\bar{p})}{n}} \quad (5.16)$$ where: $n =$ size of each sample

EXAMPLE 5.8

Developing and Interpreting *p* Charts at Gonzo's Pizzas

Since on-time delivery is a key order winner in the pizza business, the manager of Gonzo's Pizzas has decided to set up a control chart to track the proportion of deliveries that take longer than 30 minutes. The manager's first step is to take some samples of deliveries when things are working normally. As a general rule, when sampling by attribute, the sample size (n) should be large enough that:

$$\text{Min}\left[n(p), n(1-p)\right] \geq 5 \quad \textbf{(5.17)}$$

Sample Results ($n = 50$)

DAY	*p*
1	0.16
2	0.20
3	0.00
4	0.14
5	0.10
6	0.20
7	0.10
8	0.06
9	0.14
10	0.16
11	0.00
12	0.04
13	0.00
14	0.10
15	0.10
Sum	**1.50**

So if Gonzo's manager expects 10% of the pizzas to be late, he should choose a sample size of at least 50 observations ($50{*}0.10 = 5$), with an even larger sample size being preferable. Suppose then that the manager takes samples of 50 deliveries each ($n = 50$) over the next 15 days ($m = 15$).

The manager is careful to select these deliveries at random in order to ensure that the sample data are representative of his business. The resulting p and $\bar{p}$ values for the 15 samples are:

$$\bar{p} = \frac{1.50}{15} = 0.10 \quad S_p = \sqrt{\frac{(\bar{p})(1-\bar{p})}{n}} = 0.042$$

Based on the results of his first 15 samples, the Gonzo's manager sets up the control chart as follows:

$$UCL_p = 0.10 + 3 \times 0.042 = 0.226$$

$$\bar{p} = 0.10$$

$$LCL_p = 0.10 - 3 \times 0.042 = -0.026, \text{ or } 0$$

Like those for the $\bar{X}$ and R charts, the formulas for the p chart are set up so that sample p values should fall within the control limits 99.7% of the time, but *only if* the process itself has not changed. Note in this example that the *calculated* lower control limit calculation is actually negative. Because a negative p value is meaningless (Would this mean pizzas were delivered before they were ordered?), the lower control limit is effectively 0.

As long as the percentage of late deliveries in a sample stays below 22.6%, the Gonzo's manager can assume that the process is behaving normally. However, the Gonzo's manager might not be pleased with this definition of "normal." Indeed, he might decide to add more drivers or even shrink the store's delivery area in an effort to improve the proportion of on-time deliveries. If he takes any of these measures, the Gonzo's manager will need to recalculate the control charts based on the new *p* value.


Stephen Coburn/Shutterstock

p *charts are ideal for tracking the on-time performance of a pizza delivery service.*

As the preceding discussion suggests, results that fall outside the control limits might or might not signal trouble. Even so, it is highly unlikely that a sample $\overline{X}$, R, or p value will fall outside the control limits unless something about the process has indeed changed.

There are also patterns *within the control limits* that should be investigated. Two consecutive sample values near one of the control limits could indicate a process that is about to go out of control. Similarly, a run of five or more points on either side of the center line should be investigated, as should a definite upward or downward trend in the measures. The point is that managers do not have to wait until a sample point falls outside the control limits before taking action.

Acceptance Sampling

Even under the best circumstances, defects can occur and be sent on to the customer. Companies must, therefore, have some way to determine whether an incoming lot of material or products is of acceptable quality and to take action based on the results. One way to determine the quality levels is through 100% inspection (i.e., inspection of each and every item). While this may be necessary in some critical circumstances (e.g., donated blood), it has drawbacks.

First, 100% inspection can be extremely expensive and time-consuming, especially if there are hundreds or even thousands of items to inspect. Moreover, some quality inspection requires that goods be destroyed or otherwise used up in order to be tested. Wooden matches are a good example. When 100% inspection is not an option, companies depend on acceptance sampling to determine whether an incoming lot of items meets specifications. APICS defines **acceptance sampling** as "the process of sampling a portion of goods for inspection rather than examining the entire lot. The entire lot may be accepted or rejected based on the sample even though the specific units in the lot are better or worse than the sample."[7]

Acceptance sampling
According to APICS, "The process of sampling a portion of goods for inspection rather than examining the entire lot."

In the following example, we illustrate how acceptance sampling works and define OC curves, producer's risk, and consumer's risk.

[7]J. H. Blackstone, ed., *APICS Dictionary*, 15th ed. (Chicago, IL: APICS, 2016).

EXAMPLE 5.9

Acceptance Sampling at Chapman Industries

Acceptable quality level (AQL)
A term used in acceptance sampling to indicate a cut-off value that represents the maximum defect level at which a consumer would always accept a lot.

Lot tolerance percent defective (LTPD)
A term used in acceptance sampling to indicate the highest defect level a consumer is willing to "tolerate."

Consumer's risk (β)
A term used in acceptance sampling to indicate the probability of accepting a lot with quality worse than the LTPD level.

Producer's risk (α)
A term used in acceptance sampling to indicate the probability of rejecting a lot with quality better than the AQL level.

Operating characteristics (OC) curve
A curve used in acceptance sampling to show the probability of accepting a lot, given the actual fraction defective in the entire lot and the sampling plan being used. Different sampling plans will result in different OC curves.

Chapman Industries has received a shipment of 5,000 parts, each of which can be categorized as "good" or "defective." Rather than inspect all 5,000 parts, Chapman would like to make a decision based on a randomly selected sample of 10 parts ($n = 10$). If more than 1 part is found to be defective ($c = 1$), Chapman will reject the entire lot.

In addition, Chapman would like to accept all lots with a defect rate ≤5%. This is known as the **acceptable quality level (AQL).** However, because Chapman will be making its decision based on a small sample of parts, there is always the possibility that the company will accidentally accept a lot with a much higher defect level. After much debate, management has agreed to risk accepting lots with defect levels as high as 30%. This upper limit is referred to as the **lot tolerance percent defective (LTPD).**

Using random samples to make decisions about an entire lot has risks. On the one hand, Chapman may accept a lot that is even worse than the LTPD level. The probability of this occurring is called the **consumer's risk (β).** On the other hand, Chapman may actually reject a lot that meets its AQL. The probability of this outcome is known as the **producer's risk (α).**

Figures 5.9 and 5.10 illustrate these concepts. Under 100% inspection, the probability of accepting a "good" lot (defect level of 5% or less) is 100%, while the probability of accepting a bad lot is 0%. In contrast, the **operating characteristics (OC) curve** in Figure 5.9 shows the probability of accepting a lot, given the *actual* fraction defective in the entire lot and the sampling plan being used ($n = 10, c = 1$). It is important to note that different n and c values will result in differently shaped curves.[8]

According to the OC curve in Figure 5.9, there is an 80% chance that Chapman will accept a lot that is 90% defect-free but only a 5% chance that it will accept a lot that is around 40% defect-free. Figure 5.10 shows the actual producer's risks and consumer's risks faced by

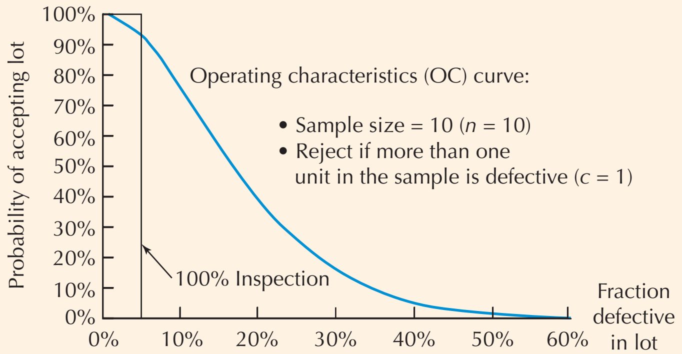


FIGURE 5.9 OC Curve for Chapman Industries

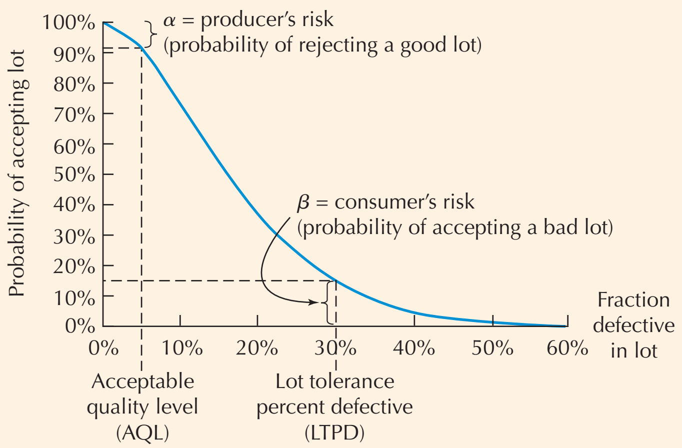


FIGURE 5.10 Producer's and Consumer's Risk

[8] A. J. Duncan, *Quality Control and Industrial Statistics*, 5th ed. (Homewood, IL: Irwin, 1986), pp. 214–48.

Chapman under the current sampling plan. Specifically, for an AQL of 5%, the probability of rejecting a good lot (producer's risk) is around 8%. More importantly from Chapman's perspective, the probability of accepting a lot that doesn't meet Chapman's LTPD level (consumer's risk) is approximately 15%.

What can Chapman do to reduce these risks? In Figure 5.11, we show a new OC curve based on a sample plan that calls for a sample size of 20 ($n = 20$) and $c = 2$. Because the larger sample size is more representative of the entire lot and less likely to be overly influenced by a single observation, the result is a steeper OC curve, which lowers both the consumer's risk and the producer's risk. In fact, under the new OC curve, producer's risk drops to around 7%, and consumer's risk falls dramatically, to less than 5%. This highlights a general rule about acceptance sampling: The larger the sample size, the lower the producer's and consumer's risks. Of course, this greater accuracy must be balanced against the increased sampling costs.

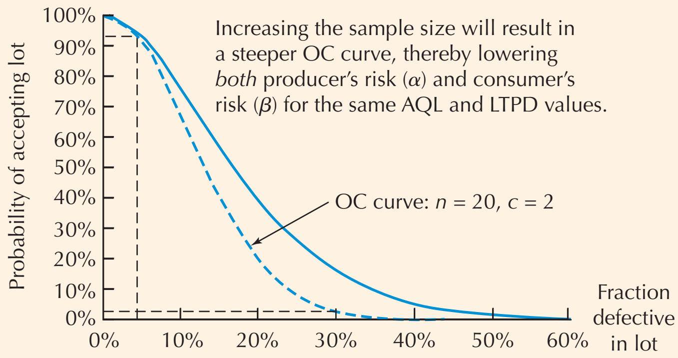


FIGURE 5.11 **New OC Curve Based on New Sampling Plan**

Taguchi's Quality Loss Function

As you read through the previous sections, you may have thought to yourself, "Is a unit slightly within tolerances really of better quality than one just outside the tolerances?" After all, in Example 5.2, an axle with a diameter of 25.019 cm (within tolerances) is only slightly narrower than one with a diameter of 25.021 cm, and both are larger than the target value of 25 cm.

In fact, upper and lower tolerance limits are really just convenient fictions. If we were to take tolerance limits at face value, we would have to assume that there is no failure cost associated with units that fall within the tolerance limits, while units outside the tolerance limits immediately result in failure costs (Figure 5.12).

The reality is that the quality of any good or service starts to fall off as soon as the measure of interest drifts from the target value. Examples abound:

- The temperature of a cup of coffee
- The length of a pair of pants
- The amount of medicine in a capsule

Taguchi's quality loss function, shown in Figure 5.13, reflects the idea that any deviation from the target value results in some failure cost. The parabolic shape suggests that these costs

FIGURE 5.12 **Implied Failure Costs Associated with Tolerance Limits**

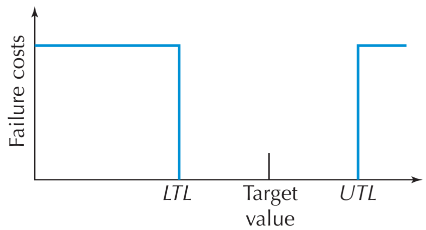
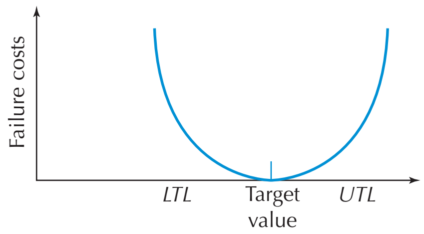


FIGURE 5.13
Taguchi's Quality Loss Function



start to accrue as soon as there is any deviation from the target and that they grow exponentially as actual results drift even farther away.

Why do we mention Taguchi's quality loss function? First, it supports the continuous improvement philosophy we described earlier in the chapter. Figure 5.13 suggests that as long as there is *any* variability in the process, there is room for improvement. Taguchi's quality loss function is also consistent with our description of the total costs of quality: Failure costs do not disappear completely until the defect level is zero.

5.5 MANAGING QUALITY ACROSS THE SUPPLY CHAIN

So far, much of our attention has been devoted to managing and improving the quality of processes, products, and services within an organization. But the interdependent nature of supply chains suggests that quality management must extend beyond the four walls of an organization. In this section, we talk about two ways in which organizations manage quality across the supply chain. The first, ISO 9000, is a highly successful program that has helped spread quality management practices worldwide. Companies seek ISO 9000 certification both as a way to proactively address quality issues and as a way to signal to potential supply chain partners that they are serious about managing quality. Then we consider how companies deal with external failures in the supply chain.

ISO 9000 Family

ISO 9000
A family of standards, supported by the International Organization for Standardization, representing an international consensus on good quality management practices. ISO 9000 addresses business processes rather than specific outcomes.

Supported by the International Organization for Standardization (ISO), **ISO 9000** is a family of standards that represents an international consensus on good management practices. ISO 9000 seeks to help organizations deliver products or services that simultaneously:

- Meet the customer's quality requirements.
- Satisfy regulatory requirements, while aiming to
- Enhance customer satisfaction.
- Achieve continual improvement of the organization's performance in pursuit of these objectives.[9]

Unlike traditional standards, ISO 9000 focuses more on practices than outcomes. Companies following ISO 9000 standards will often have independent auditors "certify" that their business processes are ISO 9000 compliant. In some industries, certification is a requirement for doing business, and industry-specific standards may also apply. In others, ISO 9000 may simply signal potential supply chain partners that an organization has quality systems in place.

Since 1987, the ISO 9000 family of standards has been regularly updated to reflect developments in managerial thought. For example, ISO 9001:2015 is used by companies seeking to establish a quality management system that provides confidence in the conformance of their products and services to established or specified requirements. ISO 9004:2009 is used to extend the benefits obtained from ISO 9001 to all parties that are interested in or affected by a particular business's operations. The International Organization for Standardization has even used ISO 9001 as the basis for developing standards for specific industries, including petrochemical products, medical devices, and software engineering.

[9]International Organization for Standardization, **www.iso.org/iso-9001-quality-management.html.**

External Failures in the Supply Chain

Even with the best quality programs, companies still need to put in place processes to catch defective products once they have left the organization and entered the supply chain. How quickly and effectively companies handle this can have a great impact on the resulting external failure costs. Tracking systems, lot identification numbers, and explicit procedures for returning or destroying defective (and potentially harmful) goods are all examples of solutions that are used to deal with such problems. In *Supply Chain Connections*, we consider how one pharmaceutical firm dealt with the potential problems caused by mislabeled drugs.

SUPPLY CHAIN CONNECTIONS

REMOVING MISLABELED DRUGS FROM THE SUPPLY CHAIN

In May 2004, McNeil Consumer & Specialty Pharmaceuticals realized that it had made a serious mistake: It had accidentally put Adult-Strength Tylenol in bottles meant to hold Children's Motrin. What made this mistake especially worrisome is that the bottles had been released into the supply chain. In an effort to help retailers and consumers track down the defective bottles before anyone was seriously injured, McNeil released a notice that was listed on the Food and Drug Administration (FDA) Web site. The notice gave information regarding:

- The manufacturing lots affected (information readily found on the carton)
- The dates the bottles were distributed
- The visible differences between the two drugs (specifically, Children's Motrin Grape Chewable Tablets are round, purple-colored, scored tablets that have a grape smell, while the Tylenol 8-Hour Geltabs are hard, round, gelatin coated, and shiny)
- A contact number for anyone finding a bottle or having a question

Through its quick actions, McNeil hoped to minimize any injuries. Clearly, McNeil's job would have been much more difficult if it had not kept track of the manufacturing lot numbers or the shipping dates for the bottles in question.

CHAPTER SUMMARY

As an area of intense business interest, quality is here to stay. Operations and supply chain personnel in particular need to be familiar with the major quality topic areas, including the different philosophical perspectives on quality and the tools used to manage quality levels on a day-to-day basis. In this chapter, we gave you a solid introduction to quality topics, ranging from high-level discussions of quality issues to detailed descriptions of tools and techniques. We started by defining quality and describing a total cost of quality model. We then presented an overview of total quality management (TQM), as well as a section on statistical quality control (SQC). We ended the chapter with a discussion of how organizations manage quality across the supply chain and some of the issues they face.

We encourage you not to let your quality education end here. The American Society for Quality **(www.asq.org)**, the Juran Institute **(www.juran.com)**, the W. Edwards Deming Institute **(www.deming.org)**, and the ISO **(www.iso.org)** are four organizations that provide a wealth of information for those interested in quality. Regardless of what you do, you can be assured that you will deal with quality issues in your career.

KEY FORMULAS

Process capability ratio (page 118):

$$C_p = \frac{UTL - LTL}{6\sigma} \tag{5.1}$$

where:

UTL = upper tolerance limit
LTL = lower tolerance limit
σ = process standard deviation for the variable of interest

Estimated process standard deviation for the variable of interest (page 118):

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^{n}(\overline{X} - X_i)^2}{n - 1}} \tag{5.2}$$

where:

$\overline{X}$ = sample mean
X_i = value for the ith observation
n = sample size

Process capability index (page 119):

$$C_{pk} = \min\left[\frac{\mu - LTL}{3\sigma}, \frac{UTL - \mu}{3\sigma}\right] \tag{5.3}$$

where:

μ = process mean
UTL = upper tolerance limit
LTL = lower tolerance limit
σ = standard deviation

Sample average for a continuous variable (page 121):

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{5.4}$$

where:

n = number of observations in the sample
X_i = value of the ith observation

Sample range (R) for a continuous variable (page 121):

$$R = (\text{highest value in the sample}) - (\text{lowest value in the sample}) \tag{5.5}$$

Sample proportion (page 121):

$$p = \frac{\sum_{i=1}^{n} a_i}{n} \tag{5.6}$$

where:

n = number of observations in the sample
a_i = 0 if the attribute is not present for the ith observation and 1 if it is

Average sample mean for a continuous variable (page 123):

$$\overline{\overline{X}} = \frac{\sum_{j=1}^{m} \overline{X}_j}{m} \tag{5.7}$$

where:

$\overline{\overline{X}}$ = grand mean
m = number of samples used to develop the $\overline{X}$ chart
$\overline{X}_j$ = Average for the jth sample

Average range value for samples of a continuous variable (page 123):

$$\overline{R} = \frac{\sum_{j=1}^{m} R_j}{m} \tag{5.8}$$

where:

m = number of samples used to develop the control charts
R_j = range for the jth sample

Upper control limit for *p* chart (page 123):

$$\text{Upper control limit} = UCL_{\overline{X}} = \overline{X} + A2(\overline{R}) \tag{5.9}$$

Lower control limit for *p* chart (page 123):

$$\text{Lower control limit} = LCL_{\overline{X}} = \overline{X} - A2(\overline{R}) \tag{5.10}$$

Upper control limit for *R* chart (page 123):

$$\text{Upper control limit} = UCL_R = D4(\overline{R}) \tag{5.11}$$

Lower control limit for *R* chart (page 123):

$$\text{Lower control limit} = LCL_R = D3(\overline{R}) \tag{5.12}$$

Average sample proportion for an attribute (page 126):

$$\overline{p} = \frac{\sum_{j=1}^{m} p_j}{m} \tag{5.13}$$

where:

p_j = p value for the jth sample

m = number of samples used to develop the control chart

Upper control limit for *p* chart (page 126):

$$\text{Upper control limit} = UCL_P = \overline{p} + 3(S_p) \tag{5.14}$$

Lower control limit for *p* chart (page 126):

$$\text{Lower control limit} = LCL_P = \overline{p} - 3(S_p) \tag{5.15}$$

where:

S_p = standard deviation for attribute samples

Standard deviation for attribute samples (page 126):

$$S_p = \sqrt{\frac{(\overline{p})(1 - \overline{p})}{n}} \tag{5.16}$$

where:

n = size of each sample

$$\text{Min}[n(p), n(1 - p)] \geq 5 \tag{5.17}$$

KEY TERMS

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Acceptance sampling 127
Appraisal costs 113
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Conformance perspective 111
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USING EXCEL IN QUALITY MANAGEMENT

Spreadsheet applications such as Microsoft Excel are ideally suited to performing the large numbers of calculations needed to support statistical quality control efforts. The following spreadsheet calculates the average sample proportion and standard deviation for 30 samples. (The sample results are arranged in two columns to save space.) The highlighted cells represent the input values. The calculated cells are as follows:

Cell D23
(average sample proportion): = AVERAGE (*B7:C21*)/C4
Cell D24 (standard deviation): = SQRT(D23*(1 − D23)/C4)

	A	B	C	D	E	F	G
1	**Calculating the average sample proportion from 30 samples**						
2	**and standard deviation, S_p, from 30 samples**						
3							
4	Sample size:		150				
5							
6	***No. of observations in each sample displaying the attribute***						
7		17	13				
8		10	10				
9		13	20				
10		12	6				
11		16	16				
12		17	21				
13		16	6				
14		13	10				
15		13	3				
16		12	10				
17		13	13				
18		12	7				
19		13	16				
20		10	16				
21		12	14				
22							
23	**Average sample proportion:**			**0.08444**			
24	**Standard deviation, S_p:**			**0.0227**			
25							

SOLVED PROBLEM

PROBLEM

Pulley Engineering

Pulley Engineering manufactures needle bearings for use in high-tech machinery. The target diameter for one particular bearing is 0.125 inches. The quality control staff has taken 15 samples of five observations each with the manufacturing processes under control and has measured the diameter. The results are as follows:

	OBSERVATION				
SAMPLE	**1**	**2**	**3**	**4**	**5**
1	0.1253	0.1262	0.1254	0.1240	0.1230
2	0.1242	0.1247	0.1251	0.1238	0.1241
3	0.1225	0.1258	0.1229	0.1242	0.1255
4	0.1249	0.1259	0.1249	0.1240	0.1257
5	0.1245	0.1252	0.1261	0.1238	0.1225
6	0.1273	0.1234	0.1248	0.1241	0.1260
7	0.1226	0.1239	0.1227	0.1252	0.1259
8	0.1244	0.1238	0.1254	0.1261	0.1260
9	0.1236	0.1262	0.1250	0.1247	0.1250
10	0.1251	0.1264	0.1233	0.1233	0.1246
11	0.1253	0.1248	0.1237	0.1252	0.1226
12	0.1232	0.1251	0.1259	0.1263	0.1257
13	0.1231	0.1242	0.1256	0.1252	0.1257
14	0.1256	0.1240	0.1246	0.1250	0.1252
15	0.1243	0.1240	0.1239	0.1262	0.1246

Use these data to develop control limits for the $\overline{X}$ and R charts. In addition, suppose that engineering has established upper and lower tolerance limits of 0.129 inches and 0.121 inches, respectively. Calculate the process capability ratio and interpret the results.

Solution

The first step is to calculate the $\overline{X}$ and R values for each sample and then the $\overline{\overline{X}}$ and $\overline{R}$ values:

	OBSERVATION						
SAMPLE	**1**	**2**	**3**	**4**	**5**	$\overline{X}$	R
1	0.1253	0.1262	0.1254	0.1240	0.1230	0.1248	0.0032
2	0.1242	0.1247	0.1251	0.1238	0.1241	0.1244	0.0013
3	0.1225	0.1258	0.1229	0.1242	0.1255	0.1242	0.0033
4	0.1249	0.1259	0.1249	0.1240	0.1257	0.1251	0.0018
5	0.1245	0.1252	0.1261	0.1238	0.1225	0.1244	0.0036
6	0.1273	0.1234	0.1248	0.1241	0.1260	0.1251	0.0039
7	0.1226	0.1239	0.1227	0.1252	0.1259	0.1241	0.0032
8	0.1244	0.1238	0.1254	0.1261	0.1260	0.1251	0.0024
9	0.1236	0.1262	0.1250	0.1247	0.1250	0.1249	0.0026
10	0.1251	0.1264	0.1233	0.1233	0.1246	0.1246	0.0031
11	0.1253	0.1248	0.1237	0.1252	0.1226	0.1243	0.0027
12	0.1232	0.1251	0.1259	0.1263	0.1257	0.1252	0.0031
13	0.1231	0.1242	0.1256	0.1252	0.1257	0.1248	0.0026
14	0.1256	0.1240	0.1246	0.1250	0.1252	0.1249	0.0016
15	0.1243	0.1240	0.1239	0.1262	0.1246	0.1246	0.0023
					Average:	**0.1247**	**0.0027**

Combining these results with the appropriate $A2$, $D3$, and $D4$ values from Table 5.4 yields the following control chart limits:

$$UCL_{\overline{X}} = 0.1247 + 0.58*0.0027 = 0.1263$$
$$LCL_{\overline{X}} = 0.1247 - 0.58*0.0027 = 0.1231$$

$$UCL_R = 2.11*0.0027 = 0.0057$$
$$LCL_R = 0*0.0027 = 0$$

To calculate the process capability ratio, we must first estimate the standard deviation of the individual observations, $\hat{\sigma}$. We can quickly do this by using the = STDEV(number1, number2, …) function of Microsoft Excel, where the values in parentheses represent the raw diameter measurements. Doing so results in the following estimate:

$$\hat{\sigma} = 0.0011$$

Therefore, the process capability ratio is

$$C_p = \frac{0.129 - 0.121}{6(0.0011)} = \frac{0.008}{0.0066} = 1.21$$

The results suggest that the current process is capable of meeting the tolerance limits more than 99.7% of the time.

DISCUSSION QUESTIONS

1. What costs of quality were highlighted in the opening case study? How can Delta Air Lines justify spending $100 million to reengineer the baggage-handling process at just one airport?
2. Why can two people perceive the same product or service as having different quality levels? From a business perspective, why is it important, then, to "know your customer"?
3. Several years ago, a major automotive manufacturer was sued because the latch on a minivan's rear door failed after the vehicle was hit from the side at 30 miles per hour. The plaintiff argued that the latch was of poor quality

because it didn't hold up under the stress. The manufacturer disagreed, noting that the latch had met all government requirements and had been made to specifications. According to our definition of quality, can both sides be right?

4. Recall the DMAIC process described in Chapter 4. At what stage would statistical quality control tools be used?

5. Suppose that the actual range for a sample falls *below* the lower control limit for the *R* chart? Is this a good thing or a bad thing? Explain.

PROBLEMS

Additional homework problems are available at www.pearsonhighered.com/bozarth. These problems use Excel to generate customized problems for different class sections or even different students.

(* = easy; ** = moderate; *** = advanced)

Problems for Section 5.4: Statistical Quality Control

1. (*) Tyler Apiaries sells bees and beekeeping supplies. Bees (including a queen) are shipped in special packages according to weight. The target weight of a package is 1.4 kg. Historically, Tyler's shipments have weighed on average 1.4 kg, with a standard deviation of 0.15 kg.

a. (*) Calculate the process capability ratio, assuming that the lower and upper tolerance limits are 1.1 kg and 1.7 kg, respectively. Is Tyler Apiaries currently able to meet the tolerance limits 99.7% of the time?

b. (**) What would the standard deviation have to be for Tyler Apiaries to achieve Six Sigma quality levels with regard to the weight of the bee packages?

c. (**) The average bee weighs 0.1 grams. Use this information to convert the target package weight and tolerance limits into number of bees for Tyler Apiaries. How might the company use this information to better control the package weights? Should Tyler Apiaries think about resetting the tolerance limits?

2. (*) Tyler Apiaries sells bees and beekeeping supplies. Bees (including a queen) are shipped in special packages according to weight. Suppose Tyler changes its processes so that the average package weight is now 1.5 kg, with a new standard deviation of 0.2 kg. Tyler markets the packages of bees as weighing 1.4 kg, and the tolerance limits remain as before. Calculate the process capability index for the weight of the bee packages. Is Tyler able to meet the tolerance limits?

3. (*) Leah's Toys produces molded plastic baby rattles. These rattles must be completely smooth. That is, there can be no rough edges where the molded halves fit together. Rattles are judged to be either acceptable or defective with regard to this requirement. Leah's has determined that the current process has an underlying *p* value of 0.01, meaning that, on average, 1 out of 100 rattles is currently judged to be defective. Calculate the standard deviation for the process and the resulting control limits for samples of 200 rattles each.

4. Leah's Toys makes rubber balls. The current process is capable of producing balls that weigh, on average, 3 ounces, with a standard deviation of 0.25 ounces.

a. (*) What is the process capability ratio, assuming upper and lower tolerance limits of 3.5 and 2.5 ounces? Is Leah's able to meet the tolerance limits 99.7% of the time? Explain.

b. (**) What would the standard deviation have to be to *exactly* meet the tolerance limits 99.7% of the time?

c. (**) Suppose Leah's Toys invests in process improvements that lower the standard deviation to just 0.10 ounces. Is this enough for Leah's to achieve Six Sigma quality levels with regard to the weight of the balls? Explain.

5. Leah's Toys guarantees to ship customer orders in 24 hours or less. The following chart contains results for five samples of nine customer orders each:

SAMPLE	SAMPLE CUSTOMER ORDERS (HOURS TO SHIP)								
1	3	5	21	4	15	9	7	3	6
2	22	16	8	16	11	38	11	25	15
3	9	2	5	17	2	19	4	2	4
4	6	7	18	9	16	18	7	10	1
5	11	10	20	18	1	6	3	18	9

a. (**) Based on these results, estimate the $\bar{p}$ and S_p values.

b. (**) A student comments, "Time is a continuous variable. We should really be looking at the $\bar{\bar{X}}$ and $\bar{R}$ values." Do you agree or disagree? Explain your rationale.

6. BlueBolt Bottlers has a bottle-filling process with a mean value of 64 ounces and a standard deviation of 8 ounces.

a. (**) Suppose that the upper and lower tolerance limits are 71 and 57 ounces, respectively. What is the process capability ratio? What would the standard deviation have to be in order for the process to meet the tolerance limits 99.7% of the time?

b. (***) Now suppose BlueBolt Bottlers makes some process improvements, thereby lowering the standard deviation of the process to 1.5 ounces, rather than 8 ounces. Using the data in problem 10 and the new standard deviation, calculate the process capability ratio. Is the filling process able to meet the tolerance limits 99.7% of the time? Does the process provide Six Sigma quality levels? Explain.

7. (*) The River Rock Company sells 200-pound bags of decorative rocks for landscaping use. The current bagging process yields samples with $\bar{\bar{X}}$ and $\bar{R}$ values of 200 pounds and 12 pounds, respectively. Each sample consists of 12 observations. Develop the appropriate control charts.

8. (**) LaBoing produces springs, which are categorized as either acceptable or defective. During a period in which the manufacturing processes are under control, LaBoing takes multiple samples of 100 springs each, resulting in a calculated $\bar{p}$ value of 0.07. Develop the appropriate control chart for the springs.

9. AnderSet Laboratories produces rough lenses that will ultimately be ground into precision lenses for use in laboratory equipment. The company has developed the following thickness measures, based on 15 samples of four lenses that were taken when the process was under control:

MEAN (MICRONS) (n = 4)	MINIMUM	MAXIMUM
3.900	3.617	3.989
4.206	3.971	4.302
4.214	4.062	4.400
3.890	3.749	3.937
4.036	3.501	4.084
4.134	3.543	4.584
3.037	2.935	3.929
5.082	3.797	5.695
3.404	2.837	4.255
5.246	5.106	6.382
4.197	4.085	4.239
4.312	3.949	4.356
4.302	3.989	4.400
3.867	3.617	3.900
4.170	4.046	4.206

a. (**) Use these data to calculate $\bar{\bar{X}}$ and $\bar{R}$ and set up the appropriate control charts.

b. (**) Can the process be "under control" in statistical terms but still fail to meet the needs of AnderSet's customers? Explain, using a numerical example.

c. (**) Suppose AnderSet Laboratories takes some additional samples of the same size, yielding the following results. Plot these samples on the control charts and circle any observations that appear to be out of control.

MEAN (MICRONS) (n = 4)	MINIMUM	MAXIMUM
4.134	4.011	4.612
3.913	3.891	4.474
4.584	4.499	5.145
4.009	3.934	4.891
4.612	4.085	4.983
5.627	5.183	6.080

10. (**) Lazy B Ranch produces leather hides for use in the furniture and automotive upholstery industry. The company has taken 10 samples of nine observations each, measuring the square footage of each hide. Summary data are as follows:

MEAN (SQ FT) (n = 9)	MINIMUM	MAXIMUM
13.2	12.7	13.5
12.8	12.5	13.3
13.3	12.6	13.7
13.1	12.5	13.5
12.7	12.2	13.0
12.9	12.5	13.3
13.2	12.9	13.5
13.0	12.6	13.6
13.1	12.7	13.4
12.7	12.3	13.5

Use these data to set up control limits for the hides. Why would it be important for the Lazy B Ranch to track this information? Why might it be harder for the Lazy B Ranch to reduce process variability than it would be for a more typical "manufacturer"?

11. An insurance company has an online help service for its customers. Customer queries that take more than 5 minutes to resolve are categorized as "unsatisfactory" experiences. To evaluate the quality of its service, the company takes 10 samples of 100 calls each while the process is under control. The resulting p values are as follows:

p VALUES (n = 100)
0.08
0.11
0.12
0.06
0.13
0.09
0.16
0.09
0.18
0.15

a. (**) Calculate the $\bar{p}$ and S_p values and set up control limits so that future sample p values should fall within the control limits 99.7% of the time.

b. (**) Suppose the insurance company takes four additional samples, yielding the following p values: 0.9, 0.12, 0.25, and 0.10. Plot the results and circle all values that suggest that the process is "out of control." Is it possible that a sample result could fall outside the control limits due to pure chance? Explain.

c. (**) Now suppose that the sample size is actually 50, not 100. Recalculate the control limits for the p chart. What happened? Explain.

12. EK Chemical Company sells a specialty chemical in packages marked 100 g. In reality, EK has set the process mean at 100.5 g, and the process currently has a standard deviation of 0.50 g. Suppose the customer will accept anywhere from 98 to 102 g, as long as the average package has at least 100 g.

a. (**) Calculate the process capability index for the current manufacturing process. Is the process capable of meeting the tolerance limits more than 99.7% of the time? Explain.

b. (***) Now suppose EK recenters the manufacturing process so that the process mean is exactly 100 g, while the standard deviation remains the same. Calculate the process capability ratio. Is the process still capable of meeting the tolerance limits more than 99.7% of the time? Explain.

13. Crawford Pharmaceuticals has developed a new drug, Vaxidene. The target amount for a single dose of Vaxidene is 100 mg. Patients can receive as little as 98 mg or as much as 102 mg without experiencing any ill effects. Because of potential liability issues, Crawford has determined that it is imperative that manufacturing be able to provide Six Sigma quality levels. At present, the manufacturing process has a process mean of 100 mg and a standard deviation of 0.25 mg.

a. (*) What are the upper and lower tolerance limits for Vaxidene?

b. (**) Is Crawford's manufacturing process currently able to meet the dosage specifications at least 99.7% of the time? Show your work.

c. (**) What would the standard deviation for the process have to be in order for Crawford to achieve Six Sigma quality levels?

14. BHC produces bags of cement. The stated weight for a bag of cement is 100 pounds. Customers will accept an occasional bag weighing as little as 96 pounds, as long as the average weight is at least 100 pounds. At the same time, BHC doesn't want to give away cement, so it has set an upper tolerance limit of 104 pounds. The current filling process has an actual process mean of 101 pounds and a standard deviation of 0.65 pound.

a. (**) Calculate the process capability index for BHC. In this example, why should we use the process capability index rather than the process capability ratio to assess capability?

b. (**) Can you think of any reason BHC might want a process mean higher than the target value?

15. Central Airlines would like to set up a control chart to monitor its on-time arrival performance. Each day over a 10-day period, Central Airlines chose 30 flights at random and tracked the number of late arrivals in each sample. The results are as follows:

DAY	SAMPLE SIZE	NUMBER OF LATE-ARRIVING FLIGHTS
1	30	2
2	30	3
3	30	4
4	30	0
5	30	1
6	30	6
7	30	4
8	30	2
9	30	3
10	30	5

a. (*) Calculate $\bar{p}$.

b. (**) Set up a p chart to track the proportion of late arrivals. (*Note:* Each sample consists of 30 observations.)

c. (***) Airline travel is characterized by busy and slow seasons. As a result, what is "normal" during one time of the year wouldn't be "normal" at some other time. What difficulties might arise as a result of using a single control chart to track the proportion of late arrivals? What could Central Airlines do about this?

16. The Oceanside Apparel Company manufactures men's knit shirts. The production process requires material to be cut into large patterned squares, which are then sewn together. If the squares are not the correct length, the final shirt will be either too large or too small. The target length is 36 inches. In order to monitor the cutting process, Oceanside managers took 22 samples of four squares each and measured the lengths. For each sample, they then calculated the sample mean and range. Finally, they calculated the average sample mean (36.0 inches) and average range value (1.8 inches) for the 22 samples. Managers felt that these values were acceptable; that is, the process was in control.

a. (**) Develop the appropriate control chart(s) to monitor the fabric length.

b. (**) Using the control chart(s) you developed in part a, plot the following samples. Circle any that appear to be out of control.

SAMPLE (n = 4)	MEASUREMENTS (IN INCHES)			
1	37.3	36.5	38.2	36.2
2	33.4	35.8	37.9	36.2
3	32.1	34.8	39.1	35.3
4	36.1	37.2	36.7	34.2
5	32.1	34.0	35.6	36.1

17. (***) (*Microsoft Excel problem*) The following Excel spreadsheet calculates the upper and lower control limits for a continuous variable. **Re-create this spreadsheet in Excel.** You should develop the spreadsheet so that the results will be recalculated if any of the values in the highlighted cells are changed. Your formatting does not have to be exactly the same, but the numbers should be. (As a test, see what happens if all five observations in Sample 1 are 40. Your new upper and lower control limits for the sample means should be 36.05 and 34.28, respectively.)

	A	B	C	D	E	F	G	H	I	J	K
1	**Calculating upper and lower control limits for a continuous variable (sample size = 5)**										
2											
3			*****Observations*****								
4	*Sample*	*1*	*2*	*3*	*4*	*5*	$\overline{X}$	*R*			
5	*1*	*34.26*	*34.66*	*35.53*	*34.62*	*35.87*	*34.99*	*1.61*			
6	*2*	*34.75*	*35.10*	*34.00*	*35.48*	*36.64*	*35.19*	*2.64*			
7	*3*	*34.11*	*35.17*	*34.54*	*35.25*	*34.97*	*34.81*	*1.14*			
8	*4*	*34.31*	*34.56*	*35.36*	*35.38*	*34.30*	*34.78*	*1.08*			
9	*5*	*34.65*	*35.39*	*34.87*	*34.90*	*35.70*	*35.10*	*1.05*			
10	*6*	*33.78*	*35.26*	*35.79*	*34.52*	*34.51*	*34.77*	*2.01*			
11	*7*	*35.13*	*35.42*	*34.73*	*36.27*	*34.67*	*35.24*	*1.60*			
12	*8*	*35.23*	*34.06*	*35.50*	*34.96*	*35.43*	*35.04*	*1.44*			
13	*9*	*34.80*	*34.60*	*34.69*	*32.94*	*33.87*	*34.18*	*1.86*			
14	*10*	*35.16*	*33.26*	*35.92*	*34.08*	*33.33*	*34.35*	*2.66*			
15	*11*	*33.81*	*34.81*	*34.27*	*34.54*	*35.17*	*34.52*	*1.36*			
16	*12*	*35.70*	*33.74*	*34.59*	*35.38*	*34.34*	*34.75*	*1.96*			
17	*13*	*33.97*	*34.81*	*34.93*	*34.27*	*35.47*	*34.69*	*1.50*			
18	*14*	*35.36*	*34.47*	*35.67*	*35.86*	*34.34*	*35.14*	*1.52*			
19	*15*	*35.39*	*35.41*	*35.06*	*34.52*	*34.27*	*34.93*	*1.14*			
20						*Average:*	*34.83*	*1.64*			
21											
22		**Upper control limit for sample means:**				**35.78**					
23		**Lower control limit for sample means:**				**33.88**					
24											
25		**Upper control limit for sample ranges:**				**3.46**					
26		**Lower control limit for sample ranges:**				**0.00**					

18. (***) (*Microsoft Excel problem*) The following Excel spreadsheet calculates the upper and lower control limits for an attribute (in this case, the proportion of dissatisfied customers). **Re-create this spreadsheet in Excel.** You should develop the spreadsheet so that the results will be recalculated if any of the values in the highlighted cells are changed. Your formatting does not have to be exactly the same, but the numbers should be. (As a test, see what happens if you change the sample size to 200. The new *UCL* and *LCL* values should be 0.0909 and 0.0017, respectively.)

	A	B	C	D	E	F	G	H
1	**Setting Up 99.7% Control Limits, Sampling by Attribute**							
2								
3		No. of dissatisfied			Sample size =		100	
4	Sample	customers	*p*-value		$\bar{p}$	=	0.0927	
5	1	9	0.0900		S_p	=	0.0290	
6	2	11	0.1100					
7	3	13	0.1300					
8	4	8	0.0800		*UCL for sample p values:*			0.1797
9	5	9	0.0900		*LCL for sample p values:*			0.0057
10	6	10	0.1000					
11	7	9	0.0900					
12	8	8	0.0800					
13	9	11	0.1100					
14	10	12	0.1200					
15	11	10	0.1000					
16	12	7	0.0700					
17	13	8	0.0800					
18	14	9	0.0900					
19	15	8	0.0800					
20	16	8	0.0800					
21	17	9	0.0900					
22	18	10	0.1000					
23	19	6	0.0600					
24	20	9	0.0900					
25	21	11	0.1100					
26	22	8	0.0800					
27	23	11	0.1100					
28	24	6	0.0600					
29	25	9	0.0900					
30	26	9	0.0900					
31	27	8	0.0800					
32	28	12	0.1200					
33	29	9	0.0900					
34	30	11	0.1100					

CASE STUDY

Dittenhoefer's Fine China

Pawel Kwasnicki/Alamy Stock Photo

Introduction

Overall, Steve Edwards, vice president of marketing at Dittenhoefer's Fine China, is very pleased with the success of his new line of *Gem-Surface* china plates. *Gem-Surface* plates are different from regular china in that the plates have a special polymer coating that makes them highly resistant to chipping and fading. Not only are the plates more durable, they are also completely dishwasher safe.

In order to manufacture the new plates, Dittenhoefer's has leased a special machine to apply the coating and has put in place a drying system to "cure" the coating on the plates. The research and development (R&D) lab has determined that in order to prevent defective plates, it is important that the machine apply the polymer coating at the proper temperature and in the proper thickness. Specifically, R&D has written up the following guidelines:

Coating thickness. The optimal polymer-coating thickness is 4 microns. If the coating is >5 microns, the plates will take too long to dry. If the coating is <3 microns, the plates will be inadequately protected.

Coating temperature. The polymer coating needs to be applied at a temperature between 160 degrees Fahrenheit and 170 degrees Fahrenheit, with the target temperature being 165 degrees Fahrenheit. If the temperature is lower than 160 degrees, the polymer will not adhere properly and will flake off. If the temperature is higher than 170 degrees, the polymer coating will fade the design on the plates.

Quality Problems

Traditionally, quality control at Dittenhoefer's has consisted of visually inspecting finished items for defects (chips, cracks, etc.) as they are being packed for shipment. This was acceptable in the past, when defects were few and far between. With the new polymer-coating technology, however, this has caused some serious problems.

For instance, on one Friday during the Christmas season, the packers noticed that nearly all of the plates they were getting ready to ship had faded designs, which suggested that the temperature of the polymer-coating machine might be too high. Sure enough, when a supervisor went back to check on the polymer-coating machine, he found that the thermostat was set at 190 degrees. Apparently, someone had set the temperature higher to clean the machine but had forgotten to reset it back to 165 degrees. The good news was that the problem was easily fixed. The bad news was that the machine had been running at 190 degrees since *Wednesday*. In the interim, 2,400 plates had been run through the coating machine. In the end, Dittenhoefer's had to destroy all 2,400 plates and was late making shipments to several important customers.

In another instance, a worker just happened to notice that the polymer-coating machine was not using as much raw material as expected. When the worker measured the thickness of the coating being applied to the plates, she found out why: The coating thickness was only 2.4 microns. A quick check of plates being dried and those being packed revealed that they, too, had a coating thickness of around 2.4 microns. While manufacturing was able to correct the problem and save *these* plates, no one knew how many plates had been shipped before the problem was discovered.

The Customer Service Department

The customer service office is responsible for pricing and entering customer orders, tracking the progress of orders, and making sure orders are shipped when promised. If an order is going to be late or there is some other problem, the customer service office is also responsible for notifying the customer. In addition, the customer service office handles customer complaints.

As would be expected, Steve Edwards often visits the larger dealers to find out how satisfied they are with the products and service they have received. During one of these trips, Steve realizes there might be problems with the customer service office. When visiting Nancy Sanders, owner of Lenoir Home Furnishings, Steve gets an earful:

> *Steve, I understand that you have been busier ever since you introduced the new line of plates. However, I feel that the service quality has deteriorated and no one seems to care! Just last week, I found that an order I had expected in on Monday was not even ready to ship. No one called me—I just happened to find out when I was calling to place another order. Your information system also seems to be antiquated. The sales assistant apologized for the shipment delay and tried to be helpful, but she couldn't tell me the status of my order or even when I had placed it! It seemed that the previous sales assistant had changed jobs, and no one knew where her notes were. Notes!? Why isn't this stuff on a computer? It makes me have serious reservations about doing business with you.*

Steve is caught flat-footed by the criticism. When he gets back to the office, he puts together a letter to his top 200 customers. In the letter, he gives customers a self-addressed stamped postcard and asks them to list any problems they have had dealing with the sales office. He gets responses from 93 of the customers. Their responses are summarized here:

PROBLEM	NUMBER OF RESPONDENTS CITING PROBLEMS
Incorrect pricing	23
Lost the order	8
Did not notify customer with regard to change in delivery date	54
Did not know status of customer's order	77
Order incorrect—wrong products shipped	4
Slow response to inquiries	80
Other problems, not listed above	11

Questions

1. On which dimensions of quality does Dittenhoefer's compete? How are these dimensions being threatened by the problems in the manufacturing and customer service areas?
2. What do you think are the problems with the current manufacturing process as a whole and with the polymer-coating machine in particular? How might you use process mapping and root cause analysis to get to the bottom of these problems?
3. Develop a Pareto chart based on the customer survey results for the customer service office. What seem to be the key problems? How might you use the PDCA cycle to go about resolving these problems?
4. Suppose the polymer-coating machine currently provides the following results:

VARIABLE	PROCESS MEAN	PROCESS STANDARD DEVIATION
Temperature	165 degrees	2.55 degrees
Thickness	4 microns	0.42 micron

Calculate the process capability ratio (C_p) for both the temperature and thickness variables. Is the polymer-coating process able to meet the engineering standards 99.7% of the time? Explain.

5. After making numerous process improvements, Steve Edwards decides to set up control charts to monitor the temperature and thickness results for the polymer-coating machine. Sample temperature and thickness data are shown in the following table. Set up the appropriate control charts.

Polymer-Coating Machine: Sample Temperature and Thickness Measurements (taken when the process was under control)

SAMPLE	TEMP/ THICK	TEMP/ THICK	TEMP/ THICK	TEMP/ THICK	TEMP/ THICK
June 10	165/4.2	169/3.9	165/4.0	164/4.0	169/3.9
June 15	161/3.8	165/4.2	166/4.0	167/4.8	165/4.2
June 20	169/3.9	161/3.8	167/4.8	164/4.0	167/4.8
June 25	164/4.1	168/4.0	166/4.0	165/4.0	163/3.5
June 30	166/4.0	168/4.0	169/3.9	163/4.3	166/3.7
July 5	168/4.0	163/3.5	167/4.8	164/4.0	166/4.0
July 10	162/4.5	164/4.1	169/3.9	167/4.8	163/3.9
July 15	163/3.5	168/4.0	165/4.0	165/4.0	167/4.8
July 20	167/4.8	167/3.2	164/4.1	167/4.8	164/4.1
July 25	167/3.2	163/3.5	168/4.0	165/3.8	168/4.0
July 30	163/4.0	165/3.8	165/4.2	169/3.9	163/4.0
August 5	163/3.8	165/4.2	169/3.8	165/4.2	163/3.5

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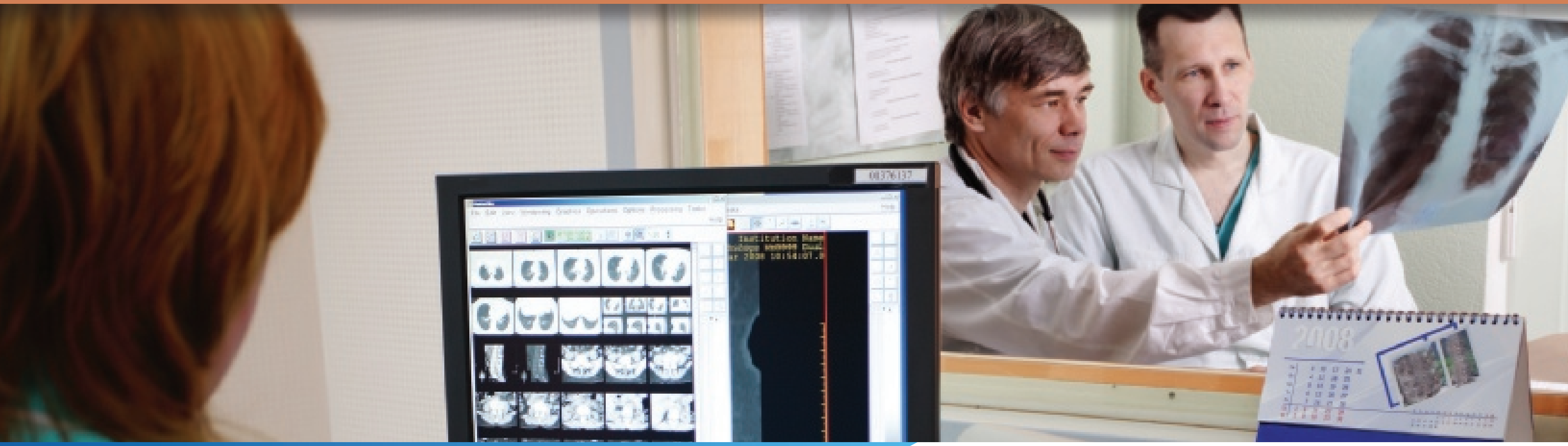


Kiselev Andrey Valerevich / Shutterstock

CHAPTER **six**

Managing Capacity

CHAPTER OUTLINE

CHAPTER OBJECTIVES

By the end of this chapter, you will be able to:

- Explain what capacity is, how firms measure capacity, and the difference between theoretical and rated capacity.
- Describe the pros and cons associated with three different capacity strategies: lead, lag, and match.
- Apply a wide variety of analytical tools for choosing between capacity alternatives, including expected value and break-even analysis, decision trees, and learning curves.
- Apply the Theory of Constraints, waiting line theory, and Little's Law to analyze and understand capacity issues in a business process environment.

THINKING OUTSIDE THE BOX: BUILDING THE NEXT-GENERATION PHARMACEUTICAL PLANT


Chip Chipman/Bloomberg/Getty Images

Many of today's breakthrough pharmaceutical drugs are produced via a process called biomanufacturing. Unlike traditional drug manufacturing, which is based on a chemical formulation, biomanufacturing uses biological systems to produce commercial volumes of important biomaterials and biomolecules. The key input to biomanufactured products are biological materials such as blood, animal cells and plant cells grown in special equipment. Some of these cells are naturally occurring, but others are created through genetic engineering.

Investing in a biomanufacturing facility is a long-term, strategic capacity decision. And as you can imagine, it is not for the faint-hearted. First, building a traditional plant can take three or more years and cost hundreds of millions of dollars. Even worse, construction often has to start years before the commercial success of the proposed drug is ensured. As a result, firms run the very real risk of spending several years and millions of dollars building a plant, only to learn that the drug does not perform as expected and the plant is not needed.

In response to these challenges, GE Healthcare Life Sciences has developed a new way to build biomanufacturing plants that cuts the time in half while reducing construction costs by 25% to 50%. Specifically, GE builds the plant in the form of prefabricated modules—literally, stand-alone rooms that represent the various steps in the biomanufacturing process. These modules are built in Germany and then shipped to the final site, where they are linked together into the final configuration. The modules "arrive 80 to 90% pre-equipped. The units include heating, ventilation and air-handling systems, the clean room, most of the utility equipment, and all of the piping needed to run the plant."[1]

Modular manufacturing has several benefits beyond lower construction costs. First, because modular construction reduces the overall time required to put a plant in place, firms can hold off building the plant until they have more information about whether the proposed drug is going to be a success or not. Even delaying the construction decision by one year can improve the odds of a successful outcome. Second, because the modules are built under controlled conditions at GE, conformance quality is enhanced while keeping costs under control.

[1]M. Egan, "Think Inside the Box: Pfizer Will Use GE's Mobile Biotech Factory to Make Next-Generation Drugs in China," *GE Reports,* June 30, 2016, **www.gereports.com/pfizer-will-use-ges-modular-factory-to-make-next-generation-drugs-in-china/**.

INTRODUCTION

Some of the most important strategic decisions managers face revolve around capacity. *How much* capacity do we need? *When* do we need it? *What form* should the capacity take? This chapter starts with a discussion of capacity and introduces several tools that managers use to evaluate capacity choices, including break-even analysis, expected value analysis, and learning curves. The second half of the chapter deals with the unique challenge of understanding and analyzing capacity in a *business process* environment where work units (people or products) must travel through several different steps before they leave the process.

For now, as you go through this chapter, keep in mind the following points:

- Capacity can take many different forms, and capacity planning is an important activity in both service and manufacturing organizations.
- While there are many quantitative tools to help managers make informed capacity decisions, there is some degree of risk inherent in nearly all such decisions.

With that background, let's dive in.

TABLE 6.1 Examples of Capacity in Different Organizations

ORGANIZATION	CAPACITY MEASURE	FACTORS AFFECTING CAPACITY
Law firm	Billable hours available each month	Number of lawyers and paralegals; education and skill levels; supporting software
Textile-spinning plant	Spinning hours per shift; number of spindles produced per week	Number of machines running; quality of raw materials; maintenance
Automatic car wash	Cars per hour	Availability of water and chemicals; reliability of the car wash (Is it frequently down for repairs?)
Airline	(Seats) × (miles flown)	Number of jets, pilots, and terminals

6.1 CAPACITY

Capacity
The capability of a worker, a machine, a workcenter, a plant, or an organization to produce output in a time period.

Simply put, **capacity** is the capability of a worker, machine, workcenter, plant, or organization to produce output per time period.[2] As the definition suggests, there are many forms of capacity in an organization. Operations and supply chain managers must make decisions regarding how much capacity their organizations need and what types. In making these decisions, managers must consider several issues:

- How capacity is measured
- Which factors affect capacity
- The impact of the supply chain on the organization's effective capacity

Measures of Capacity

Managers are constantly evaluating whether their organizations' resources are adequate to meet current or future demands. To do so, they need measures of capacity. Such measurements vary widely. In general, though, companies measure capacity in terms of inputs, outputs, or some combination of the two. The manager of a textile plant that makes thread from raw cotton might express its capacity in terms of the number of spinning hours available each month or the number of square feet of available warehouse space (both of which are inputs) or in terms of the number of finished pounds it can produce in a single period (an output).

In organizations that provide standard products or services, capacity is likely to be expressed in terms of outputs because the output doesn't change radically from one period to the next. In organizations that provide customized services or products, capacity is more likely to be expressed in terms of inputs. That is why the managing partners in a consulting firm are more likely to think in terms of available consultant hours (an input) than of consulting projects completed over a certain period. Table 6.1 shows the capacity measures used in a variety of business settings. Note which measures express capacity in terms of inputs and which express it in terms of output. Note, too, that many of the measures have a time element—such as spinning hours *per shift* and units *per day*.

Theoretical capacity
The maximum output capability, allowing for no adjustments for preventive maintenance, unplanned downtime, or the like.

Rated capacity
The long-term, expected output capability of a resource or system.

Organizations also differentiate between theoretical capacity and rated capacity. **Theoretical capacity** is the maximum output capability, allowing no adjustments for preventive maintenance, unplanned downtime, or the like, while **rated capacity** represents the long-term, expected output capability of a resource or system.[3] Managers understand that work levels must sometimes exceed levels that are typical, or even desirable, over the long haul. High-tech manufacturers often experience a big surge in demand during the fourth quarter of the year, as customers seek to use up their budgets. A salmon-processing plant might run 24 hours a day during the peak season. And personnel at an accounting firm might work 18 hours a day the week before April 15. Peak periods such as these are usually short in duration and are often characterized by high levels of overtime and reactive "fire fighting" (instead of proactive planning). Yet running at or near the theoretical capacity for a short time is often a better option than increasing resource levels permanently. Good managers know the

[2]J. H. Blackstone, ed., *APICS Dictionary,* 15th ed. (Chicago, IL: APICS, 2016).
[3]Ibid.

difference between theoretical capacity and more sustainable rated capacity levels, and they use that knowledge when measuring and planning capacity.

Factors That Affect Capacity

Even in seemingly simple environments, many factors affect capacity, and many assumptions must be made. Take the following formula, which describes capacity for an assembly plant with three assembly lines and a maximum of two 8-hour shifts per day:

$$\text{Capacity} = (800 \text{ units per line per shift})(\text{number of lines})(\text{number of shifts})$$

What is the “capacity” of the plant? It could be as low as 800 units per day (1 line, 1 shift) or as high as 4,800 units per day (3 lines, 2 shifts). The number of shifts or lines active at any time is a controllable factor that managers can use to adjust capacity in response to market demands. Other examples of controllable factors include the number of jets an airline keeps on active status, the number of temporary workers, and the number of public storage facilities, which companies can add or drop as needed.

Product variations are another source of ambiguity in measuring capacity. Suppose our hypothetical factory can assemble several different models, so that 800 units represent an *average* rated capacity. The actual output can range from 700 to 900 units, depending on the complexity of the model being assembled. If that is the case, capacity can range from 700 to 5,400 units.

Another factor that affects capacity is conformance quality, which we discussed in Chapter 5. In general, poor conformance quality reduces available capacity because employees must spend valuable time and resources resolving quality problems or reworking “defective” products or service outcomes. In contrast, quality improvement can increase an organization’s effective capacity by reducing the resources needed to provide a product or service.

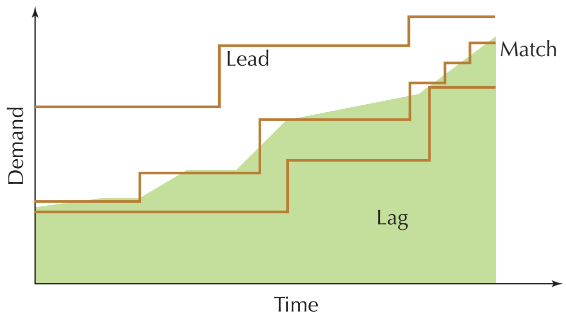
Supply Chain Considerations

A firm’s capacity concerns certainly aren’t limited to just *its* activities. In many cases, a firm must also consider the capacities of key suppliers and distributors. Suppose Procter & Gamble (P&G) decides to launch a new line of children’s shampoos. P&G will need to fill the downstream supply chain with product. Among other things, P&G managers must make sure that suppliers have adequate capacity to provide the necessary raw materials when they are needed. They must also arrange for adequate trucking, warehousing, and shelf space—all forms of capacity—in order to move the products and display the new line in retail stores. The point is this: A firm’s ability to use its own capacity is often directly dependent on capacity up and down the supply chain. We will revisit this point in our discussion of the Theory of Constraints.

6.2 THREE COMMON CAPACITY STRATEGIES

Oftentimes capacity decisions are made to accommodate expected growth in demand or product lines. The question managers must deal with is how quickly to increase capacity. Three common strategies for timing capacity expansions are the lead, lag, and match strategies (see Figure 6.1).

FIGURE 6.1
When to Add Capacity: Lead, Lag, and Match Strategies



Lead capacity strategy
A capacity strategy in which capacity is added in anticipation of demand.

When using a **lead capacity strategy,** capacity is added in anticipation of demand. This strategy has several advantages. First, it ensures that the organization has adequate capacity to meet all demand, even during periods of high growth. This is especially important when the availability of a product or service is crucial, as in the case of emergency care or a hot new product. For many new products, being late to market can mean the difference between success and failure.

Another advantage of a lead capacity strategy is that it can be used to preempt competitors who might be planning to expand their own capacity. Being the first in an area to open a large grocery or home improvement store gives a retailer a definite edge. Finally, many businesses find that overbuilding in anticipation of increased usage is cheaper and less disruptive than constantly making small increases in capacity. Of course, a lead capacity strategy can be very risky, particularly if demand is unpredictable or technology is evolving rapidly.

Lag capacity strategy
A capacity strategy in which capacity is added only after demand has materialized.

The opposite of a lead capacity strategy is a **lag capacity strategy,** whereby organizations add capacity only *after* demand has materialized. Three clear advantages of this strategy are a reduced risk of overbuilding, greater productivity due to higher utilization levels, and the ability to put off large investments as long as possible. Organizations that follow this strategy often provide mature, cost-sensitive products or services. Many government agencies try to avoid adding extra capacity and their requisite costs until absolutely necessary. Yet one can easily imagine the drawbacks of a lag capacity strategy, the most evident being the reduced availability of products or services during periods of high demand.

Most organizations do not follow one strategy. For one thing, different products and services require different approaches. Consider a community hospital. If you are the chief executive officer, you will follow a lead capacity strategy for expanding critical emergency services, especially if yours is the only hospital in the region. You will not apply the same rationale to noncritical services.

Match capacity strategy
A capacity strategy that strikes a balance between the lead and lag capacity strategies by avoiding periods of high under- or overutilization.

Virtual supply chain
A collection of firms that typically exists for only a short period. Virtual supply chains are more flexible than traditional supply chains, but they are also less efficient.

A **match capacity strategy** strikes a balance between the lead and lag capacity strategies by avoiding periods of high under- or overutilization. A relatively new concept in capacity planning is the **virtual supply chain,** which is really a collection of firms, each of which does only one or two core activities—design, manufacturing, distribution, marketing, and so on. The firms coordinate their activities by using advanced information systems to share critical data.

Unlike a traditional supply chain, a virtual supply chain might exist for only a short period. The virtual supply chain might be pulled together during the holiday season to produce and market a new toy, after which it will disappear. The members of the virtual supply chain might even change from one week to the next. What virtual supply chains gain in short-term flexibility, however, they lose in long-term efficiency. As a result, traditional supply chains are more likely to prevail in markets in which long-term relationships or costs are critical.

6.3 METHODS OF EVALUATING CAPACITY ALTERNATIVES

An organization usually has many ways to meet its capacity needs. Manufacturers often have a choice between building their own facilities or leasing capacity from other firms. Airlines debate whether to purchase or lease jets. On the human side, organizations make choices between full-time and temporary employees and among different types of skills. An organization might even have to choose between using inventory ("stored" capacity) and using overtime to meet demand during peak seasons. Clearly, managers need some help in evaluating these alternatives.

In this section, we discuss several approaches that are useful in evaluating capacity alternatives. They include the concept of fixed versus variable costs, expected value, and break-even analysis. Keep in mind as we describe these approaches that they deal primarily with *financial* considerations—the costs and/or revenues associated with a particular capacity option. Nevertheless, they provide a good starting point.

Cost

Fixed costs
The expenses an organization incurs regardless of the level of business activity.

Many capacity alternatives have both fixed and variable cost components. **Fixed costs** are the expenses an organization incurs regardless of the level of business activity. Examples include lease payments on equipment, mortgage payments on buildings, and monthly maintenance

Variable costs
Expenses directly tied to the level of business activity.

charges for software. The company must pay these expenses regardless of the number of customers it serves or products it makes. **Variable costs,** on the other hand, are expenses that are directly tied to the level of business activity. Material costs are a good example. If the fabric cost per pair of jeans is \$4.35, then we can calculate fabric cost as \$4.35 $\times$ (number of jeans produced). The general formula for describing the total cost of a capacity alternative is:

$$TC = FC + VC{*}X \tag{6.1}$$

where:

TC = total cost
FC = fixed cost
VC = variable cost per unit of business activity
X = amount of business activity (number of customers served, number of units produced, etc.)

The distinction between fixed and variable costs is important because it shows how the level of business activity affects costs. This kind of information can be critical in choosing between several capacity alternatives.

EXAMPLE 6.1

Analyzing the Cost of Capacity Alternatives at Ellison Seafood Company

Chuck Pefley/Alamy Stock Photo

Ellison Seafood Company ships fresh seafood to customers in a nearby city. The logistics manager has identified three shipping alternatives. The first is to call a common carrier (i.e., a trucking company) each time a shipment is ready to go. This alternative would have no fixed cost, but the variable cost per shipment would be about \$750. At the other extreme, Ellison Seafood could lease its own refrigerated trucks. The logistics manager has determined that the yearly cost to lease three trucks would be \$21,000, including insurance and prepaid maintenance. Because Ellison would have to pay the lease charge regardless of how many shipments were made, the \$21,000 would be a fixed expense. On the other hand, the variable cost would drop dramatically to \$50 per shipment—just enough to cover the cost of fuel and the driver's wages. Somewhere between these two extremes is the third option: a contractual arrangement with a local carrier. For a yearly fixed charge of $5,000, the local carrier would agree to make all of Ellison's deliveries at a variable cost of just $300 per delivery. Table 6.2 summarizes the three options.

TABLE 6.2 Capacity Alternatives and Costs for Ellison Seafood Company

	COMMON CARRIER	CONTRACT CARRIER	LEASING
Fixed cost	None	$5,000	$21,000
Variable cost	$750	$300	$50

Figure 6.2 shows the total cost (fixed cost + variable cost) of each alternative as the number of shipments increases. By looking at the graph, we can see that the cost of using a common carrier starts out the lowest, but it quickly becomes much more expensive than the other two options. As the number of shipments nears 11, using a contract carrier becomes cheaper. The contract carrier remains the cheapest option until the activity level approaches 64 shipments, at which point leasing becomes the cheapest option.

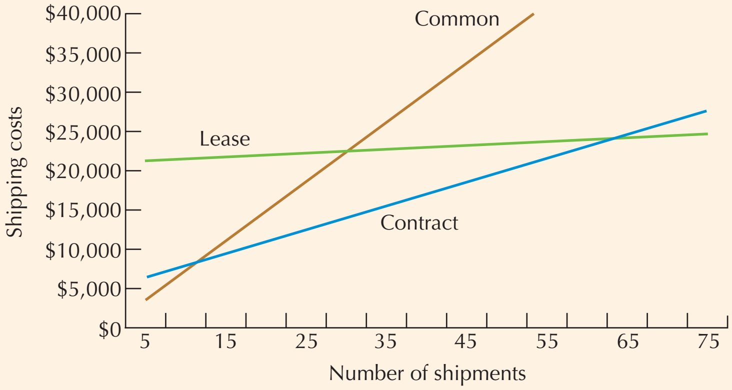


FIGURE 6.2 Total Cost of Three Capacity Alternatives, Ellison Seafood Company

Indifference point
The output level at which two capacity alternatives generate equal costs.

We can find the exact output level at which two capacity alternatives generate equal costs, called the **indifference point,** by setting their two cost functions equal to one another and solving for the number of shipments, *X*. For instance, the indifference point for the common carrier and contract carrier options would be calculated as follows:

$$\text{Total cost of common carrier option} = \text{total cost of contract carrier option}$$
$$\$0 + \$750X = \$5{,}000 + \$300X$$
$$X = (\$5{,}000 - \$0)/(\$750 - \$300) = 11.11, \text{ or about } \textit{11 shipments}$$

We can use the same logic to find the indifference point for the contract carrier and leasing options:

$$\text{Total cost of contract carrier option} = \text{total cost of leasing}$$
$$\$5{,}000 + \$300X = \$21{,}000 + \$50X$$
$$X = (\$21{,}000 - \$5000)/(\$300 - \$50) = \textit{64 shipments}$$

Figure 6.3 provides a different view of the same three options. In this case, we have plotted the cost *per shipment*, which is calculated by dividing total cost by the number of shipments. Not surprisingly, the cost per shipment for the common carrier option is flat. Notice, however, that as the number of shipments increases, the cost per shipment for the leasing option drops dramatically. This is because the total cost per shipment drops when the fixed cost of $21,000 is spread across more shipments. Finally, note that the cost curves in Figure 6.3 cross at the same levels shown in Figure 6.2—the two indifference points.

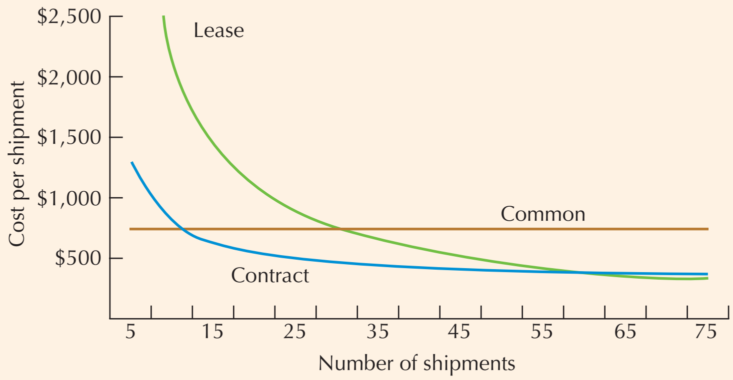


FIGURE 6.3 Total Cost per Shipment of Three Capacity Alternatives, Ellison Seafood Company

Demand Considerations

While understanding the cost structure of various capacity alternatives is important, it is not enough. Managers must also know something about the expected demand levels. Otherwise, how will they know which capacity alternative will provide the best financial result? Table 6.3 makes this point. If Ellison Seafood expects to make 40 shipments per year, the contract carrier option makes the most sense. However, if demand is expected to be as high as 75 shipments per year, leasing is cheaper.

Of course, predicting demand with certainty is rarely easy. In many business situations, it makes more sense to develop *multiple* estimates of demand that capture a range of possibilities, as in Table 6.3. Even so, how should we interpret Table 6.3? While leasing is the cheapest alternative for a yearly total of 75 shipments, how *likely* is demand to reach that level? Similarly, how likely is the number of shipments to fall in the range in which contracting is cheapest? To tackle this type of problem, managers turn to expected value analysis.

Expected Value

Expected value
A calculation that summarizes the expected costs, revenues, or profits of a capacity alternative, based on several demand levels, each of which has a different probability.

One way companies evaluate capacity alternatives when demand is uncertain is to use a decision tool called the expected value approach. In a nutshell, **expected value** is a calculation that summarizes the expected costs, revenues, or profits of a capacity alternative, based on several different demand levels, each of which has a different probability.

The major steps of the expected value approach are as follows:

1. Identify several different demand-level scenarios. These scenarios are not meant to identify all possible outcomes. Rather, the intent is to approximate the *range* of possible outcomes.
2. Assign a probability to each demand-level scenario.
3. Calculate the expected value of each alternative. This is done by multiplying the expected financial result (cost, revenue, or profit) at each demand level by the probability of each demand level and then summing across all levels. The equation is:

$$EV_j = \sum_{i=1}^{I} P_i C_i \qquad \textbf{(6.2)}$$

where:

EV_j = expected value of capacity alternative j
P_i = probability of demand level i
C_i = financial result (cost, revenue, or profit) at demand level i

TABLE 6.3 Total Cost of Three Capacity Alternatives at Different Demand Levels, Ellison Seafood Company

TOTAL COST EQUATION	15 SHIPMENTS (LOW DEMAND)	40 SHIPMENTS (MEDIUM DEMAND)	75 SHIPMENTS (HIGH DEMAND)
Common carrier: $0 + $750*X*	$11,250	$30,000	$56,250
Contract carrier: $5,000 + $300*X*	**$9,500**	**$17,000**	$27,500
Leasing: $21,000 + $50*X*	$21,750	$23,000	**$24,750**

EXAMPLE 6.2

Expected Value Analysis at Ellison Seafood Company

Suppose Ellison Seafood wants to know the *expected cost* of one of the options, contracting. As a first step, management needs to identify some potential demand scenarios:

Low demand	→	30 shipments per year
Medium demand	→	50 shipments per year
High demand	→	80 shipments per year

Next, management must assign a probability to each. The only stipulation is that the probabilities must sum to 100%. This is what management finds:

Low demand	→	30 shipments per year	→	25%
Medium demand	→	50 shipments per year	→	60%
High demand	→	80 shipments per year	→	15%
		Total		100%

Based on the total cost equations in Table 6.3, the costs associated with contracting at each demand level are:

$$\begin{aligned} C(\text{low demand}) &= \$5{,}000 + \$300(30) = \$14{,}000 \\ C(\text{medium demand}) &= \$5{,}000 + \$300(50) = \$20{,}000 \\ C(\text{high demand}) &= \$5{,}000 + \$300(80) = \$29{,}000 \end{aligned}$$

And the expected cost of contracting is:

$$\begin{aligned} EV_{Contract} &= (\$14{,}000 * 25\%) + (\$20{,}000 * 60\%) + (\$29{,}000 * 15\%) \\ &= \$3{,}500 + \$12{,}000 + \$4{,}350 = \$19{,}850 \end{aligned}$$

Using similar logic, we can calculate the expected costs of using a common carrier or of leasing:

$$\begin{aligned} EV_{Common} &= (\$22{,}500 * 25\%) + (\$37{,}500 * 60\%) + (\$60{,}000 * 15\%) \\ &= \$37{,}125 \\ EV_{Lease} &= (\$22{,}500 * 25\%) + (\$23{,}500 * 60\%) + (\$25{,}000 * 15\%) \\ &= \$23{,}475 \end{aligned}$$

The analysis suggests that, on average, the contracting option has the lowest expected costs, at $19,850. Intuitively, this result seems consistent with Figures 6.2 and 6.3, which show that the contracting option is cheapest for a fairly wide range of shipping levels.

Decision Trees

Decision tree
A visual tool that decision makers use to evaluate capacity decisions. The main advantage of a decision tree is that it enables users to see the interrelationships between decisions and possible outcomes.

A **decision tree** is a visual tool that decision makers use to evaluate capacity decisions. The main advantage of a decision tree is that it enables users to see the interrelationships between decisions and possible outcomes. Decision trees are particularly good at helping users visualize complex *series* of decisions and outcomes.

The basic rules for using decision trees are as follows:

1. Draw a tree from left to right, starting with a decision point or an outcome point, and develop branches from there.
2. Represent each *decision point* with a square, with the different branches coming out of the square representing alternative choices.
3. Represent *outcome points* (which are beyond the control of the decision maker) with circles. Each possible outcome is represented by a branch off the circle. Assign each

branch a probability, indicating the possibility of that outcome, and ensure that the total probability for all branches coming out of an outcome equals 100%.

4. For expected value problems, calculate the financial result for each of the smaller branches and move backward by calculating weighted averages for the branches, based on their probabilities.

EXAMPLE 6.3

Decision Trees at Ellison Seafood Company

Figure 6.4 shows a decision tree for the transportation decision facing Ellison Seafood (Example 6.2). Reading from left to right, the tree starts with the selection of one of the three transportation options. Once the transportation decision is made, there are three possible demand outcomes: 30 shipments, 50 shipments, and 80 shipments, each with different probabilities. Because the actual demand is an outcome and not a decision, a circle is used to represent these branch points.

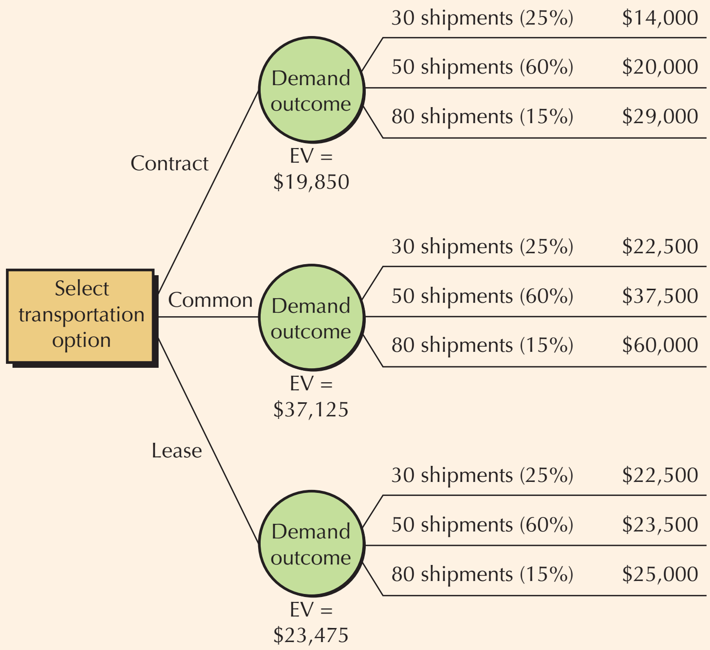


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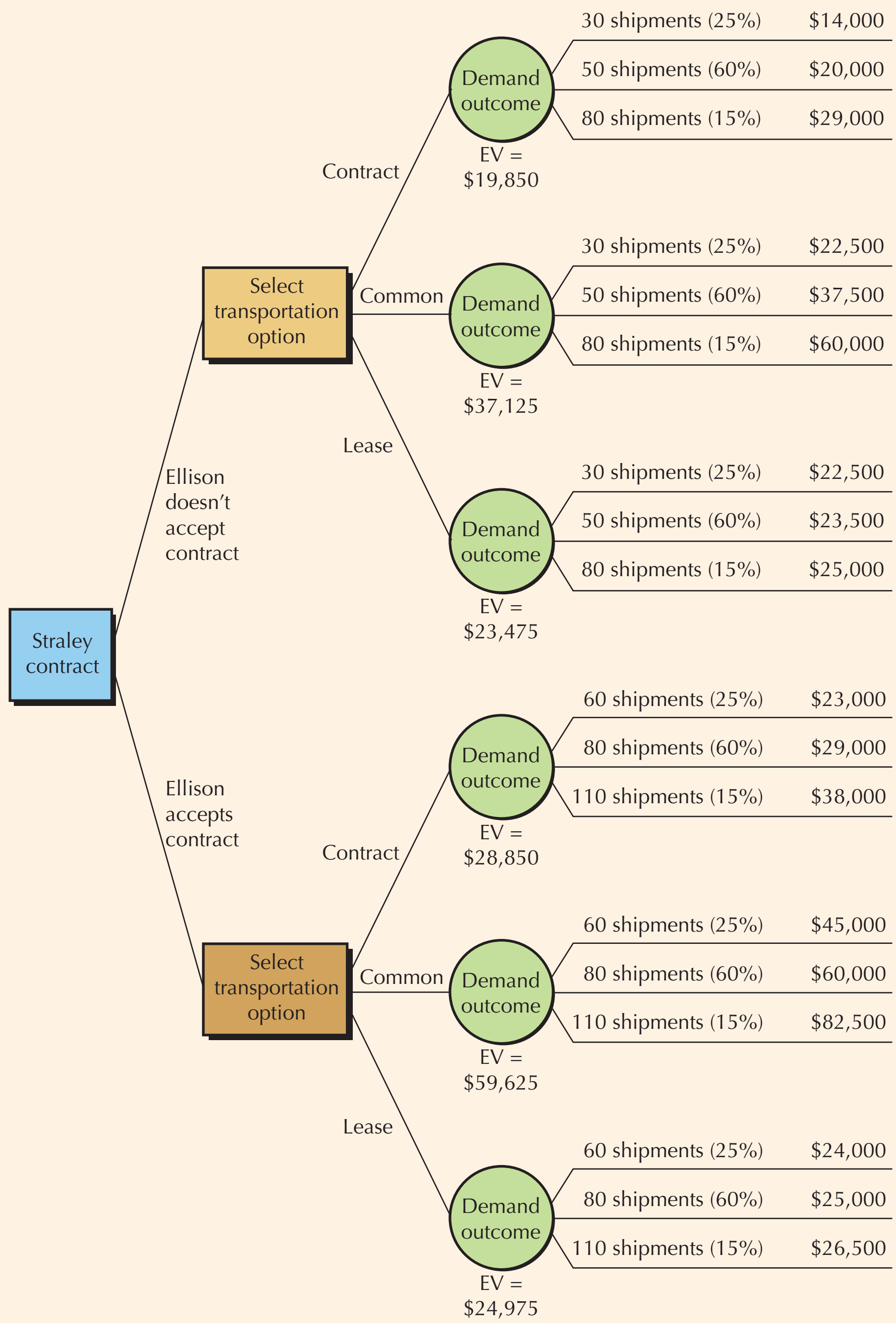
FIGURE 6.4 Decision Tree for Transportation Decision at Ellison Seafood Company

The combination of three different transportation options and three demand scenarios results in $3 \times 3 = 9$ branches, each of which has a resulting cost. Finally, the expected value of each decision branch is calculated as the weighted average of the possible demand outcome branches. Note that the numbers in Figure 6.4 match those in Example 6.2.

Now suppose that a potential new customer, Straley Grocers, has approached Ellison Seafood. Straley wants Ellison to sign a contract promising 30 deliveries a year. These deliveries would be *in addition to* Ellison's normal business. Ellison management would like to develop a decision tree to understand how the Straley contract might affect the transportation decision.

Figure 6.5 shows the updated decision tree. Ellison *first* has to make a decision about whether to accept the Straley contract, and, based on that decision, it has to select a transportation option. The added decision point effectively doubles the size of the tree.

Note how the demand levels and resulting costs for each demand outcome branch in the lower half have been updated to show the impact of the additional 30 shipments. Looking at the tree, it becomes clear that if Ellison decides *not* to accept the Straley contract, the lowest expected cost is to go with the contract carrier; this is the same result as in Example 6.2. But if Ellison *does* accept the contract, the lowest expected cost is to lease a truck.



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Animation

FIGURE 6.5 Updated Decision Tree for Transportation Decision at Ellison Seafood Company, Reflecting Straley Contract Decision

Break-Even Analysis

Break-even point
The volume level for a business at which total revenues cover total costs.

When the focus is on profitability, a key question managers often face is "At what volume level do total revenues cover total costs?" This volume level is referred to as the **break-even point.** Managers are very interested in knowing what the break-even point is because once business volume passes the break-even point, the company begins to make money.

The formula for the break-even point is:

$$BEP = \frac{FC}{R - VC} \tag{6.3}$$

where:

BEP = break-even point
FC = fixed cost
V = variable cost per unit of business activity
R = revenue per unit of business activity

EXAMPLE 6.4

Break-Even Analysis at Ellison Seafood Company

Ellison makes a $1,000 profit on each shipment *before* transportation costs are considered. What is the break-even point for each shipping option?

For the common carrier option:

$$BEP = \frac{FC}{R - VC}$$
$$BEP = \$0/\$250, \text{ or } 0 \textit{ shipments}$$

For the contracting option:

$$BEP = \$5{,}000/\$700 = 7.1, \text{ or, rounding up, } 8 \textit{ shipments}$$

And for the leasing option:

$$\$21{,}000 + \$50X = \$1{,}000X$$
$$BEP = \$21{,}000/\$950 = 22.1, \text{ or, rounding up, } 23 \textit{ shipments}$$

The common carrier option has the lowest break-even point, which arguably makes it the least risky option. However, Ellison Seafood will clear only ($1,000 − 750) = $250 on each shipment. On the other hand, the leasing option has a break-even point of 23 shipments, yet each additional shipment beyond 23 contributes ($1,000 − $50) = $950 to the bottom line. In choosing the appropriate shipping option, Ellison Seafood must carefully consider the risks as well as the expected demand levels.

Learning Curves

Here's a question to ponder: Can the effective capacity of operations or supply chains *increase* even though the level of resources remains the *same*? In many cases, the answer is "yes." Recall that in Chapter 4, we defined *productivity* as follows:

$$\text{Productivity} = \text{outputs/inputs} \tag{6.4}$$

If organizations can improve their productivity, they can get more output from the same amount of resources or, conversely, the same output from fewer resources. Either way, changes in productivity imply changes in effective capacity. **Learning curve theory** suggests that productivity levels can improve at a predictable rate as people and even systems "learn" to do tasks more efficiently. In formal terms, learning curve theory states that *for every doubling of cumulative output, there is a set percentage reduction in the amount of inputs required*. The learning curve is defined as follows:

Learning curve theory
A body of theory based on applied statistics which suggests that productivity levels can improve at a predictable rate as people and even systems "learn" to do tasks more efficiently. In formal terms, learning curve theory states that for every doubling of cumulative output, there is a set percentage reduction in the amount of inputs required.

$$T_n = T_1 n^b \tag{6.5}$$

where:

T_n = resources (usually labor) required for the nth unit
T_1 = resources required for the 1st unit
b = ln(Learning percentage)/ln2

The rate at which learning occurs is captured by the learning percentage, where 80% would be expressed as 0.80.

EXAMPLE 6.5

Learning Curves at a Service Call Center

A video game producer has hired a new service technician to handle customer calls. The times it takes the new service technician to help the first, second, fourth, and eighth callers, as well as the resulting productivity figures, are shown below:

CALL	TIME FOR CALL	PRODUCTIVITY
1	5.00 minutes	0.20 calls per minute
2	4.00 minutes	0.25 calls per minute
4	3.20 minutes	0.31 calls per minute
8	2.56 minutes	0.39 calls per minute

Notice that the second call takes 80% of the time of the first ($4/5 = 80\%$). Similarly, the fourth call takes 80% of the time of the second, and the eighth call takes 80% of the time of the fourth. In effect, for every doubling of cumulative output, the service technician is experiencing a 20% reduction in the amount of time required. This represents an 80% learning curve.

For our service technician, then, we can use Equation (6.5) to estimate the time it will take her to handle her 25th call:

$$\begin{aligned} T_{25} &= T_1\left(25^{\frac{\ln(0.80)}{\ln(2)}}\right) \\ &= (5 \text{ minutes})(25^{-0.32193}) \\ &= (5 \text{ minutes})(0.355) \\ &= 1.78 \text{ minutes} \end{aligned}$$

Figure 6.6 uses the learning curve equation to plot the expected service times for the first 50 calls, based on an 80% learning curve. As you can see, the learning curve is characterized by quick improvements in productivity early on, followed by more gradual improvements.

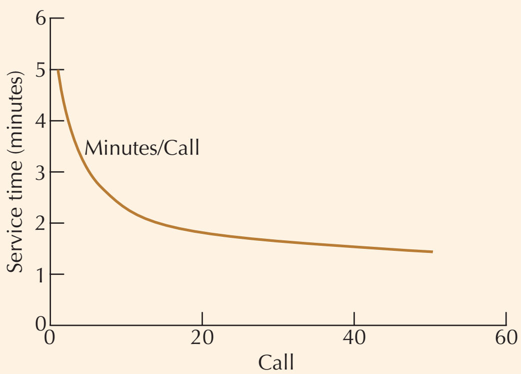


FIGURE 6.6 Eighty Percent Learning Curve for Service Technician

Table 6.4 contains calculated n^b values, as well as cumulative n^b values, for a wide range of n values and learning curve percentages.

To see how the table works, suppose the video game producer mentioned earlier hires a second service technician. The second service technician takes 5 minutes for his first call, followed by 4.5 minutes for the second call. Based on this information:

- Estimate the learning rate.
- Calculate the time it should take to handle the 25th call.
- Calculate the total time it should take to handle *the next 23 calls* (i.e., calls 3 through 25).

TABLE 6.4 Selected n^b and $\sum n^b$ Values for Different Learning Curves

UNIT NUMBER	70% LEARNING		75% LEARNING		80% LEARNING		85% LEARNING		90% LEARNING	
	n^b	$\sum n^b$	n^b	$\sum n^b$	n^b	$\sum n^b$	n^b	$\sum n^b$	n^b	$\sum n^b$
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.700	1.700	0.750	1.750	0.800	1.800	0.850	1.850	0.900	1.900
3	0.568	2.268	0.634	2.384	0.702	2.502	0.773	2.623	0.846	2.746
4	0.490	2.758	0.563	2.946	0.640	3.142	0.723	3.345	0.810	3.556
5	0.437	3.195	0.513	3.459	0.596	3.738	0.686	4.031	0.783	4.339
6	0.398	3.593	0.475	3.934	0.562	4.299	0.657	4.688	0.762	5.101
7	0.367	3.960	0.446	4.380	0.534	4.834	0.634	5.322	0.744	5.845
8	0.343	4.303	0.422	4.802	0.512	5.346	0.614	5.936	0.729	6.574
9	0.323	4.626	0.402	5.204	0.493	5.839	0.597	6.533	0.716	7.290
10	0.306	4.932	0.385	5.589	0.477	6.315	0.583	7.116	0.705	7.994
11	0.291	5.223	0.370	5.958	0.462	6.777	0.570	7.686	0.695	8.689
12	0.278	5.501	0.357	6.315	0.449	7.227	0.558	8.244	0.685	9.374
13	0.267	5.769	0.345	6.660	0.438	7.665	0.548	8.792	0.677	10.052
14	0.257	6.026	0.334	6.994	0.428	8.092	0.539	9.331	0.670	10.721
15	0.248	6.274	0.325	7.319	0.418	8.511	0.530	9.861	0.663	11.384
16	0.240	6.514	0.316	7.635	0.410	8.920	0.522	10.383	0.656	12.040
17	0.233	6.747	0.309	7.944	0.402	9.322	0.515	10.898	0.650	12.690
18	0.226	6.973	0.301	8.245	0.394	9.716	0.508	11.405	0.644	13.334
19	0.220	7.192	0.295	8.540	0.388	10.104	0.501	11.907	0.639	13.974
20	0.214	7.407	0.288	8.828	0.381	10.485	0.495	12.402	0.634	14.608
21	0.209	7.615	0.283	9.111	0.375	10.860	0.490	12.892	0.630	15.237
22	0.204	7.819	0.277	9.388	0.370	11.230	0.484	13.376	0.625	15.862
23	0.199	8.018	0.272	9.660	0.364	11.594	0.479	13.856	0.621	16.483
24	0.195	8.213	0.267	9.928	0.359	11.954	0.475	14.331	0.617	17.100
25	0.191	8.404	0.263	10.191	0.355	12.309	0.470	14.801	0.613	17.713
26	0.187	8.591	0.259	10.449	0.350	12.659	0.466	15.267	0.609	18.323
27	0.183	8.774	0.255	10.704	0.346	13.005	0.462	15.728	0.606	18.929
28	0.180	8.954	0.251	10.955	0.342	13.347	0.458	16.186	0.603	19.531
29	0.177	9.131	0.247	11.202	0.338	13.685	0.454	16.640	0.599	20.131
30	0.174	9.305	0.244	11.446	0.335	14.020	0.450	17.091	0.596	20.727
31	0.171	9.476	0.240	11.686	0.331	14.351	0.447	17.538	0.593	21.320
32	0.168	9.644	0.237	11.924	0.328	14.679	0.444	17.981	0.590	21.911
33	0.165	9.809	0.234	12.158	0.324	15.003	0.441	18.422	0.588	22.498
34	0.163	9.972	0.231	12.389	0.321	15.324	0.437	18.859	0.585	23.084
35	0.160	10.133	0.229	12.618	0.318	15.643	0.434	19.294	0.583	23.666
36	0.158	10.291	0.226	12.844	0.315	15.958	0.432	19.725	0.580	24.246
37	0.156	10.447	0.223	13.067	0.313	16.271	0.429	20.154	0.578	24.824
38	0.154	10.601	0.221	13.288	0.310	16.581	0.426	20.580	0.575	25.399
39	0.152	10.753	0.219	13.507	0.307	16.888	0.424	21.004	0.573	25.972
40	0.150	10.902	0.216	13.723	0.305	17.193	0.421	21.425	0.571	26.543
41	0.148	11.050	0.214	13.937	0.303	17.496	0.419	21.844	0.569	27.111
42	0.146	11.196	0.212	14.149	0.300	17.796	0.416	22.260	0.567	27.678
43	0.144	11.341	0.210	14.359	0.298	18.094	0.414	22.674	0.565	28.243
44	0.143	11.484	0.208	14.567	0.296	18.390	0.412	23.086	0.563	28.805
45	0.141	11.625	0.206	14.773	0.294	18.684	0.410	23.496	0.561	29.366
46	0.139	11.764	0.204	14.977	0.292	18.975	0.408	23.903	0.559	29.925
47	0.138	11.902	0.202	15.180	0.290	19.265	0.405	24.309	0.557	30.482
48	0.136	12.038	0.201	15.380	0.288	19.552	0.403	24.712	0.555	31.037
49	0.135	12.173	0.199	15.579	0.286	19.838	0.402	25.113	0.553	31.590
50	0.134	12.307	0.197	15.776	0.284	20.122	0.400	25.513	0.552	32.142

The estimated learning rate $=$ 4.5 minutes/5 minutes $=$ 90%. Looking at Table 6.4, we can see that we have an entire column of n^b values and cumulative n^b values $\left(\sum n^b\right)$ for a 90% learning curve. Looking down the table until we find the row for the 25th unit (in this case, a customer call), we find n^b for a 90% learning curve $=$ 0.613. Therefore:

$$\text{Estimated time for the 25th call} = (5 \text{ minutes})(0.613) = 3.065 \text{ minutes}$$

To estimate the time for the next 23 calls, we calculate the expected time for the first 25 calls and subtract the time for the first 2. Working off the same row of Table 6.4:

$$\begin{aligned}\text{Estimated time for the next 23 calls} &= \text{Estimated time for the first 25 calls} \\ &\quad - \text{Time for the first 2 calls} \\ &= 5 \text{ minutes} \left(\sum n^b\right) - (5 + 4.5 \text{ minutes}) \\ &= 5 \text{ minutes } (17.713) - 9.5 \text{ minutes} \\ &= 79 \text{ minutes}\end{aligned}$$

When learning occurs in an organization, productivity will improve over time, and the effective capacity of the organization will grow—even if the level of resources remains the same. This has important implications for capacity planning. If managers expect their employees or work systems to experience learning effects, then they must anticipate these effects when making capacity decisions. Otherwise, they may overestimate the capacity needed to meet future requirements.

Of course, in nearly every case there is a minimum amount of time or resource that will be required, regardless of how many times the task is repeated. This puts an effective limit on the learning curve effect. Also, it is normal for learning improvements to not follow a smooth trajectory of improvement, as suggested by Equation (6.5). Rather, organizations may be able to see the actual improvement only over large numbers of observations.

One final observation about learning curves: In many industrial buyer–supplier settings, buyers *expect* their suppliers to experience productivity improvements due to learning over time. Buyers might even build price reductions based on anticipated learning into long-term purchasing contracts. Walmart, for instance, may purchase a new item from a supplier, expecting overall costs to follow a 90% learning curve. This creates an incentive for the supplier to proactively look for ways to decrease costs through learning or other means.

Other Considerations

Not all capacity problems can be solved using the quantitative models just described. Other considerations that will affect a firm's choice include:

- The strategic importance of an activity to the firm
- The desired degree of managerial control
- The need for flexibility

These considerations are usually relevant to the choice between developing internal capacity and outsourcing, a topic we consider in more depth in Chapter 7.

The more strategically important an activity is to a firm, the more likely the firm is to develop the internal capacity to perform the activity. Strategic activities are often called *core activities* because they are a major source of competitive advantage. Product design at Cisco Systems, a provider of telecommunications equipment, is one example. Cisco spends millions of dollars each year on developing the internal capacity needed to design innovative products. Engineers, designers, equipment, and facilities are crucial to this strategic activity. But while Cisco does not want to depend on outside sources for new technologies or product ideas, the firm's managers will outsource nonstrategic manufacturing activities. For instance, Cisco depends on Flex Ltd., a contract manufacturer, to assemble many of its products.

Managerial control is another issue in the choice between internal and external capacity. Whenever a firm outsources an activity, it loses some control over it. Consider Cisco's relationship with Flex Ltd. No doubt Cisco and Flex Ltd. have a contract that establishes expected quality levels, volume levels, delivery times, and cost targets. However, Cisco's managers cannot just pick up the phone and tell Flex Ltd. to stop assembling another firm's products in order to make room for a new Cisco product. Cisco managers lose some control by outsourcing the company's assembly capacity.

The flip side of this is flexibility. A firm might favor the capacity alternative that requires the least commitment on its part, especially if long-term needs are uncertain. In the case of Ellison Seafood, while the common carrier option becomes quite expensive as the number of shipments increases, it is also the most flexible option. If it chooses this option, Ellison can decide to stop making shipments at any time and will not pay another dime for trucking.

6.4 UNDERSTANDING AND ANALYZING PROCESS CAPACITY

This section deals with the unique challenge of understanding and analyzing capacity in a *business process* environment. For example, think about a business process where work units (people or products) must travel through several different steps before they leave the process. How does the capacity at *each step* affect the capacity of the overall process? What impact does variability in arrival times and processing times have on the level of inventory and the length of time work units spend in the system? And what is the relationship between inventory levels, flow times, and process capacity? These are important and complex questions, and we use the Theory of Constraints, waiting line theory, and Little's Law to address them.

The Theory of Constraints

Theory of Constraints (TOC) An approach to visualizing and managing capacity which recognizes that nearly all products and services are created through a series of linked processes, and in every case, there is at least one process step that limits throughput for the entire chain.

Constraint The process step (or steps) that limits throughput for an entire process chain.

In recent years, a fundamentally different approach to visualizing and managing capacity has emerged. Developed by Eliyahu Goldratt,[4] the **Theory of Constraints (TOC)** is based on the recognition that many products and services proceed through a series of linked processes like the ones we described in Chapters 3 and 4. These process steps can be contained within a single organization or stretched across multiple organizations (i.e., a supply chain). Each process step has its own capacity level, and in every case there is at least one process step that limits throughput for the entire chain. This process step is referred to as the **constraint.** Consider Figure 6.7.

The movement of customers or products through a series of process steps is analogous to the movement of liquid through a pipeline. Each process step has a certain capacity, as represented by the diameter of the "pipe." In Figure 6.7, process E has the largest capacity, while process C has the smallest capacity. Because process C is the constraint, it will limit the amount of throughput for the entire process chain. Increasing the capacity at any other process step will not increase throughput for the entire process chain.

Figure 6.8 provides a numerical example. It should be clear from this simple illustration that process 3 limits total throughput for the chain to 40 units per hour. Pushing out more than 40 units an hour in processes 1 and 2 will simply create a glut of inventory in front of process 3. Furthermore, output from process 3 will limit process 4 to just 40 units per hour.

FIGURE 6.7 Throughput of a "Pipeline" Is Determined by the Smallest "Pipe"

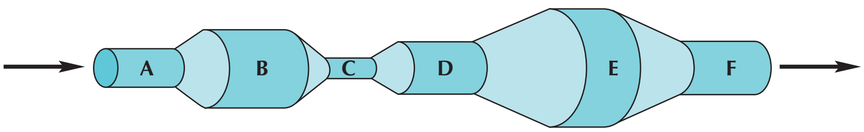
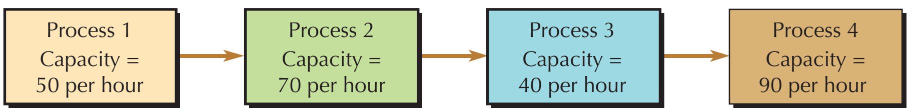


FIGURE 6.8 Throughput Is Controlled by the Constraint, Process 3



[4]E. Goldratt, *The Goal*, 2nd ed. (Great Barrington, MA: North River Press, 1992).

TOC experts have suggested a five-step approach to managing the constraint, and hence throughput, for a process chain:

1. **Identify the constraint.** The constraint can be anywhere in the chain—including upstream or downstream supply chain partners. When the constraint occurs outside the company, it is often referred to as an *external constraint*. In contrast, if the constraint is within a company's set of activities, it is referred to as an *internal constraint*. Consider Figure 6.8. Suppose customers are buying products at the rate of only 30 per hour. In this case, demand, not process 3, is the constraint.
2. **Exploit the constraint.** An hour of throughput lost at the constraint is an hour of throughput lost for the entire chain. It is, therefore, imperative that organizations carefully manage the constraint to ensure an uninterrupted flow of customers or products through the constraint.
3. **Subordinate everything to the constraint.** If conflicts arise between exploiting the constraint and efforts to "improve" performance elsewhere (e.g., letting an upstream process decrease inventory in a way that "starves" the constraint for work), management needs to remember that it is the constraint that determines throughput and act accordingly.
4. **Elevate the constraint.** If the organization needs to increase throughput, find ways to increase the capacity of the constraint.
5. **Find the new constraint and repeat the steps.** As the effective capacity of the constraint is increased, it may cease to be a constraint. In that case, the emphasis should shift to finding and exploiting the new constraint.

In Example 6.6, we illustrate how the Theory of Constraints can be applied in a simple service environment.

EXAMPLE 6.6

Constraint Management at Tracy's Hair Salon

Tracy's Hair Salon follows a three-step process in serving its customers. First, the customer's hair is shampooed. Next, a stylist cuts and styles the customer's hair. Finally, the customer pays $25 to the cashier.

At present, Tracy's Hair Salon has one shampooer, one stylist (Tracy), and one cashier (Tracy's son Larry). The average processing time for each worker, as well as his or her effective capacity and hourly wage, is shown in Table 6.5. Notice how the average processing time and effective capacity relate to one another. For example, it takes Tracy 15 minutes, on average, to cut and style a customer's hair. This implies that the effective capacity for a single stylist is (60 minutes)/(15 minutes per customer) $=$ 4 customers per hour. Although Tracy has never performed a detailed market study, her experience tells her that approximately 10 customers an hour would use her service *if* she had the capacity to handle them all.

TABLE 6.5 Capacity and Cost Data for Workers at Tracy's Hair Salon

	SHAMPOO	CUT AND STYLE	COLLECT MONEY
Average processing time per customer	10 minutes	15 minutes	3 minutes
Effective capacity per worker	6 per hour	4 per hour	20 per hour
Labor cost per worker	$15 per hour	$20 per hour	$10 per hour

Figure 6.9 shows the potential hourly demand as well as hourly capacities for each process step. As the bar graph shows, styling is the current constraint, limiting throughput to four customers per hour. Financially, this translates into revenues of 4 customers* $25 $=$ $100 an hour, for a profit of $55 after labor costs.

Constraint: Style step (Internal constraint)
Resulting process capacity: 4 customers per hour

Expected Hourly results:
Revenue: 4 customers *$25 = $100
Labor costs: (1 shampooer)*$15 + (1 stylist)*$20 + (1 cashier)$10 = $45
Profit = $100 – $45 = $55

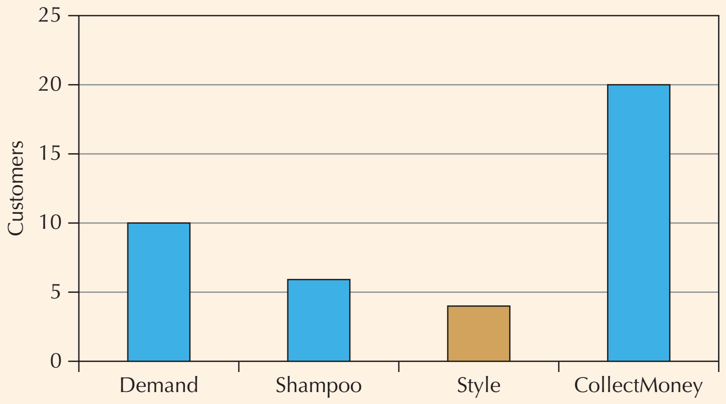


FIGURE 6.9 Tracy's Hair Salon, Current Process

Tracy wonders if she can do better. She decides to hire a second stylist, thereby doubling capacity at this step to eight customers per hour. The result, shown in Figure 6.10, is that the *shampoo step* becomes the new constraint (6 customers per hour), and profit improves to $85 per hour.

Constraint: Shampoo step (Internal constraint)
Resulting process capacity: 6 customers per hour

Expected Hourly results:
Revenue: 6 customers *$25 = $150
Labor costs: (1 shampooer)*$15 + (2 stylists)*$20 + (1 cashier)$10 = $65
Profit = $150 – $65 = $85

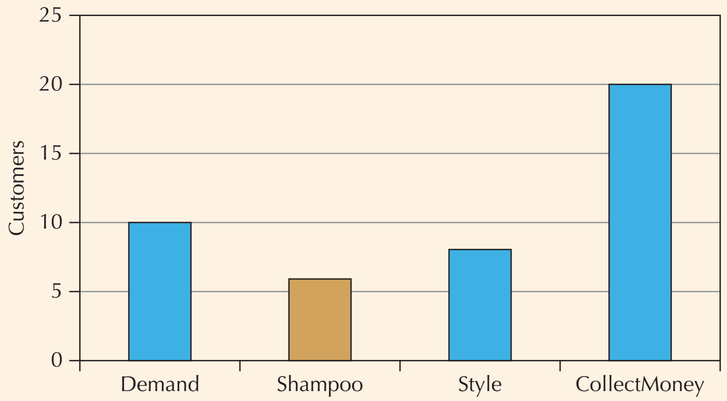


FIGURE 6.10 Tracy's Hair Salon, Adding a Second Stylist

Encouraged by the results, Tracy contemplates increasing her workforce to two shampooers, three stylists, and one cashier. Doing so would make *demand* the new constraint (Figure 6.11). But does hiring one additional shampooer and two additional stylists make financial sense? The results suggest yes: Revenues would increase to 10 customers * $25 = $250 per hour, while labor costs would increase to $100 per hour, resulting in an hourly profit of $150.

Even with all this expansion, Tracy notices that her cashier is not even close to being fully utilized. Maybe there are some other tasks she can have Larry do.

Constraint: Demand (External constraint)
Resulting process capacity: 10 customers per hour

Expected Hourly results:
Revenue: 10 customers *$25 = $250
Labor costs: (2 shampooers)*$15 + (3 stylists)*$20 + (1 cashier)$10 = $100
Profit = $250 – $100 = $150

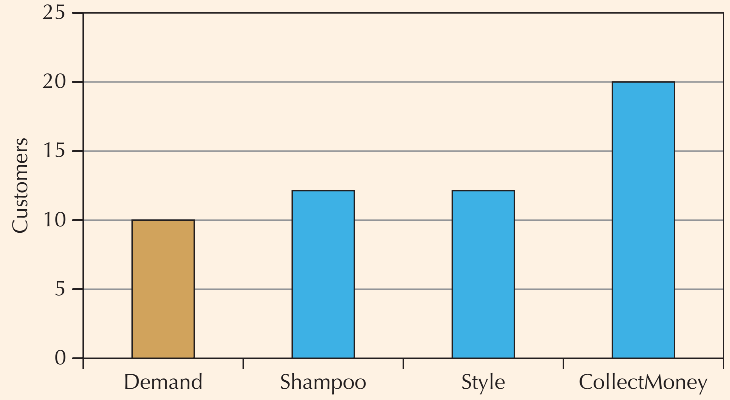


FIGURE 6.11 Tracy's Hair Salon, Adding One Shampooer and Two Stylists

Waiting Line Theory

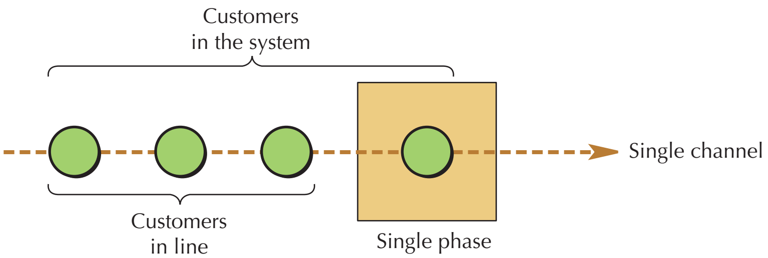
If you have ever sat in an emergency room, waiting for a doctor, you have experienced firsthand the relationship between capacity and waiting lines. Waiting lines are a concern for manufacturers as well. When materials and components must wait to be worked on, they tie up capital and push back the time manufacturers get paid by the customer.

The purpose here is twofold. First, we want to highlight the relationship between capacity and waiting lines. Second, we want to introduce you to some common tools that can be used to analyze waiting line performance. To illustrate the relationship between waiting lines and capacity, let's consider an environment we are all familiar with: the drive-up window at a fast-food restaurant. In the language of waiting lines, the drive-up window represents a *single-channel, single-phase system* (Figure 6.12). There is a single channel, or path, through the system. The single phase is at the drive-up window, where the employee takes your money and gives you your food.

If you have ever sat in line at a drive-up window, you may have thought about (or maybe cursed) the system's performance. Managers have the very same concerns. Some of the specific questions that managers have include the following:

- *What percentage* of the time will the server be busy?
- On average, *how long* will a customer have to wait in line? How long will the customer be in the system (i.e., waiting and being served)?
- On average, *how many* customers will be in line?
- How will these averages be affected by the arrival rate of customers and the service rate of the drive-up window personnel?

FIGURE 6.12
Single-Channel, Single-Phase System



Ryan McVay/Photodisc/Getty Images

Long wait times can dramatically affect customers' perceptions of service performance. As a result, many service firms use waiting line theory to understand how capacity decisions affect waiting times.

Waiting line theory
A body of theory based on applied statistics that helps managers evaluate the relationship between capacity decisions and important performance issues such as waiting times and line lengths.

Fortunately, researchers have developed a body of theory based on applied statistics to address these types of questions. **Waiting line theory** helps managers evaluate the relationship between capacity decisions and such important performance issues as waiting times and line lengths.

Following are some of the key assumptions and terminology of waiting line theory and some basic formulas for determining waiting line performance for a single-channel, single-phase system. We should point out that there are many different waiting line environments, most of which are much more complex than the example we will present. In some cases, no formulas exist for estimating waiting line performance. When this occurs, more sophisticated simulation modeling techniques are needed to analyze the systems. The supplement at the end of this chapter discusses simulation modeling in more detail.

Arrivals. In most waiting line models, customers are assumed to arrive at *random* intervals, based on a Poisson distribution. The probability of n arrivals in T time periods is calculated as follows:

$$P_n = \frac{(\lambda T)^n}{n!} e^{-\lambda T} \quad \textbf{(6.6)}$$

where:

P_n = probability of n arrivals in T time periods
λ = arrival rate
T = number of time periods

EXAMPLE 6.7

Arrivals at a Drive-Up Window

Customers arrive at a drive-up window at a rate of three per minute ($\lambda = 3$). If the number of arrivals follows a Poisson distribution, what is the probability that two or fewer customers would arrive in 1 minute?

The probability of two or fewer customers is actually the probability of no arrivals *plus* the probability of one arrival *plus* the probability of two arrivals, or:

$$P(\leq 2) = P(0) + P(1) + P(2)$$
$$= 0.050 + 0.149 + 0.224 = 0.423, \text{ or } 42.3\%$$

Service Times. As with arrivals, waiting line models assume that service times will either be constant (a rare occurrence) or vary. In the latter case, modelers often use the exponential distribution to model service times, using the symbol μ to refer to the service rate.

Priority rules
Rules for determining which customer, job, or product is processed next in a waiting line environment.

Other Assumptions. Finally, we need to make some assumptions about the order in which customers are served, the size of the customer population, and whether customers can balk or renege. We will assume that customers are served on a first-come, first-served (FCFS) basis. Other **priority rules** might consider the urgency of the customers' needs (as in an emergency room), the speed with which customers can be served, or even the desirability of different customer types. In addition, we will assume that the population of customers is effectively infinite; that is, we are not likely to run through all the possible customers any time soon. This assumption seems reasonable for a fast-food restaurant next to a busy highway. On the other hand, different formulas are needed if the population is substantially restricted.

We will also assume that customers enter the system and remain there until they are served, regardless of the length of the line or the time spent waiting. They neither balk (i.e., decide against entering the system to begin with) nor renege (i.e., leave the line after entering).

With that background, we can now apply some basic formulas. Suppose that customers arrive at a rate of four per minute ($\lambda = 4$) and that the worker at the drive-up window is able to handle, on average, five customers a minute ($\mu = 5$). The average utilization of the system is:

$$\rho = \frac{\lambda}{\mu} \qquad \textbf{(6.7)}$$

where:

ρ = average utilization of the system
λ = arrival rate
μ = service rate

For the drive-up example, $\rho = \frac{\lambda}{\mu} = 4/5$, or 80%.

"Great!" you say. "It looks like we have plenty of capacity. After all, the drive-up window is not being fully utilized." But there is a catch. Because the actual number of arrivals per minute and the service rate *both vary*, there can be periods of time where there is no one in line, but other times when significant queues develop. For instance, the drive-up window may go for 2 minutes without a customer, only to have four SUVs filled with screaming kids pull up at the same time.

In fact, according to waiting line theory, the *average number of customers waiting* (C_W) at the drive-up window can be calculated using the following formula:

$$C_W = \frac{\lambda^2}{\mu(\mu - \lambda)} \qquad \textbf{(6.8)}$$

And the *average number of customers in the system* (C_S) is:

$$C_S = \frac{\lambda}{\mu - \lambda} \qquad \textbf{(6.9)}$$

EXAMPLE 6.8

Average Number of Customers Waiting and in the System at a Drive-Up Window

Given an arrival rate of four customers per minute and a service rate of five customers per minute, the average number of customers waiting is:

$$C_W = \frac{\lambda^2}{\mu(\mu - \lambda)} = \frac{16}{5(1)} = 3.2 \text{ customers}$$

And the average number in the system is:

$$C_S = \frac{\lambda}{\mu - \lambda} = \frac{4}{1} = 4 \text{ customers}$$

But what about the average amount of *time* customers spend waiting and in the system? There are formulas to estimate these values as well:

$$\text{Average time spent waiting} = T_W = \frac{\lambda}{\mu(\mu - \lambda)} \qquad \textbf{(6.10)}$$

$$\text{Average time spent in the system} = T_S = \frac{1}{\mu - \lambda} \qquad \textbf{(6.11)}$$

EXAMPLE 6.9

Average Time a Customer Spends Waiting and in the System at a Drive-Up Window

Returning to the drive-up example, the average time spent waiting is:

$$T_W = \frac{\lambda}{\mu(\mu - \lambda)} = \frac{4}{5(1)} = 0.80 \text{ minutes, or 48 seconds}$$

And the average time spent in the system (waiting and being served) is:

$$T_S = \frac{1}{\mu - \lambda} = \frac{1}{1} = 1 \text{ minute}$$

The results in Examples 6.7 through 6.9 may not surprise you, but look at what happens as the arrival rate approaches the service rate (Table 6.6). *Even though the utilization level never reaches 100%,* the lines and waiting times get longer and longer—in fact, they grow exponentially. Note that the formulas don't even work for arrival rates greater than the service rate. This is because, under such conditions, the systems can never reach a steady-state, "average" level.

All of this points to an important general truth:

In operations and supply chain environments that must deal with random demand and variable processing times, it is virtually impossible to achieve very high capacity utilization levels and still provide acceptable customer service.

Some organizations get around this by attempting to "de-randomize" demand. For example, doctors' offices make appointments, and manufacturers fit jobs into a preset schedule. But this is not always an option. If you are injured in a car wreck, you need an ambulance now, not three hours from now. Capacity decisions in such environments often come down to striking the best balance between costs and customer service.

Suppose that the fast-food restaurant in our example can have a second worker help out at the drive-up window for $15,000 a year. The second worker would allow the drive-up window to handle six customers per minute. As Table 6.7 shows, waiting line performance statistics would improve considerably. Whether or not the restaurant should expand capacity may ultimately depend on whether the additional revenue from shorter lines and happier customers offsets the cost of hiring the second worker.

TABLE 6.6 **Waiting Line Performance (service rate = 5 customers per minute)**

ARRIVAL RATE (CUSTOMERS PER MINUTE)	AVERAGE UTILIZATION OF THE SYSTEM (ρ)	AVERAGE NUMBER OF CUSTOMERS WAITING (C_W)	AVERAGE TIME SPENT WAITING (MINUTES) (T_W)
3.0	60.0%	0.90	0.30
3.1	62.0%	1.01	0.33
3.2	64.0%	1.14	0.36
3.3	66.0%	1.28	0.39
3.4	68.0%	1.45	0.43
3.5	70.0%	1.63	0.47
3.6	72.0%	1.85	0.51
3.7	74.0%	2.11	0.57
3.8	76.0%	2.41	0.63
3.9	78.0%	2.77	0.71
4.0	**80.0%**	**3.20**	**0.80**
4.1	82.0%	3.74	0.91
4.2	84.0%	4.41	1.05
4.3	86.0%	5.28	1.23
4.4	88.0%	6.45	1.47
4.5	90.0%	8.10	1.80
4.6	92.0%	10.58	2.30
4.7	94.0%	14.73	3.13
4.8	96.0%	23.04	4.80
4.9	98.0%	48.02	9.80
4.95	99.0%	98.01	19.80
4.995	99.9%	998.00	199.80

TABLE 6.7 Waiting Line Performance (service rate = 6 customers per minute)

ARRIVAL RATE (CUSTOMERS PER MINUTE)	AVERAGE UTILIZATION OF THE SYSTEM (ρ)	AVERAGE NUMBER OF CUSTOMERS WAITING (C_W)	AVERAGE TIME SPENT WAITING (MINUTES) (T_W)
3.0	50.0%	0.50	0.17
3.1	51.7%	0.55	0.18
3.2	53.3%	0.61	0.19
3.3	55.0%	0.67	0.20
3.4	56.7%	0.74	0.22
3.5	58.3%	0.82	0.23
3.6	60.0%	0.90	0.25
3.7	61.7%	0.99	0.27
3.8	63.3%	1.09	0.29
3.9	65.0%	1.21	0.31
4.0	**66.7%**	**1.33**	**0.33**
4.1	68.3%	1.47	0.36
4.2	70.0%	1.63	0.39
4.3	71.7%	1.81	0.42
4.4	73.3%	2.02	0.46
4.5	75.0%	2.25	0.50
4.6	76.7%	2.52	0.55
4.7	78.3%	2.83	0.60
4.8	80.0%	3.20	0.67
4.9	81.7%	3.64	0.74
4.95	82.5%	3.89	0.79
4.995	83.3%	4.14	0.83

EXAMPLE 6.10

Waiting Line Performance at a Snappy Lube

Snappy Lube is a quick-change oil center with a single service bay. On average, Snappy Lube can change a car's oil in 10 minutes. Cars arrive, on average, every 15 minutes. From these numbers, we can estimate the average arrival rate and service rate:

$$\text{Arrival rate} = \lambda = 60 \text{ minutes}/15 \text{ minutes} = 4 \text{ per hour}$$
$$\text{Service rate} = \mu = 60 \text{ minutes}/10 \text{ minutes} = 6 \text{ per hour}$$

Therefore:

$$\text{Average utilization} = 4/6 = 67\%$$
$$\text{Average number of cars waiting} = 16/(6{*}2) = 1.33 \text{ cars}$$
$$\text{Average number of cars in the system} = 4/2 = 2 \text{ cars}$$
$$\text{Average time spent waiting} = 4/(6{*}2) = 0.33 \text{ hour}$$
$$\text{Average time spent in the system} = 1/2 = 0.50 \text{ hour}$$

Little's Law

As you might have realized in our discussion of waiting line theory, there is a relationship between the number of units in the system and time spent in the system. *Little's Law*[5] formalizes this relationship:

$$I = RT \tag{6.12}$$

where:

I = average number of units in the system (also called *inventory*)

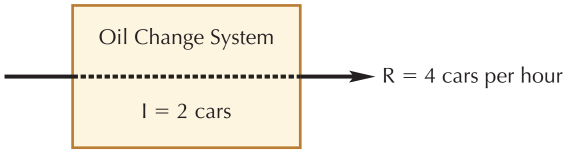
R = average arrival rate (i.e., *throughput rate*)

T = average time a unit spends in the system (i.e., *throughput time*)

Little's Law holds for any system that has reached *steady state*. The steady state is the point where inventory has had time to build up in the system and the average number of arrivals per period of time equals the average number of units leaving the system.

[5] Named for John D. C. Little, who provided the first mathematical proof for it in 1961.

FIGURE 6.13
Using Little's Law to Analyze Snappy Lube



T = I/R = (2 cars)/(4 cars per hour) = 0.5 hours

To illustrate how we can use Little's Law, let's return to Snappy Lube from Example 6.10. Figure 6.13 shows what the system looks like.

Snappy Lube's throughput rate is four cars per hour. This is because, even though Snappy Lube is capable of handling up to six cars per hour, it cannot handle cars faster than the cars arrive. As we calculated in Example 6.10, the average number of cars in the Snappy Lube system is two. It stands to reason, then, that if Snappy Lube is processing four cars per hour, and the average inventory is two cars, each car will spend on average (2 cars/4 cars per hour) = 0.5 hours in the system.

While Little's Law may seem rather simple, it's actually very powerful. A major advantage of Little's Law is that the relationships expressed in Equation (6.12) are always true, regardless of how complex the system is, how much arrivals or service times vary, or what the flow units are (money, people, orders, etc.). Furthermore, we can apply Little's Law to a single activity, a multistep process, or even an entire supply chain. Example 6.11 illustrates how Little's Law can be applied in a more complex business situation.

EXAMPLE 6.11
Applying Little's Law in a Manufacturing Plant

A manufacturing plant has 100 orders arrive each day (Figure 6.14) All orders go through the order processing area, where, on average, there are 25 orders in the system. Of the incoming orders, 70% are "A" orders, which are routed through workcenter A, where the average inventory of orders is 14. The remaining 30% are "B" orders, which are routed through workcenter B, where the average inventory is 1.5 orders. Because the total number of orders that exit the system (70 + 30) equals the number coming in, the system is in steady state.

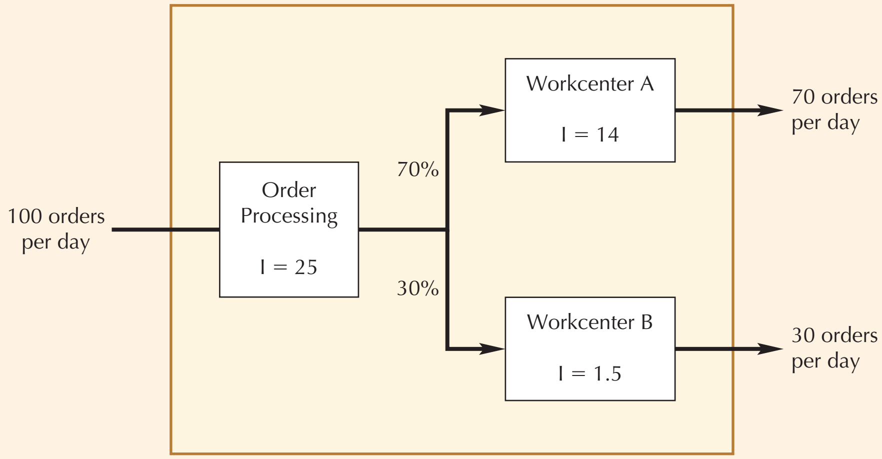


FIGURE 6.14 Order Flow in a Manufacturing Environment

The plant manager wants to know, on average:

1. How long does an order (A or B) stay in the order processing area?
2. How long does it take an A order to work its way through the plant?
3. How long does it take a B order to work its way through the plant?
4. How long does it take the average order (A or B) to work its way through the plant?

To answer the first question, note that the throughput rate for order processing is 100 orders per day. Since the average inventory level in the order processing area is 25, the average throughput time for just this step is calculated as:

$$T = I/R = (25 \text{ orders})/(100 \text{ orders per day}) = 0.25 \text{ days in order processing}$$

70 orders per day go through workcenter A. Therefore, the estimated average time an order spends in workcenter A is:

$$T = I/R = (14 \text{ orders})/(70 \text{ orders per day}) = 0.2 \text{ days in workcenter A}$$

Putting together these two pieces of information, we find that the amount of time the average A order spends in the plant is:

$$\text{Order processing time} + \text{workcenter A time}$$
$$= 0.25 \text{ days} + 0.2 \text{ days} = 0.45 \text{ days}$$

By analogy, the amount of time the average B order spends in the plant is:

$$\text{Order processing time} + \text{workcenter B time}$$
$$= 0.25 \text{ days} + (1.5 \text{ orders}/30 \text{ orders per day})$$
$$= 0.25 \text{ days} + 0.05 \text{ days} = 0.30 \text{ days}$$

Now for the last question: How much time does the *average* order stay in the plant? One way to determine this is to take a weighted average of the times for the A orders and the B orders:

$$70\%{*}0.45 \text{ days} + 30\%{*}\,0.30 \text{ days} = 0.405 \text{ days for the average order}$$

But a more clever way is to recognize that for the *entire* system, throughput rate $R = 100$ and average inventory $I = 25 + 14 + 1.5 = 40.5$. The estimated average throughput time for the entire system can then be calculated as:

$$T = I/R = (40.5 \text{ orders})/(100 \text{ orders per day}) = 0.405 \text{ days for the average order}$$

This result reinforces the idea that Little's Law can be used to analyze the process or system at multiple levels.

CHAPTER SUMMARY

Capacity decisions are among the most important strategic decisions operations and supply chain managers make. As the opening case study on adding pharmaceutical manufacturing capacity suggests, such decisions can have far-reaching effects for a business, its customers, and even society. Even though capacity decisions are inherently risky, this chapter showed how managers can think about and analyze these decisions in a logical manner.

Specifically, we talked about three common capacity strategies and also demonstrated various methods for evaluating the financial pros and cons of capacity alternatives. We devoted the last section of the chapter to analyzing *process* capacity using the Theory of Constraints (TOC), waiting line theory, and Little's Law. These advanced perspectives help us understand how capacity behaves across a supply chain, how higher resource levels drive down waiting times, and the relationship between inventory, throughput times, and throughput rates.

KEY FORMULAS

Total cost of a capacity alternative (page 147):

$$TC = FC + VC{*}X \quad \textbf{(6.1)}$$

where:

TC = total cost
FC = fixed cost
VC = variable cost per unit of business activity
X = amount of business activity (number of customers served, number of units produced, etc.)

Expected value of a capacity alternative (page 149):

$$EV_j = \sum_{i=1}^{I} P_i C_i \quad \textbf{(6.2)}$$

where:

EV_j = expected value of capacity alternative j

P_i = probability of demand level i

C_i = financial result (cost, revenue, or profit) at demand level i

Break-even point (page 153):

$$BEP = \frac{FC}{R - VC} \tag{6.3}$$

where:

BEP = break-even point

FC = fixed cost

V = variable cost per unit of business activity

R = revenue per unit of business activity

Productivity (page 153):

$$\text{Productivity} = \text{outputs/inputs} \tag{6.4}$$

Learning curve theory estimate of resources (usually labor) required to complete the *n*th unit (page 153):

$$T_n = T_1 n^b \tag{6.5}$$

where:

T_n = resources (usually labor) required for the nth unit

T_1 = resources required for the 1st unit

b = ln(Learning percentage)/ln2

Probability of *n* arrivals in *T* time periods (page 161):

$$P_n = \frac{(\lambda T)^n}{n!} e^{-\lambda T} \tag{6.6}$$

where:

P_n = probability of n arrivals in T time periods

λ = arrival rate

T = number of time periods

Average utilization of a waiting line system (page 162):

$$\rho = \frac{\lambda}{\mu} \tag{6.7}$$

where:

λ = arrival rate

μ = service rate

Average number of customers waiting in a waiting line (page 162):

$$C_W = \frac{\lambda^2}{\mu(\mu - \lambda)} \tag{6.8}$$

Average number of customers in the waiting line system (page 162):

$$C_S = \frac{\lambda}{\mu - \lambda} \tag{6.9}$$

Average time spent waiting in a waiting line (page 162):

$$T_W = \frac{\lambda}{\mu(\mu - \lambda)} \tag{6.10}$$

Average time spent in the waiting line system (page 162):

$$T_S = \frac{1}{\mu - \lambda} \tag{6.11}$$

Little's Law (page 164):

$$I = RT \qquad \textbf{(6.12)}$$

where:

I = average number of units in the system (also called *inventory*)
R = average arrival rate (i.e., *throughput rate*)
T = average time a unit spends in the system (i.e., *throughput time*)

KEY TERMS

USING EXCEL IN CAPACITY MANAGEMENT

Many of the capacity decision models we have shown in this chapter can easily be incorporated into a spreadsheet application, such as Microsoft Excel. The following spreadsheet calculates the break-even points and indifference points for three capacity alternatives.

For instance, the break-even point for option B (cell C14) is calculated as follows:

$$BEP = \text{fixed cost}/(\text{revenue per unit} - \text{variable cost per unit})$$

$$= C8/(D4 - D8) = 14.71$$

Likewise, the indifference point for options B and C (cell E15) is:

$$= \frac{(\text{option C fixed cost} - \text{option B fixed cost})}{(\text{option B variable cost} - \text{option C variable cost})}$$

$$= (C9 - C8)/(D8 - D9)$$

$$= 366.67$$

Of course, the key advantage of using the spreadsheet is that we can quickly evaluate new scenarios simply by changing the input values.

	A	B	C	D	E	F
1	**Evaluating Alternative Capacity Options**					
2	**(Enter inputs in shaded cells)**					
3						
4		Revenue per unit of output:		$100.00		
5						
6		Capacity Option	Fixed cost	Variable cost per unit of output	Max. output	
7		Option A	$0.00	$30.00	200	
8		Option B	$1,250.00	$15.00	300	
9		Option C	$4,000.00	$7.50	400	
10						
11				*** Indifference Points ***		
12			*** Break-even point ***	Option A	Option B	Option C
13		Option A	0.00	---		
14		Option B	14.71	83.33	---	
15		Option C	43.24	177.78	366.67	---

SOLVED PROBLEM

PROBLEM

Auvia Cruise Lines

With the market for luxury cruises burgeoning, Auvia Cruise Lines is debating whether to invest in a large cruise ship to serve what would be a new market for the company—cruises around Alaska. This is no small investment: Auvia management figures that the new 86,000-gross-registered-tons vessel will cost approximately \$375 million. Spread over 25 years (the useful life of the ship), this amounts to a fixed cost of \$375 million/25 = \$15 million per year. The new ship can carry 2,000 passengers at a time, or up to 40,000 per year.

Management has determined that the average passenger will generate revenues of \$2,400 and variable costs of \$1,300. Furthermore, marketing has put together the following demand estimates for the new cruise:

ANNUAL DEMAND (PASSENGERS)	PROBABILITY
10,000	30%
30,000	50%
38,000	20%

Calculate the yearly break-even point for the new cruise ship. Determine the expected value of the new cruise ship and draw out the decision tree for Auvia Cruise Lines.

Solution

The break-even point for the new cruise ship is:

$$FC + VC(X) = R(X)$$
$$\$15{,}000{,}000 + \$1{,}300X = \$2{,}400X$$
$$X = \$15{,}000{,}000/\$1{,}100, \textit{ or about 13,636 passengers per year}$$

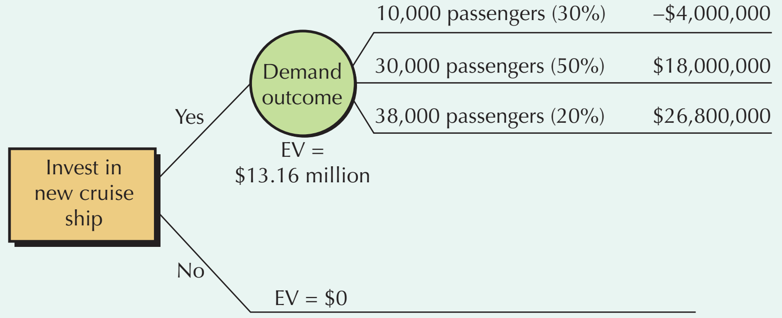
And the expected financial results under the three demand scenarios are as follows:

$$(R - VC) * X - FC$$
$$\text{10,000 passenger: } (\$2{,}400 - \$1{,}300) * 10{,}000 - \$15{,}000{,}000 = -\$4{,}000{,}000$$
$$\text{30,000 passenger: } (\$2{,}400 - \$1{,}300) * 30{,}000 - \$15{,}000{,}000 = \$18{,}000{,}000$$
$$\text{38,000 passenger: } (\$2{,}400 - \$1{,}300) * 38{,}000 - \$15{,}000{,}000 = \$26{,}800{,}000$$

The expected value is simply the average of these three results, weighted by the respective probabilities:

$$\text{Expected value for the new cruise ship} =$$
$$30\% * (-\$4{,}000{,}000) + 50\% * (\$18{,}000{,}000) + 20\% * (\$26{,}800{,}000) = \$13{,}160{,}000$$

The decision tree follows. Note that the expected value of not investing in the new ship is \$0. This reflects the fact that if Auvia does not invest in the new ship, it will incur neither the expenses nor the revenues associated with cruises around Alaska. If Auvia is willing to take the risk of losing up to \$4 million a year, the new cruise line looks very promising.



DISCUSSION QUESTIONS

1. Which type of operations and supply chain environment do you think would have a more difficult time managing capacity—an environment supporting standardized products/services or one supporting customized products/services? Why?
2. What kind of capacity strategy—lead, lag, or match—would you expect a fire station to follow? What about a driver's license testing center? Why?
3. Who do you think would benefit more from a "virtual supply chain" capacity strategy—a small start-up firm with few resources or an older, more established company? Why? What are the risks associated with such a strategy?
4. The manager at a grocery store says to you, "I want my checkout clerks to be busy 100% of the time. I can't afford to have them sit around." How would you use waiting line theory to explain the problems with this thinking? Is there some way to have checkout clerks do productive work even when they aren't dealing with customers?
5. What are the relationships among learning, productivity, and effective capacity? What are the pros and cons of using learning curves to estimate future resource requirements?
6. A manufacturer takes raw material from a supplier, processes it using a single manufacturing step, and then sells it to its customers. Suppose the manufacturer decides to double the capacity of the manufacturing step. Under what conditions will throughput for the system double? What other factors might be constraining the throughput of the system?

PROBLEMS

(* = easy; ** = moderate; *** = advanced)

Problems for Section 6.3: Methods of Evaluating Capacity Strategies

1. (*) The Shelly Group has leased a new copier that costs $700 per month plus $0.10 for each copy. What is the total cost if Shelly makes 5,000 copies a month? If it makes 10,000 copies a month? What is the per-copy cost at 5,000 copies? At 10,000 copies?
2. Arktec Manufacturing must choose between the following two capacity options:

	FIXED COST (PER YEAR)	VARIABLE COST (PER UNIT)
Option 1	$500,000	$2 per unit
Option 2	$100,000	$10 per unit

   a. (*) What would the cost be for each option if the demand level is 25,000 units per year? If it is 75,000 units per year?
   b. (**) In general, which option do you think would be better as volume levels increase? As they decrease? Why?
   c. (*) What is the indifference point?

3. (*) Suppose the Shelly Group has identified two possible demand levels for copies per month:

COPIES (PER MONTH)	PROBABILITY
5,000	50%
10,000	50%

What is the expected cost if it costs $700 per month to lease a new copier and the variable cost is $0.10 for each copy?

4. Consider the two capacity options for Arktec Manufacturing shown below:

	FIXED COST (PER YEAR)	VARIABLE COST (PER UNIT)
Option 1	$500,000	$2 per unit
Option 2	$100,000	$10 per unit

Suppose the company has identified the following three possible demand scenarios:

DEMAND (UNITS PER YEAR)	PROBABILITY
25,000	30%
60,000	40%
100,000	30%

   a. (**) What is the expected value of each option? Which option would you choose, based on this information?
   b. (**) Suppose the lowest and highest demand levels are updated to 40,000 and 110,000, respectively. Recalculate the expected values. What happened?
   c. (**) Draw the decision tree for Arktec Manufacturing. When drawing your tree, assume that managers must select a capacity option *before* they know what the demand level will actually be.
   d. (**) Calculate the expected value for each decision branch. Which option would you prefer? Why?

5. You are the new CEO of DualJet, a U.S. company that makes premium kitchen stoves for home use. You must decide whether to assemble the stoves in-house or to have a Mexican company do it. The fixed and variable costs for each option are as follows:

	FIXED COST	VARIABLE COST
Assemble in-house	$55,000	$620
Contract with Mexican assembler	$0	$880

   a. (**) Suppose DualJet's premium stoves sell for $2,500. What is the break-even volume point for assembling the stoves in-house?
   b. (*) At what volume level do the two capacity options have identical costs?
   c. (**) Suppose the expected demand for stoves is 3,000. Which capacity option would you prefer, from a cost perspective?

6. Emily Watkins, a recent college graduate, faces some tough choices. Emily must decide whether to accept an offer for a job that pays $35,000 or hold out for another job that pays $45,000 a year. Emily thinks there is a 75% chance that she will get an offer for the higher-paying job. The problem is that Emily has to make a decision on the lower-paying job within the next few days, and she will not know about the higher-paying job for two weeks.

a. (**) Draw out the decision tree for Emily Watkins.
b. (**) What is the key decision Emily faces? What is the expected value of each decision branch?
c. (**) What other factors might Emily consider, aside from expected value?

7. Philip Neilson owns a fireworks store. Philip's fixed costs are $12,000 a month, and each fireworks assortment he sells costs, on average, $8. The average selling price for an assortment is $25.

a. (*) What is the break-even point for Philip's fireworks store?

Suppose Philip decides to expand his business. His new fixed expenses will be $20,000, but the average cost for a fireworks assortment will fall to just $5 due to Philip's higher purchase volumes.

b. (*) What is the new break-even point?
c. (**) At what volume level is Philip indifferent to the two capacity alternatives outlined above?

8. Merck is considering launching a new drug called Laffolin. Merck has identified two possible demand scenarios:

DEMAND LEVEL	PROBABILITY
1 million patients	30%
2 million patients	70%

Merck also has the following information:

Revenue	$140 per patient
Fixed costs to manufacture and sell Laffolin	$70 million
Variable costs to manufacture and sell Laffolin	$80 per patient
Maximum number of patients that Merck can handle	3 million

a. (*) How many patients must Merck have in order to break even?
b. (**) How much money will Merck make if demand for Laffolin is 1 million patients? If demand is 2 million patients?
c. (**) What is the expected value of making Laffolin?
d. (**) Draw the decision tree for the Laffolin decision, showing the profits for each branch (Total revenues – total variable costs – total fixed costs) and all expected values.

9. Clay runs a small hotdog stand in downtown Chapel Hill. Clay can serve about 30 customers an hour. During lunchtime, customers randomly arrive at a rate of 20 per hour.

a. (*) What percentage of the time is Clay busy?
b. (*) On average, how many customers are waiting to be served? How many are in the system (i.e., waiting and being served)?
c. (*) On average, how long will a customer wait to be served? How long will a customer be in the system?

10. Peri Thompson is the sole dispatcher for Thompson Termite Control. Peri's job is to take customer calls, schedule appointments, and in some cases resolve any service or billing questions while the customer is on the phone. Peri can handle about 15 calls an hour.

a. (*) Typically, Peri gets about 10 calls an hour. Under these conditions, what is the average number of customers waiting, and what is the average waiting time?
b. (**) Monday mornings are unusually busy. During these peak times, Peri receives around 13 calls an hour, on average. Recalculate the average number of customers waiting and the average waiting time. What can you conclude?

11. Benson Racing is training a new pit crew for its racing team. For its first practice run, the pit crew is able to complete all the tasks in exactly 30 seconds—not exactly world-class. The second time around, the crew shaves 4.5 seconds off its time.

a. (*) Estimate the learning rate for the pit crew, based on the times for the first two practice runs.
b. (**) Mark Benson, owner of Benson Racing, says that the pit crew must be able to complete all the tasks in less than 15 seconds in order to be competitive. Based on your answer to part a, how many times will the pit crew need to practice before it breaks the 15-second barrier?
c. (**) Is it realistic to expect the pit crew to experience learning improvements indefinitely? Explain.

12. Wake County has a special emergency rescue team. The team is practicing rescuing dummies from a smoke-filled building. The first time, the team took 240 seconds (4 minutes). The second time, it took 180 seconds (3 minutes).

a. (*) What is the estimated learning rate for the rescue team, based on the information provided?
b. (**) Suppose that the team's learning rate for the rescue exercise is 80%. How many times will the team need to repeat the exercise until its time is *less than 120 seconds* (50% of the original time)?
c. (**) How long will it take the emergency team to perform its 20th rescue if the learning rate is 80%?

13. After graduating from college, your friends and you start an Internet job search site called TriangCom. Business has been fantastic, with 10 million customer hits to the site in the past year. You have several capacity decisions to consider. One key decision involves the number of computer servers needed. You are considering putting in 10, 20, or 30 servers. Costs and capacity limits are as follows:

NUMBER OF SERVERS	FIXED COST PER YEAR	VARIABLE COST PER HIT	MAXIMUM HITS PER YEAR
10	$50,000	$.005	20 million
20	$90,000	$.003	40 million
30	$120,000	$.002	60 million

In addition, marketing has developed the following demand scenarios:

YEARLY DEMAND	PROBABILITY
15 million hits	30%
30 million hits	60%
45 million hits	10%

Finally, TriangCom generated $5 million last year, based on 10 million hits. Put another way, each hit generated, on average, $0.50 in revenue.

a. (**) Calculate the break-even point for each capacity alternative.
b. (**) At what demand level will you be indifferent to having either 10 or 20 servers?
c. (***) Calculate the expected value for each capacity alternative. (*Hint:* Don't forget about capacity constraints that can limit the number of hits each capacity alternative can handle.) Which alternative will you prefer if you want to maximize the expected value?

TriangCom has hired Donna Olway to add new features to the Web site. Donna completes her first job in five weeks and her second job in four weeks. Assume that (1) Donna continues to learn at this rate and (2) her time improvements will follow a learning curve.

d. (**) How long will you expect Donna to take to complete her sixth job?
e. (**) How long will you expect Donna to take to complete the next five jobs (jobs 3 through 7)?

With thousands of customers, TriangCom has established a hotline to take customer calls. The hotline is staffed by one person 24 hours a day. You have the following statistics:

Service rate for calls	15 per hour, on average
Arrival rate for calls	11 per hour, on average

As part of your customer service policy, you have decided that the average waiting time should not exceed 2.5 minutes.

f. (*) What is the average number of callers being served?
g. (*) On average, how many callers are waiting to be served?
h. (**) What is the average waiting time for a customer? Is this time acceptable, given the customer service policy?

14. Rich Sawyer runs a landscaping firm. Each year Rich contracts for labor and equipment hours from a local construction company. The construction company has given Rich three different capacity options:

CAPACITY OPTION	LABOR HOURS	EQUIPMENT HOURS
High capacity	9,000	6,000
Medium capacity	6,750	4,500
Low capacity	4,500	3,000

Cost per labor hour:	$10 per hour
Cost per equipment hour:	$20 per hour

Once Rich has chosen a capacity option, he cannot change it later. In addition, the cost for each capacity option is fixed. That is, Rich must pay for all labor and equipment hours he contracts for, even if he doesn't need them all. Therefore, there are essentially no variable costs. Rich also has information concerning the amount of revenue and the labor and equipment hours needed for the "typical" landscaping job:

Job revenue	$2,000 per job
Labor hours per job	30 hours
Equipment hours per job	20 hours

Finally, Rich has identified three possible demand levels. These demand levels, with their associated probabilities, are as follows:

DEMAND LEVEL	NUMBER OF JOBS	PROBABILITY
High demand	300	30%
Medium demand	200	40%
Low demand	120	30%

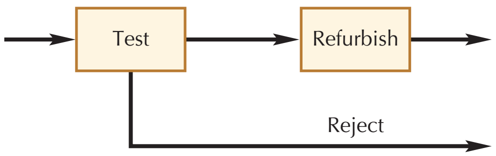
a. (***) Determine the total fixed costs and the break-even point for each capacity option. What is the maximum number of jobs that can be handled under each capacity option?
b. (***) Draw a decision tree for Rich's firm. What are the nine possible outcomes Rich is facing? (*Hint:* One is "Rich subcontracts for low capacity and demand turns out to be low.") What is the profit (Revenue − fixed costs) associated with each of the nine outcomes? Be sure to consider the capacity limits of each alternative when calculating revenues.
c. (***) Using the information from part b, calculate the expected profit of each capacity alternative. Which option will Rich prefer if he wants to maximize expected profit?

15. (***) (*Microsoft Excel problem*) The following figure shows an expanded version of the Excel spreadsheet described in *Using Excel in Capacity Management*. In addition to the break-even and indifference points, the expanded spreadsheet calculates financial results for three capacity options under three different demand scenarios. **Re-create this spreadsheet in Excel.** You should develop the spreadsheet so that the results will be recalculated if any of the values in the highlighted cells are changed. Your formatting does not have to be exactly the same, but the numbers should be. (As a test, see what happens if you change the "Max. output" and "Variable cost" for Capacity Option A to 250 units and $35, respectively. Your new expected value for Capacity Option A should be $14,218.75.)

	A	B	C	D	E	F
1	**Evaluating Alternative Capacity Options**					
2	**(Enter inputs in shaded cells)**					
3						
4		Revenue per unit of output:		$100.00		
5						
6		Capacity Option	Fixed cost	Variable cost per unit of output	Max. output	
7		Option A	$0.00	$30.00	200	
8		Option B	$1,250.00	$15.00	300	
9		Option C	$4,000.00	$7.50	400	
10						
11		Demand Scenario	Demand level	Probability		
12		Low	125	25%		
13		Medium	275	55%		
14		High	425	20%		
15			Total:	100%		
16						
17				*** Indifference Points ***		
18			*** Break-even point ***	Option A	Option B	Option C
19		Option A	0.00	---		
20		Option B	14.71	83.33	---	
21		Option C	43.24	177.78	366.67	---
22						
23			*** Results for different capacity/demand combinations ***			
24						
25			Low	Medium	High	*** Expected value ***
26		Option A	$8,750.00	$14,000.00	$14,000.00	$12,687.50
27		Option B	$9,375.00	$22,125.00	$24,250.00	$19,362.50
28		Option C	$7,562.50	$21,437.50	$33,000.00	$20,281.25

Problems from Section 6.4: Understanding and Analyzing Process Capacity

16. The Lenovo Refurbishing Center repairs used laptops that are returned under warranty.

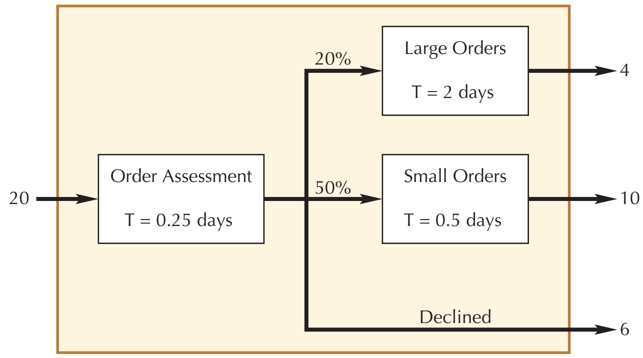


- The center receives and processes, on average, 200 laptops per day.
- All laptops are tested upon receipt: 30% are immediately rejected, and the remaining 70% are sent to the refurbishing area.
- On average, there are 21 laptops in the testing area waiting or being worked on.
- On average, there are 16 laptops in the refurbishing area waiting or being worked on.

a. (*) What is the average throughput time for *all* laptops entering the system?

b. (**) What is the average throughput time for a laptop that goes through both testing and refurbishing? Suppose Lenovo wants this time to be less than one day. Is the current system meeting this performance goal? Justify your answer.

17. ABS sells construction materials to commercial and home builders. One of ABS's key processes is the order fulfillment process shown below and described as follows:



- **All orders are assessed on arrival.** Of the orders, 30% are immediately declined for various reasons. The typical order spends 0.25 days in this order assessment step before moving on.
- **20% of all orders are large orders.** Average total time in this large orders processing step, including waiting and actual process time, is 2 days.

- **50% of all orders are small orders.** Average time in this small orders processing step, including waiting and processing, is 0.5 days.
- **ABS receives an average of 20 order requests a day.** The system is currently in steady state.

a. (**) What is the estimated total inventory for the entire order fulfillment process?

b. (**) Based on the information given above and your answer to part a, what is the estimated total flow time for the average order entering the process?

CASE STUDY

Forster's Market

Introduction

Forster's Market is a retailer of specialty food items, including premium coffees, imported crackers and cheeses, and the like. Last year, Forster's sold 14,400 pounds of coffee. Forster's pays a local supplier $3 per pound and then sells the coffees for $7 a pound.

The Roaster Decision

While Forster's makes a handsome profit on the coffee business, owner Robbie Forster thinks he can do better. Specifically, Robbie is considering investing in a large industrial-sized coffee roaster that can roast up to 40,000 pounds per year. By roasting the coffee himself, Robbie will be able to cut his coffee costs to $1.60 a pound. The drawback is that the roaster will be quite expensive; fixed costs (including the lease, power, training, and additional labor) will run about $35,000 every year.

The roaster capacity will also be significantly more than the 14,400 pounds that Forster's needs. However, Robbie thinks he will be able to sell coffee to area restaurants and coffee shops for $2.90 a pound. Robbie has outlined three possible demand scenarios:

Low demand	18,000 pounds per year
Medium demand	25,000 pounds per year
High demand	35,000 pounds per year

These numbers include the 14,400 pounds sold at Forster's Market. In addition, Robbie thinks all three scenarios are equally likely.

Questions

1. What are the two capacity options that Robbie needs to consider? What are their fixed and variable costs? What is the indifference point for the two options? What are the implications of the indifference point?
2. Draw the decision tree for the roaster decision. If Forster's does not invest in the roaster, does Robbie need to worry about the different demand scenarios outlined above? Why or why not?
3. Calculate the expected value for the two capacity options. Keep in mind that, for the roaster option, any demand above 14,400 pounds will generate revenues of only $2.90 a pound. Update the decision tree to show your results.
4. What is the worst possible financial outcome for Forster's? The best possible financial outcome? What other factors—core competency, strategic flexibility, etc.—should Robbie consider when making this decision?

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SUPPLEMENT

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CHAPTER six

SUPPLEMENT OUTLINE

Advanced Waiting Line Theory and Simulation Modeling

SUPPLEMENT OBJECTIVES

By the end of this supplement, you will be able to:

- Use statistics-based formulas to estimate waiting line lengths and waiting times for three different types of waiting line systems.
- Develop a simple Monte Carlo simulation using Microsoft Excel, and develop and analyze a system using SimQuick.

INTRODUCTION

Chapter 6 introduced waiting line theory and provided some formulas for calculating waiting times and line lengths for a simple waiting line situation. In this supplement, we describe two additional waiting line environments and demonstrate how statistically derived formulas can be used to assess the performance of these systems as well.

The second half of this supplement introduces simulation modeling. Simulation is often described in conjunction with waiting lines because many complex waiting line systems cannot be analyzed using neatly derived formulas. That said, simulation can be used in any environment where actual occurrences of interest—arrivals, quality problems, work times, etc.—can be modeled mathematically. We show how Monte Carlo simulation can be used to develop a very simple simulation using Excel. We then use one particular simulation package, SimQuick, to illustrate simulation model building and analysis.

6S.1 ALTERNATIVE WAITING LINES

In Chapter 6, we illustrated how waiting line theory works, using the example of a waiting line environment with a single path through one process step. In that example, both the arrival rate and service rate were probabilistic. In the language of waiting line theory, this is known as a *single channel, single phase system* (see Figure 6S.1).

We then illustrated how statistics-based formulas could be used to answer questions such as:

- What percentage of the time will the process be busy?
- On average, *how long* will a unit have to wait in line? How long will it be in the system (i.e., waiting and being served)?
- On average, *how many* units will be in line?
- How will these averages be affected by the arrival rate of units and the service rate at the process step?

Of course, there are many waiting line environments that do not fit this mold. An automatic car wash, for example, may have one line and one process step, but the service time is *constant*. Or we may be interested in a multiple-channel, single-phase system, such as a bank. Here, there is only a one-process step, but there can be multiple paths through the system, depending on how many tellers are working (see Figure 6S.2).

Or we may be interested in a single-channel, multiple-phase system. Examples include a hospital emergency room, where you wait to check in (phase 1) and then you wait to see a doctor or nurse (phase 2). Figure 6S.3 illustrates such a system. We can even have multiple-channel, multiple-phase systems. In general, the more complex the environment, the less likely we are to be able to analyze it using preestablished formulas.

In the remainder of this supplement, we review some of the key assumptions and terminology that make up waiting line theory and introduce some formulas for determining waiting line performance for two additional waiting line environments: the single-channel, single-phase system with constant service times and the multiple-channel, single-phase system. In the second half of the supplement, we introduce simulation modeling, which can be used to model more complex environments.

FIGURE 6S.1
Single-Channel, Single-Phase System

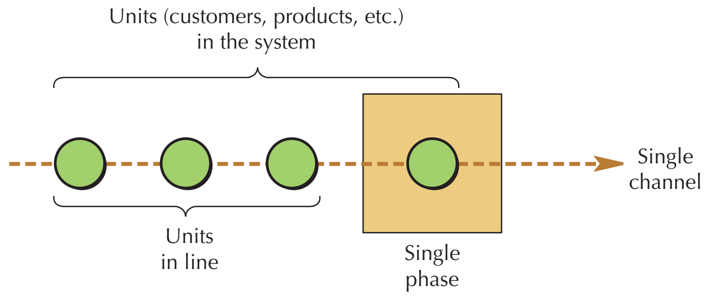


FIGURE 6S.2
Multiple-Channel, Single-Phase System

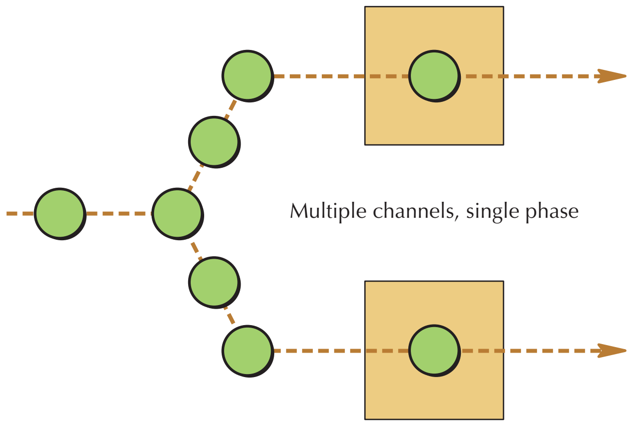
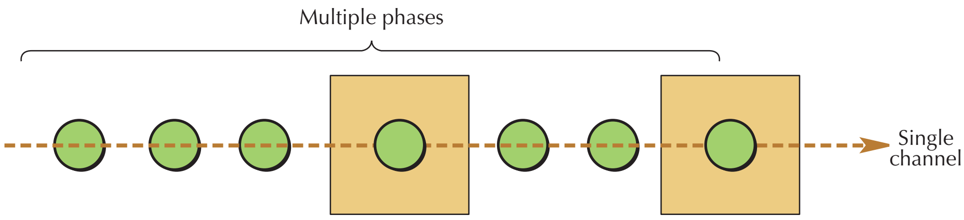


FIGURE 6S.3
Single-Channel, Multiple-Phase System



Assumptions behind Waiting Line Theory

Arrivals. In most waiting line models, customers are assumed to arrive at random intervals, based on a Poisson distribution. The probability of n arrivals in T time periods is calculated as follows:

$$P_n = \frac{(\lambda T)^n}{n!} e^{-\lambda T} \quad \textbf{(6S.1)}$$

where:

P_n = probability of n arrivals in T time periods
λ = arrival rate
T = number of time periods

Service Times. Waiting line models assume that service times will either be constant or vary. In the latter case, modelers often use the exponential distribution to model service times, using the symbol μ to refer to the service rate.

Other Assumptions. Finally, we need to make some assumptions about the order in which customers are served, the size of the customer population, and whether customers can balk or renege. All waiting line formulas assume that customers are served on a first-come, first-served (FCFS) basis. Other priority rules might consider the urgency of the customers' needs (as in an emergency room), the speed with which customers can be served, or the desirability of different customer types. In addition, we will assume that the population of customers is effectively infinite; that is, we are not likely to run through all the possible customers anytime soon.

Finally, we will assume that customers enter the system and remain there until they are served, regardless of the length of the line or time spent waiting. They neither balk (decide against entering the system to begin with) nor renege (leave the line after entering).

Waiting Line Formulas for Three Different Environments

Table 6S.1 contains formulas for estimating performance in three different waiting line environments. In all three cases, the formulas require that we know:

- The average number of arrivals per period of time, λ
- The average time each server takes to service a unit, μ

TABLE 6S.1 Waiting Line Formulas for Three Different Environments

WAITING LINE ENVIRONMENT: λ = **average number of arrivals per period of time** μ = **average time each server takes to service a unit** M = **number of channels**	**AVERAGE NUMBER OF UNITS WAITING, C_W**	**AVERAGE NUMBER OF UNITS IN SYSTEM, C_S**	**AVERAGE TIME SPENT WAITING, T_W**	**AVERAGE TIME SPENT IN SYSTEM, T_S**
Single-channel, single-phase system with Poisson arrivals and exponential service times	$\frac{\lambda^2}{\mu(\mu - \lambda)}$ **(6S.2)**	$C_W + \frac{\lambda}{\mu}$ **(6S.3)**	$\frac{\lambda}{\mu(\mu - \lambda)}$ **(6S.4)**	$T_W + \frac{1}{\mu}$ **(6S.5)**
Single-channel, single-phase system with Poisson arrivals and constant service times	$\frac{\lambda^2}{2\mu(\mu - \lambda)}$ **(6S.6)**	$C_W + \frac{\lambda}{\mu}$ **(6S.7)**	$\frac{\lambda}{2\mu(\mu - \lambda)}$ **(6S.8)**	$T_W + \frac{1}{\mu}$ **(6S.9)**
Multiple-channel, single-phase system with Poisson arrivals and exponential service times ("multi-server model") where: P_0 = probability of 0 units in the system $= \frac{1}{\left[\sum_{n=0}^{M-1} \frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n\right] + \frac{1}{M!}\left(\frac{\lambda}{\mu}\right)^M \left(\frac{M\mu}{M\mu - \lambda}\right)}$ **(6S.10)**	$C_S - \frac{\lambda}{\mu}$ **(6S.11)**	$\frac{\lambda\mu\left(\frac{\lambda}{\mu}\right)^M}{(M - 1)!(M\mu - \lambda)^2} P_0 + \left(\frac{\lambda}{\mu}\right)$ **(6S.12)**	$T_S - \frac{1}{\mu}$ **(6S.13)**	$\frac{\mu\left(\frac{\lambda}{\mu}\right)^M}{(M - 1)!(M\mu - \lambda)^2} P_0 + \left(\frac{1}{\mu}\right)$ **(6S.14)**

The first row of formulas is for a single-channel, single-phase system with probabilistic arrivals and service times. These are the same formulas we used in Chapter 6 to introduce waiting line theory. The second row is for a single-channel, single-phase system where service times are constant. The third row described a multiple-channel, single-phase system (Figure 6S.2). We illustrate how these formulas can be used in Examples 6S.1 through 6S.3.

EXAMPLE 6S.1

Luc's Deluxe Car Wash, Part 1: Probabilistic Arrivals and Service Times

Luc Shields, an enterprising high school student, runs a car wash where he has a single crew of workers wash cars by hand (i.e., a single-channel, single-phase system). Cars arrive about every 8 minutes, on average. Luc's crew can wash, on average, one car every 6 minutes. Arrivals follow a Poisson distribution, and the service times are exponentially distributed.

Luc would like to estimate (1) the average number of cars waiting and in the system and (2) the average time a car spends waiting and in the system. From the information provided, we know that:

$$\text{Arrival rate} = \lambda = \frac{60 \text{ minutes}}{8 \text{ minutes}} = 7.5 \text{ cars per hour}$$

$$\text{Service rate} = \mu = \frac{60 \text{ minutes}}{6 \text{ minutes}} = 10 \text{ cars per hour}$$

Therefore, applying Equations (6S.2) through (6S.5):

$$\text{Average number of cars waiting } (C_w) = \frac{\lambda^2}{\mu(\mu - \lambda)} = \frac{7.5^2}{10(10 - 7.5)} = 2.25 \text{ cars}$$

$$\text{Average number of cars in the system } (C_s) = C_w + \frac{\lambda}{\mu} = 2.25 + 0.75 = 3 \text{ cars}$$

$$\text{Average time a car spends waiting } (T_w) = \frac{\lambda}{\mu(\mu - \lambda)} = \frac{7.5}{10(10 - 7.5)}$$
$$= 0.3 \text{ hours, or about 18 minutes}$$

$$\text{Average time a car spends in the system } (T_s) = T_w + \frac{1}{\mu} = 0.3 + 0.1$$
$$= 0.4 \text{ hours, or about 24 minutes}$$

EXAMPLE 6S.2

Luc's Deluxe Car Wash, Part 2: Probabilistic Arrivals and Constant Service Times

Luc is contemplating replacing his work crew with an automated car wash system. Although the automated system is no faster than the current work crew, it can handle cars at a *constant* rate of one car every 6 minutes. Luc is not sure if this would make any difference with regard to the waiting line performance at his car wash, so he decides to use the equations in Table 6S.1 to find out.

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Notice that the arrival rate and service rate are still 7.5 cars and 10 cars per hour, respectively. The difference is that the service rate no longer follows an exponential distribution but is constant. Applying Equations (6S.6) through (6S.9), Luc gets the following estimates:

$$\text{Average number of cars waiting } (C_w) = \frac{\lambda^2}{2\mu(\mu - \lambda)} = \frac{7.5^2}{20(10 - 7.5)} = 1.125 \text{ cars}$$

$$\text{Average number of cars in the system } (C_s) = C_w + \frac{\lambda}{\mu} = 1.125 + 0.75 = 1.875 \text{ cars}$$

$$\text{Average time a car spends waiting } (T_w) = \frac{\lambda}{2\mu(\mu - \lambda)} = \frac{7.5}{20(10 - 7.5)}$$
$$= 0.15 \text{ hours, or about 9 minutes}$$

$$\text{Average time a car spends in the system } (T_s) = T_w + \frac{1}{\mu} = 0.15 + 0.10$$
$$= 0.25 \text{ hours, or about 15 minutes}$$

Looking at the results, Luc is surprised to see that average number of cars waiting and average time waiting are cut in half. The results impress upon Luc the negative impact of variability on process performance and capacity requirements.

EXAMPLE 6S.3

Luc's Deluxe Car Wash, Part 3: Adding a Second Crew

Even though Luc likes the fact that an automated car wash system with constant service time would decrease waiting times and line lengths, he doesn't feel that he can afford the investment at this point. Rather, Luc is thinking about adding a second crew. This would effectively make his car wash a multiple-channel, single-phase system, where $M = 2$. Assuming that the second crew has the same service rate numbers as the first ($\mu = 10$; service times are exponentially distributed), Luc can estimate the performance of the system by using Equations (6S.10) through (6S.14). To use these equations, we must first calculate the probability of zero cars in the system:

$$P_0 = \frac{1}{\left[\sum_{n=0}^{M-1} \frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n\right] + \frac{1}{M!}\left(\frac{\lambda}{\mu}\right)^M\left(\frac{M\mu}{M\mu - \lambda}\right)}$$

$$= \frac{1}{\left[1 + \frac{7.5}{10}\right] + \frac{1}{2!}\left(\frac{7.5}{10}\right)^2\left(\frac{2*10}{2*10 - 7.5}\right)}$$

$$= \frac{1}{1.75 + \frac{1}{2}(0.5625)(1.6)} = \frac{1}{1.75 + 0.45} = 0.4545$$

Plugging the resulting P_0 value into the formula for C_s:

$$C_s = \frac{\lambda\mu\left(\frac{\lambda}{\mu}\right)^M}{(M-1)!(M\mu - \lambda)^2}P_0 + \left(\frac{\lambda}{\mu}\right) = \frac{7.5 \times 10\left(\frac{7.5}{10}\right)^2}{(2 \times 10 - 7.5)^2} \times (0.4545) + (7.5/10)$$

$$= \left(\frac{42.1875}{156.25}\right) \times (0.4545) + (7.5/10) = 0.873 \text{ cars in the system, on average}$$

The average number of cars waiting:

$$C_w = C_s - \frac{\lambda}{\mu} = 0.873 - 0.75 = 0.123 \text{ cars}$$

The average time a car spends in the system:

$$T_s = \frac{\mu\left(\frac{\lambda}{\mu}\right)^M}{(M-1)!(M\mu - \lambda)^2}P_0 + \left(\frac{1}{\mu}\right) = \frac{10\left(\frac{7.5}{10}\right)^2}{(20-7.5)^2}0.4545 + 0.10$$

$$= \left(\frac{5.625}{156.25}\right)0.4545 + 0.10 = 0.12 \text{ hours, or about 7 minutes}$$

Finally, we can calculate the average time a car spends waiting:

$$T_w = T_s - \frac{1}{\mu} = 0.12 - 0.10 = 0.02 \text{ hours, or roughly 1 minute}.$$

6S.2 SIMULATION MODELING

APICS defines simulation as "the technique of using representative or artificial data to reproduce in a model various conditions that are likely to occur in the actual performance of a system."[1] Although simulations can include physical re-creations of an actual system, most business simulations are computer based and use mathematical formulas to represent actual systems or policies. Simulation models have a number of advantages:

1. **Offline evaluation of new processes or process changes.** Simulation models allow the user to experiment with processes or operating procedures without endangering the performance of real-world systems. For example, the user can test new systems or evaluate the impact of changes to processes or procedures prior to implementing them.
2. **Time compression.** Simulation models allow the user to compress time. Many days, months, or even years of activity can be simulated in a short period of time.
3. **"What-if" analyses.** This type of analysis can be particularly valuable in understanding how processes or procedures would perform under extreme conditions. What if the demand rate were to double? What if one of our key support centers went down? With simulation models, managers can get an idea of the impact prior to an actual occurrence.

Of course, simulations also have disadvantages:

1. **They are, at best, only approximations of reality.** Most simulation models—like the waiting line formulas we reviewed in the first half of the supplement—make simplifying assumptions about how the real world works. While these assumptions make the model easier to develop and understand, they also make it less realistic.
2. **The more realistic a simulation model, the more costly it will be to develop and the more difficult it will be to interpret.** This is related to the first point. Model developers must strike a balance between cost, ease of use, and realism.
3. **Simulation models do not provide an "optimal" solution.** Simulation models reflect only the conditions and rules of the environments they are set up to model, not an optimal solution. This is in contrast to optimization models, discussed in Chapter 7, which do attempt to provide the user with a solution that optimizes some objective such as cost minimization or profit maximization.

[1]Definition of *simulation* in J. H. Blackstone, ed., *APICS Dictionary*, 15th ed. (Chicago, IL: APICS, 2016). Reprinted by permission.

Monte Carlo Simulation

By far, the most common form of simulation modeling is mathematical simulation, where mathematical formulas and statistical processes are used to simulate activities, decisions, and the like. One particularly well-known approach is *Monte Carlo simulation*, a technique in which statistical sampling is used to generate outcomes for a large number of trials. The results of these trials are then used to gain insight into the system of interest.

Monte Carlo simulation is used to simulate all types of systems and many types of statistical distributions. To illustrate the basic principles of the technique, we will examine a very simple system everyone is familiar with: flipping a coin. You probably understand that for a fair coin toss, each outcome—heads or tails—has a 50% chance of occurring. And you probably also understand that the outcome for any particular flip is *memoryless*; that is, the probability of coming up heads or tails is unaffected by what happened previously. Still, you may wonder how the pattern of outcomes might play out over, say, 50 flips.

Figure 6S.4 shows an Excel-based Monte Carlo simulation model for 50 coin flips, or trials. The random numbers for the 50 trials were generated using the following Excel formula:

=RAND()*100

This Excel formula generates a random number between 0 and 100, with all numbers having an equal probability of being generated. The adjacent column in the spreadsheet then translates these results into heads or tails. For example:

Formula for cell C6: = IF(B6 < 50, “Tails”, “Heads”)

FIGURE 6S.4
Excel-Based Monte Carlo Simulation of 50 Coin Tosses

	A	B	C	D	E	F	G
1	Monte Carlo simulation of 50 coin tosses						
2	Excel-generated random numbers generated between 0 and 100						
3	“Tails” if random number <50, “Heads” otherwise						
4							
5	**Trial**	**Random Number**	**Simulated Outcome**		**Trial**	**Random Number**	**Simulated Outcome**
6	1	75.79	Heads		26	41.23	Tails
7	2	54.88	Heads		27	28.41	Tails
8	3	3.20	Tails		28	80.16	Heads
9	4	89.32	Heads		29	79.27	Heads
10	5	64.62	Heads		30	6.34	Tails
11	6	25.56	Tails		31	89.72	Heads
12	7	60.99	Heads		32	14.85	Tails
13	8	77.68	Heads		33	15.76	Tails
14	9	77.14	Heads		34	99.29	Heads
15	10	51.42	Heads		35	40.66	Tails
16	11	14.43	Tails		36	19.91	Tails
17	12	27.02	Tails		37	55.73	Heads
18	13	25.73	Tails		38	83.07	Heads
19	14	43.28	Tails		39	69.75	Heads
20	15	36.91	Tails		40	14.89	Tails
21	16	49.08	Tails		41	45.60	Tails
22	17	88.84	Heads		42	0.40	Tails
23	18	45.94	Tails		43	80.11	Heads
24	19	97.69	Heads		44	16.58	Tails
25	20	27.94	Tails		45	19.35	Tails
26	21	78.90	Heads		46	15.19	Tails
27	22	90.03	Heads		47	32.78	Tails
28	23	64.11	Heads		48	25.08	Tails
29	24	60.71	Heads		49	95.15	Heads
30	25	2.02	Tails		50	45.36	Tails

Translated, if the random number in cell B6 is less than 50, write "Tails" in the cell; otherwise, write "Heads." Looking at the results, we can see that "Tails" came up 27 times and "Heads" came up 23 times—not exactly a 50/50 balance, but close. In addition, we can see that the simulated results do not alternate back and forth between heads and tails. In fact, there are several runs of four or more heads or tails.

Monte Carlo simulation can be used to simulate other statistical distributions as well. Figure 6S.5 shows another Excel-based Monte Carlo simulation model. In this case, we are trying to simulate arrivals, based on a Poisson distribution and an average arrival rate per time period of 3.

First, the spreadsheet calculates the probability of 0 through 8 arrivals per time period using Equation (6S.1). Notice that the total of these probabilities is essentially 100%. Next, we assigned random numbers between 0 and 100 to each possible arrival quantity. For example, there is a 5% chance of 0 arrivals. Therefore, we assigned all numbers r that meet the condition ($0 \leq r < 5$) to represent 0 arrivals. Since the probability of drawing such a number using the =RAND()*100 equation is also 5%, we can use this method to accurately simulate Poisson-distributed arrivals. Arrivals of 1 through 8 units per time period were simulated in a similar fashion.

FIGURE 6S.5
Excel-Based Monte Carlo Simulation of Poisson-Distributed Arrivals

Monte Carlo simulation of Poisson-distributed arrivals			
Arrival rate (λ) = 3			
Arrivals	Probability of n Arrivals	Cumulative Probability	Assigned Random Numbers (r) (0 to 100)
0	5%	5%	$0 \leq r < 5$
1	15%	20%	$5 \leq r < 20$
2	22%	42%	$20 \leq r < 42$
3	22%	64%	$42 \leq r < 65$
4	17%	82%	$65 \leq r < 82$
5	10%	92%	$82 \leq r < 92$
6	5%	97%	$92 \leq r < 97$
7	2%	99%	$97 \leq r < 99$
8	1%	100%	99 or greater
Time Period	Random no.	Simulated Arrivals	
1	75.60	4	
2	74.03	4	
3	80.70	4	
4	22.18	2	
5	88.12	5	
6	75.95	4	
7	47.38	3	
8	10.63	1	
9	34.96	2	
10	42.99	3	
11	83.14	5	
12	2.68	0	
13	8.21	1	
14	73.41	4	
15	39.71	2	
16	73.79	4	
17	99.70	8	
18	22.89	2	
19	19.32	1	
20	64.51	3	
	Average:	3.1	

The bottom half of Figure 6S.5 presents results for 20 simulated time periods. Notice how the simulated arrivals range anywhere from 0 to 8. For this particular simulation, the average arrival rate is 3.1, close to the expected arrival rate of 3 per time period.

Building and Evaluating Simulation Models with SimQuick

Developing a useful simulation model can require a great deal of creativity and practice, but the basic process can be divided into four steps:

1. Develop a picture of the system to be modeled. The process mapping material in Chapter 4 can be particularly helpful in this regard.
2. Identify the objects, elements, and probability distributions that define the system. *Objects* are the people or products that move through the system, while *elements* are pieces of the system itself, such as lines, workstations, and entrance and exit points.
3. Determine the experimental conditions and required output information. Many simulation packages provide the user with options regarding the output reports that are generated.
4. Build and test the simulation model for your system and capture and evaluate the relevant data.

When the process to be modeled is fairly complex, it usually makes sense to use a specialized simulation software package. These packages can range from very sophisticated applications that provide graphics and sophisticated what-if analyses and make use of existing company databases to simple stand-alone packages. In the following example, we build and test a simulation model of Luc's Deluxe Car Wash, using SimQuick,[2] a highly intuitive, easy-to-learn simulation package that runs under Microsoft Excel.

EXAMPLE 6S.4

Simulating Operations at Luc's Deluxe Car Wash

While Luc is generally happy with the statistics he was able to generate using the waiting line formulas (Examples 6S.1–6S.3), one thing troubles him: All of these statistics describe *averages*—average wait time, average number of cars in the system, and so on. They don't tell Luc how long the lines can actually get or what the maximum time might look like.

Luc's car wash is pictured in Figure 6S.6. For simulation modeling purposes, Luc's car wash has four elements: the car entrance, the driveway (where cars wait for an available crew), the crew, and washed cars. Two of these elements—cars arriving and the crews washing cars—are controlled by probability distributions.

Figure 6S.7 shows how the same system is defined in SimQuick. The first box is labeled "Simulation Controls." Luc has set the simulation to cover five iterations of 3,600 minutes each. In effect, *each* iteration represents a workweek consisting of five 12-hour days, or 3,600 minutes. The fact that Luc can run the simulation in a matter of seconds illustrates the time compression advantages of simulation.

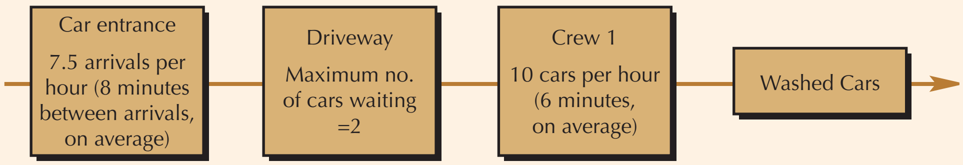

FIGURE 6S.6 Luc's Car Wash

[2]D. Hartvigsen, *SimQuick: Process Simulation in Excel*, Third Edition, 2016.

	A	B	C	D	E	F
1	**Model View**					
2	(Note: Cannot edit model here)					
3						
4		**Simulation Controls:**				
5						
6		Time units per simulation →	3,600			
7		Number of simulations →	5			
8						
9						
10		**Entrances:**				
11						
12						
13		**Name** →	Cars			
14		Time between arrivals →	Exp(8)			
15		Num. objects per arrivals →	1			
16		Output				
17		destination(s) ↓				
18		Driveway				
19						
20						
21						
22		**Work Stations:**				
23						
24						
25			**Name** →	Crew 1		
26			Working time →	Exp(6)		
27		Output	# of output	Resource	Resource	
28		destination(s) ↓	objects ↓	name(s) ↓	#units needed ↓	
29		Washed Cars				
30						
31						
32						
33		Buffers:				
34						
35		1			2	
36		**Name** →	Driveway		**Name** →	Washed Cars
37		Capacity →	10,000		Capacity →	10,000
38		Initial # objects →	0		Initial # objects →	0
39		Output	Output		Output	Output
40		destination(s) ↓	group size ↓		destination(s) ↓	group size ↓
41		Crew 1	1			
42						

FIGURE 6S.7 **SimQuick Model Specification for Single-Channel, Single-Phase System, Luc's Deluxe Car Wash**

The simulation model has one entrance point, "Cars." Cars arrive based on an exponential distribution, with an average of 8 minutes between arrivals. Note that this is the *same* as saying that the arrivals are Poisson-distributed with an average of

$$\frac{60 \text{ minutes}}{8 \text{ minutes}} = 7.5 \text{ arrivals per hour}.$$

Once a car arrives, it goes to the driveway, which is the first buffer point in the model. For now, Luc assumes that there is unlimited room for cars to wait here ("Capacity → 10,000"). If the washing crew is not busy, the car will immediately proceed to the workstation "Crew 1." Otherwise, it will wait in the driveway.

The earlier examples stated that a crew can wash, on average, 10 cars per hour. This is the same as saying that the time it takes to wash a car is 6 minutes, on average ("Exp(6)"). Once a car is finished, it proceeds to the "Washed Cars" buffer. By modeling the system this way, Luc can track how many cars are completed by the end of each iteration.

Figure 6S.8 shows the overall simulation results for five iterations of 3,600 minutes each (five workweeks, each consisting of five 12-hour days).

	A	B	C	D	E	F	G	H
1	**Results**							
2								
3	**Element**	**Statistics**	**Overall**	**Simulation Numbers**				
4	**names**		**means**	**1**	**2**	**3**	**4**	**5**
5								
6	Cars	Objects entering process	447.40	460	471	460	424	422
7		Objects unable to enter	0.00	0	0	0	0	0
8		Service level	1.00	1.00	1.00	1.00	1.00	1.00
9								
10	Crew 1	Final status	NA	Working	Working	Working	Working	Working
11		Final inventory (int. buff.)	0.00	0	0	0	0	0
12		Mean inventory (int. buff.)	0.00	0.00	0.00	0.00	0.00	0.00
13		Mean cycle time (int. buff.)	0.00	0.00	0.00	0.00	0.00	0.00
14		Work cycles started	444.20	459	466	453	421	422
15		Fraction time working	0.77	0.77	0.81	0.79	0.75	0.73
16		Fraction time blocked	0.00	0.00	0.00	0.00	0.00	0.00
17								
18	Driveway	Objects leaving	444.20	459	466	453	421	422
19		Final inventory	3.20	1	5	7	3	0
20		Minimum inventory	0.00	0	0	0	0	0
21		Maximum inventory	15.80	13	21	22	13	10
22		Mean inventory	2.58	2.07	3.74	3.84	1.75	1.47
23		Mean cycle time	20.64	16.22	28.89	30.55	15.01	12.54
24								
25	Washed Cars	Objects leaving	0.00	0	0	0	0	0
26		Final inventory	443.20	458	465	452	420	421
27		Minimum inventory	0.00	0	0	0	0	0
28		Maximum inventory	443.20	458	465	452	420	421
29		Mean inventory	219.71	233.76	228.58	223.11	196.72	216.40
30		Mean cycle time	Infinite	Infinite	Infinite	Infinite	Infinite	Infinite

FIGURE 6S.8 Simulation Results for Single-Channel, Single-Phase System, Luc's Deluxe Car Wash

Statistics regarding waiting times and waiting line lengths can be found by looking at the "Driveway" results. In this case, "inventory" represents cars waiting to be washed. The average inventory is 2.58 cars, and the mean cycle (i.e., waiting) time is 20.64 minutes. It's interesting to compare the simulation results to the formula-derived results in Example 6S.1:

$$\text{Formula-derived estimate of average number of cars waiting } (C_w) = 2.25 \text{ cars}$$

$$\text{Simulation estimate of average number of cars waiting} = 2.58 \text{ cars}$$

$$\text{Formula-derived estimate of average waiting time } (T_w) = 0.3 \text{ hours, or about 18 minutes}$$

$$\text{Simulation estimate of average number of cars waiting} = 20.64 \text{ minutes}$$

Figure 6S.8 also shows that the average maximum number of cars in line across all five simulations was 15.8, and the fraction of time the washing crew was busy was 0.77, or 77%.

EXAMPLE 6S.5

Simulating the Impact of Limited Waiting Space at Luc's Deluxe Car Wash

Satisfied that the simulation model adequately reflects his business, Luc decides to modify the model to capture one key characteristic that has not yet been considered: *There is only enough room in the driveway for two cars to be waiting*. This means that if the crew is busy washing a car and two cars are already waiting, any other car that drives up will have to go elsewhere. Luc wonders how this would affect the results.

The modified simulation model is identical to the one shown in Figure 6S.7, *except now the capacity for the driveway buffer is set at 2*. Simulation results for this new model are shown in Figure 6S.9.

	A	B	C	D	E	F	G	H
1	**Results**							
2								
3	**Elements**	**Statistics**	**Overall**	**Simulation Numbers**				
4	**names**		**means**	**1**	**2**	**3**	**4**	**5**
5								
6	Cars	Objects entering process	378.20	386	376	373	−396	360
7		Objects unable to enter	61.40	65	49	62	68	63
8		Service level	0.86	0.86	0.88	0.86	0.85	0.85
9								
10	Crew 1	Final status	NA	Working	Working	Not Working	Working	Not Working
11		Final inventory (int.buff.)	0	0	0	0	0	0
12		Mean inventory (int.buff.)	0.00	0.00	0.00	0.00	0.00	0.00
13		Mean cycle time (int.buff.)	0.00	0.00	0.00	0.00	0.00	0
14		Work cycle started	377.60	384	376	373	395	360
15		Fraction time working	0.64	0.65	0.60	0.61	0.69	0.63
16		Fraction time blocked	0.00	0.00	0.00	0.00	0.00	0.00
17								
18	Driveway	Objects leaving	377.60	384	376	373	395	360
19		Final inventory	0.60	2	0	0	1	0
20		Minimum inventory	0.00	0	0	0	0	0
21		Maximum inventory	2.00	2	2	2	2	2
22		Mean inventory	0.49	0.53	0.40	0.43	0.59	0.51
23		Mean cycle time	4.68	4.93	3.85	4.12	5.41	5.10
24								
25	Washed Cars	Objects leaving	0.00	0	0	0	0	0
26		Final inventory	377.00	383	375	373	394	360
27		Minimum inventory	0.00	0	0	0	0	0
28		Maximum inventory	377.00	383	375	373	394	360
29		Mean inventory	187.57	194.89	188.37	188.99	195.84	169.77
30		Mean cycle time	Infinite	Infinite	Infinite	Infinite	Infinite	Infinite

FIGURE 6S.9 Simulation Results for Single-Channel, Single-Phase System, with Driveway Capacity Limited to Two Cars

Looking at the results, Luc can clearly see the impact the small driveway is having on his business. According to the simulation results, on average, 61.4 cars per week are unable to enter the process. Because fewer cars enter the system, the fraction of time the washing crew is busy also suffers. In fact, it drops down to 64%. Finally, the mean time and mean number of cars in the driveway decrease dramatically, but this is only because a large number of cars are *turned away*. In Theory of Constraints terms (Chapter 6), the driveway is clearly a constraint that limits throughput for the entire system. If Luc can somehow find more space to queue up the cars (and assuming that the drivers are willing to wait), he could expect to achieve results closer to those in Figure 6S.8.

SUPPLEMENT SUMMARY

In this supplement, we described different types of waiting line systems. We also provided formulas for evaluating the steady-state performance of three different systems. The second half of the supplement introduced simulation modeling, including a discussion and examples of Monte Carlo simulation, as well as the development and analysis of a simulation model using SimQuick.

Simulation modeling is a particularly important tool that managers can use to model and gain insight into complex business processes. Simulation is often the only way managers can understand what impact changes in capacity, process flows, or other elements of the business will have on customer performance.

We encourage you not to let your education end here, however. There is much more to both of these topics, and especially simulation modeling, than can be covered in this supplement. In fact, there are books devoted to simulation modeling,[3] and many colleges offer courses or even series of courses on the topic.

[3]See, for example, J. Banks, J. Carson, B. Nelson, and D. Nicol, *Discrete-Event System Simulation* (Upper Saddle River, NJ: Prentice Hall, 2004).

DISCUSSION QUESTIONS

1. All things being equal, why do you think waiting line environments with constant service times have shorter waiting times and lines than environments with variable service times? Can you think of an example to illustrate your intuition?
2. Consider a supply chain where multiple manufacturers take turns processing a particular product. Which of the waiting line systems shown in Figures 6S.1 through 6S.3 best represent this environment? Explain.
3. We stated earlier that simulation modeling does not provide the user with an optimal solution. What did we mean by this? Explain, using one or more of the simulation examples given in the supplement.

PROBLEMS

(* = easy; ** = moderate; *** = advanced)

Problems for Section 6S.1: Alternative Waiting Lines

1. Horton Williams Airport is a small municipal airport with two runways. One of these runways is devoted to planes taking off. During peak time periods, about 8.5 planes per hour radio to the tower that they want to take off. The tower handles these requests in the order in which they arrive. Once the tower has given the go-ahead, it takes a plane, on average, 5 minutes to position itself on the runway and take off.

   a. (*) On average, how many planes will be waiting during peak time periods? How many will be in the system (i.e., waiting and on the runway)?
   b. (*) How long, on average, will a plane have to wait before it is allowed to take off?

   To deal with greater demand, Horton Williams Airport has opened a second runway devoted just to planes taking off. Peak demand has now been bumped up to 15 planes per hour. Furthermore, each plane still takes about 5 minutes to position itself and take off once it has been given the go-ahead.

   c. (***) On average, how many planes will be waiting during peak time periods? How many will be in the system (i.e., waiting and on the runway)?
   d. (***) How long, on average, will a plane have to wait before it is allowed to take off?

2. The women's department at Hector's Department Store has a single checkout register. Customers arrive at the register at the rate of 11 per hour. It takes the clerk, on average, 4 minutes to check out a customer.

   a. (**) On average, how many customers will be waiting to be checked out? Do you think this number is reasonable? Why or why not?
   b. (**) How long, on average, will a customer have to wait before the clerk starts serving him or her? Again, is this a reasonable time? If Hector's decides to open another register, what are the trade-offs to consider?

   Hector's Department Store has decided to add a second checkout register. This second register works at the same average speed as the first. Customer arrivals are the same as before.

   c. (***) On average, how many customers will be waiting to be checked out? From a business perspective, is this reasonable?
   d. (***) How long, on average, will a customer have to wait before the clerk starts serving him or her? Again, is this a reasonable time?

3. Parts arrive at an automated machining center at a rate of 100 per hour, based on a Poisson distribution. The machining center is able to process these parts at a fixed rate of 150 per hour. That is, each part will take exactly $150/6 = 0.4$ minutes to process.

   a. (*) How many parts, on average, will be waiting to be processed? How many will be in the system (i.e., waiting and being processed)?
   b. (*) How long, on average, will a part have to wait before it is processed?

Problems for Section 6S.2: Simulation Modeling

4. Consider the Monte Carlo simulation shown in Figure 6S.5.

   a. (***) Recalculate the values in the "Probability of *n* arrivals" and "Cumulative probability" columns for an arrival rate of 4. You may need to add some additional rows beyond just 8 arrivals.
   b. (***) Based on the results to part a, redo the "Assigned random numbers" column.
   c. (***) Using the same random numbers shown in Figure 6S.5, take the results from parts a and b and redo the column labeled "Simulated Arrivals." What is the new average number of arrivals per time period?

5. (***) Consider the SimQuick simulation model for Luc's Car Wash, shown in Figure 6S.6. Suppose Luc decides to put in place a second crew. Redraw Figure 6S.6 to reflect this change. What changes to the model specification (Figure 6S.7) would you need to make? (*Hint:* You will need to make changes not only to the workstations but to the "Driveway" buffer as well).

REFERENCES

Books and Articles

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CHAPTER
seven

Supply Management

CHAPTER OUTLINE

CHAPTER OBJECTIVES

By the end of this chapter, you will be able to:

- Identify and describe the various steps of the strategic sourcing process.
- Perform and interpret the results of a simple spend analysis.
- Use portfolio analysis to identify the appropriate sourcing strategy for a particular good or service.
- Describe the rationale for outsourcing and discuss when it is appropriate.
- Perform a simple total cost analysis.
- Show how multicriteria decision models can be used to evaluate suppliers and interpret the results.
- Understand when negotiations should be used and the purpose of contracts.
- Describe the major steps of the procure-to-pay cycle.
- Discuss some of the longer-term trends in supply management and why they are important.

SUPPLY CHAIN CONNECTIONS

RECYCLED MATERIALS IN SHORT SUPPLY


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"Reduce, reuse, recycle." This popular slogan suggests that if consumers learn to recycle metal, glass, and plastic, industry will find a way to reuse them. But so far the flow of recycled materials into new products has been less than smooth. One reason is that some recycled substances are in surprisingly short supply.

Electric car batteries, for instance, are rich sources of lithium, nickel, cobalt, and other metals and weigh up to 550 pounds each. But because they can still produce dangerous shocks and are fire hazards even when discharged, and because some of their components, such as lithium, remain cheaper to mine than to recycle, car makers are divided about whether or not to recycle batteries.

Car makers are often legally responsible for proper disposal or reuse of batteries, even if they didn't manufacture them. That's one reason that Honda and Toyota, for instance, are looking into global recycling partnerships, while General Motors and Nissan are working with energy companies to try remaking discharged car batteries into storage devices for wind or solar power. But the percentage of minerals returning to manufacturing assembly lines may remain low.

Meanwhile, in the soft-drink industry, the United States lags Europe in recycling plastic bottles (the U.S. rate is 31% compared to Europe's 50%). Recycled bottle-ready plastic, called PET after its main ingredient, is so scarce that it costs about 10% more than virgin plastic, and the recycled content of Coca-Cola bottles has dropped to less than 5% from 10% ten years ago. Coca-Cola Company, which wants to eventually recycle all its plastic bottles, has been running its $60 million recycling plant in Spartanburg, North Carolina, at only one-third of capacity because of the shortage, and after a recent retooling, it plans to reopen the plant at half its planned capacity.

Some feel PET recycling would increase if the soft-drink industry dropped its opposition to bottle deposits. The 10 U.S. states that mandate deposits have PET recycling rates about twice the national average.

Sources: Based on J. Kanter, "No Consensus on Reuse of Electric Car Batteries," *New York Times*, September 6, 2011, pp. B1, B7, **http://query.nytimes.com/gst/fullpage.html?res=9900E0DA133AF935A3575AC0A9679D8B63&ref=jameskanter;**
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INTRODUCTION

In Chapter 1, we noted that a supply chain is a network of manufacturers and service providers that work together to create products or services needed by end users. These manufacturers and service providers are linked together through physical flows, information flows, and monetary flows. But how does a particular firm know *when* it needs to team up with an outside manufacturer or service provider or with *whom* it should partner? And even if a buying firm has identified a potential partner, what steps are required to formally establish and then manage the relationship?

Supply management
The broad set of activities carried out by organizations to analyze sourcing opportunities, develop sourcing strategies, select suppliers, and carry out all the activities required to procure goods and services.

These questions and others like them are the focus of supply management. **Supply management** refers to the broad set of activities carried out by organizations to analyze sourcing opportunities, develop sourcing strategies, select suppliers, and carry out all the activities required to procure goods and services. The purpose of this chapter is to introduce you to the activities and challenges that make up supply management and to give you an appreciation for why supply management is so critical to the success of many firms.

7.1 WHY SUPPLY MANAGEMENT IS CRITICAL

Supply management, sometimes referred to as *sourcing* or *purchasing*, has always been an important, if underappreciated, function in many businesses. Several factors have worked together to push supply management activities into the limelight. These include increased levels of global sourcing, the financial impact of sourcing, and the impact sourced goods and services have on other performance metrics, including quality and delivery performance.

Global Sourcing

Firms compete not only against global competitors but against their competitors' supply chains. Companies that were once content to purchase services and goods from local suppliers now seek to build relationships with world-class suppliers, regardless of their location. Managers have come to realize that to compete globally, companies need to source globally.

The automotive industry is a prime example of how globalization has affected sourcing. Original equipment manufacturers (OEMs) such as Toyota, Volkswagen, and GM are looking to partner with the best suppliers, regardless of location. Furthermore, the OEMs are requiring these suppliers to take on more design and manufacturing responsibility. The result has been the rise of large, multinational first-tier suppliers (Table 7.1). While these suppliers may be headquartered in Europe, Asia, or North America, their products can be found in all makes of cars assembled throughout the world.

To keep up with global competition and tap into the abilities of world-class suppliers, many companies have put in place global sourcing systems. GM is a case in point. Every Friday at 6:30 A.M., the vice president in charge of worldwide purchasing presides over a global videoconference in which dozens of purchasing executives share information and coordinate strategy. A few years back, a GM purchasing team went on a 12-day mission to Thailand, Taiwan, South Korea, and Japan. The primary purpose of the trip was to evaluate a dozen toolmakers as potential sources of stamping dies, but GM also used the opportunity to develop valuable new sources.[1]

TABLE 7.1
Top 10 First-Tier Suppliers in Global Automotive Industry

COMPANY	HOME COUNTRY	2015 SALES ($ BILLIONS)	PRODUCTS
Bosch	Germany	$45	Gasoline & diesel systems, chassis system controls
Denso	Japan	36	Powertrain control, electronic & electric systems
Magneti Marelli	Canada	32	Body, chassis, exterior, seating, powertrain, electronic, vision,
Continental	Germany	31	Driver assistance systems, electronic brakes, stability systems
ZF Friedrichshafen AG	Germany	39	Transmissions, chassis components and systems, steering
Hyundai Mobis	Korea	26	Chassis, cockpit & front-end modules; stability control steering
Aisin Seiki Co.	Japan	26	Body, brake & chassis systems, electronics, drivetrain,
Faurecia	France	23	Seating, emissions control technologies, interior systems
Johnson Controls Inc.	USA	20	Complete automotive seats & seat components
Lear Corp.	USA	18	Seating & electrical distribution systems
Toyota	*Japan*	*248*	
Volkswagen	*Germany*	*213*	
GM	*USA*	*152*	

Source: Based on *Automotive News*, "Top Suppliers," June 20, 2016, **www.autonews.com/assets/PDF/CA105764617.PDF.**

[1]R. L. Simison, "Buyer's Market: General Motors Drives Some Hard Bargains with Asian Suppliers," *Wall Street Journal*, April 2, 1999, p. A1.

TABLE 7.2
Material Cost Ratios for Different Manufacturing Industries, 2011

INDUSTRY	COST OF MATERIAL / VALUE OF SHIPMENTS
Food	63.1%
Chemicals	52.5%
Plastics and rubber	55.8%
Computers and electronics	38.8%
Transportation equipment	62.8%
All manufacturers	***59.1%***

Source: Based on *2011 Annual Survey of Manufactures*, U.S. Census Bureau, June 2014.

Advances in information systems have served as a catalyst for global sourcing efforts. For example, engineers and suppliers around the world can share electronic "blueprints" instantaneously. Similarly, an organization can maximize buying power by consolidating purchasing requirements for dozens of sites and suppliers around the world into one large order. Companies can share anticipated requirements with key suppliers around the clock, allowing suppliers to plan their activities accordingly.

Global sourcing applies to services and business processes, as well as manufactured goods. Many firms now outsource routine business processes such as invoice processing, routine financial analysis, call centers, and IT processing to lower-cost centers around the world. In a recent study of business process outsourcing trends, researchers found that 50% of companies have outsourced at least some of their back-office activities. About 40% have developed consolidated and technology-enabled service centers, especially for functions such as IT, voice services, accounting, human resources, and legal services.[2]

Financial Impact

If you were to look at the financial statements of an average organization, how much would you guess the company spends on purchased goods and services? In manufacturing, the figure is astonishingly high; for the average manufacturer, just over 59% of the value of shipments comes from materials (Table 7.2). For some services, such as retailing or wholesaling, the figure can be even higher.

When much of a firm's revenue is spent on materials and services, supply management represents a major opportunity to increase profitability through what is known as the *profit leverage effect* (Example 7.1).

EXAMPLE 7.1
Profit Leverage at Target Corporation

Jim Parkin/Alamy Stock Photo

[2]R. Handfield, "Are Companies Considering the Risks of BPO?" *Supply Chain View from the Field*, November 10, 2010, **http://scm.ncsu.edu/blog/.**

Cost of goods sold (COGS) The purchased cost of goods from outside suppliers.

Merchandise inventory A balance sheet item that shows the amount a company paid for the inventory it has on hand at a particular point in time.

Profit margin The ratio of earnings to sales for a given time period.

Return on assets (ROA) A measure of financial performance, generally defined as earnings/total assets. Higher ROA values are preferred because they indicate that the firm is able to generate higher earnings from the same asset base.

Profit leverage effect A term used to describe the effect of $1 in cost savings increasing pretax profits by $1 and a $1 increase in sales increasing pretax profits only by $1 multiplied by the pretax profit margin.

Consider the following financial information for Target Corporation, a leading U.S. retailer. Table 7.3 shows earnings for the company for 2010, as well as key balance statement figures from January 2011.

TABLE 7.3 Selected Financial Data for Target Corporation (all figures in $ millions)

EARNINGS AND EXPENSES, 2010	
Sales	$65,786
Cost of goods sold (COGS)	$45,725
Pretax earnings	$4,629
SELECTED BALANCE SHEET ITEMS (AS OF JANUARY 29, 2011)	
Merchandise inventory	$7,596
Total assets	$17,213

Cost of goods sold (COGS) is the purchased cost of goods from outside suppliers. It tells us how much a company has paid for the goods that it sold to its customers. **Merchandise inventory** shows us how much the company paid for the inventory it had on hand at the time of the report.

With the preceding financial data, we can calculate some basic financial performance measurements for Target Corporation. **Profit margin** is defined as the ratio of earnings to sales for a given time period:

$$\text{Profit margin} = 100\% \times \frac{\text{Earnings}}{\text{Sales}} \tag{7.1}$$

The pretax profit margin for the company is:

$$100\% \times \frac{\$4{,}629}{\$65{,}786} = 7.0\%$$

The pretax profit margin means that every dollar of sales generates about 7 cents in pretax earnings. Another commonly used financial measure is **return on assets (ROA).** ROA is a measure of financial performance, generally defined as earnings/total assets. Higher ROA values are preferred because they indicate that the firm is able to generate higher earnings from the same asset base:

$$\text{Return on assets (ROA)} = 100\% \times \frac{\text{Earnings}}{\text{Assets}} \tag{7.2}$$

For this company, the pretax ROA for the fiscal year is:

$$100\% \times \frac{\$4{,}629}{\$17{,}213} = 26.9\%$$

What can this company do to improve these figures? There are two things to note:

1. **Every dollar saved in purchasing lowers COGS by $1 and increases pretax profit by $1.** In contrast, because the current pretax profit margin is 7.0%, to have the same impact on pretax profit, Target would have to generate:

   $$\$1.00 / 7.0\% = \$14.29 \text{ in new sales}$$

   This is known as the profit leverage effect. The **profit leverage effect** holds that $1 in cost savings increases pretax profits by $1, while a $1 increase in sales increases pretax profits by only $1 multiplied by the pretax profit margin. This effect is particularly important for lower-margin businesses, such as retailing.

2. **Every dollar saved in purchasing also lowers the merchandise inventory figure—and as a result, total assets—by \$1.** The result is a higher ROA for the same level of sales.

To illustrate these points, let's see what would happen if Target Corporation were able to cut its COGS by 3%. Notice that COGS and merchandise inventory each decrease by 3%:

$$\begin{aligned}
\text{New COGS} &= \text{old COGS} \times (100\% - 3\%) \\
&= \$45{,}725 \times (0.97) \\
&= \$44{,}353 \\
\text{Reduction in COGS} &= \text{old COGS} - \text{new COGS} \\
&= \$45{,}725 - 44{,}353 \\
&= \$1{,}372 \\
\text{Reduction in merchandise inventory} &= \text{old merchandise inventory} \times (3\%) \\
&= \$7{,}596 \times (0.03) = \$228 \\
\text{New total assets} &= \text{old total assets} \\
&\quad - \text{reduction in merchandise inventory} \\
&= \$17{,}213 - \$228 = \$16{,}985
\end{aligned}$$

The updated financial results are shown below:

UPDATED EARNINGS AND EXPENSES	
Sales	\$65,786
New cost of goods sold (COGS)	**\$44,353**
Old pretax earnings	\$4,629
+3% reduction in COGS:	+\$1,372
New pretax earnings	**\$6,001**
UPDATED BALANCE SHEET ITEMS	
New merchandise inventory	**\$7,368**
Old total assets	\$17,213
−3% reduction in merchandise inv.	−\$228
Net total assets	**\$16,985**

The result is that pretax earnings increase by nearly 30%, from \$4,629 million to \$6,001 million. Under the *old* pretax profit margin, sales would have to increase by (\$6,001 − \$4,629) / (7.0%) = \$19,600 million to have the same impact.

Finally, the *new* pretax profit margin and ROA values are

$$\text{New pretax profit margin} = 100\% \times \frac{\$6{,}001}{\$65{,}786} = 9.1\%$$

$$\text{New ROA} = 100\% \times \frac{\$6{,}001}{\$16{,}985} = 35.3\%$$

Performance Impact

Cost is not the only consideration. Purchased goods and services can have a major effect on other performance dimensions, including quality and delivery performance. The following example illustrates how these metrics can come into play.

EXAMPLE 7.2

Purchasing Valves at Springfield Hospital

Springfield Hospital has two dialysis machines, each with a special valve that is normally replaced every two weeks when the machines are idle. As a result, Springfield uses about 50 valves per year. The hospital has two alternative sources for the valves. The purchase price and quality for these two suppliers are as follows:

	SUPPLIER A	SUPPLIER B
Price per valve	\$10	\$2
% Good	99.8%	95%

The fact that a valve is defective becomes apparent only once treatment starts. When this occurs, it can cause an interruption in the treatment of patients, which can lead to rescheduling nightmares, a reduction in the effective capacity of the dialysis machines, and possibly even a medical emergency. The quality of the medical service will clearly fall if Springfield goes with Supplier B.

Now suppose that Springfield Hospital management has estimated that the cost of a failed valve is about \$1,000 per incident. Even before we calculate all of the costs associated with each supplier, we can see that using Supplier B has the potential to seriously disrupt Springfield's operations. These concerns are reflected in the following cost estimates:

YEARLY COSTS	SUPPLIER A	SUPPLIER B
Valves	50 × \$10 = \$500	50 × \$2 = \$100
Failure costs	0.2% of all valves fail: 0.2% × 50 valves × \$1,000 = \$100	5% of all valves fail: 5% × 50 valves × \$1,000 = \$2,500
Total cost:	\$600	\$2,600

7.2 THE STRATEGIC SOURCING PROCESS

In this section, we describe the strategic sourcing process. In contrast to more tactical day-to-day purchasing activities, which we describe later in the chapter, strategic sourcing is concerned with identifying ways to improve long-term business performance by better understanding sourcing needs, developing long-term sourcing strategies, selecting suppliers, and managing the supply base.

To illustrate the difference between strategic sourcing and tactical purchasing activities, commodity managers at a manufacturer might follow a *strategic* sourcing process to identify and negotiate three-year agreements with two major steel suppliers. Purchasing and materials managers at the manufacturer's three plants would then follow *tactical* procure-to-pay procedures to coordinate orders and shipments with these suppliers.

The six steps of the strategic sourcing process are shown in Figure 7.1. There are two things to keep in mind as we describe the strategic sourcing process. First, how much effort a company spends on each step will differ greatly from one situation to the next. The strategic sourcing process for a \$30 billion contract for military jets will be much more complex and detailed than the strategic sourcing process for office supplies. Second, as we discuss the different steps in the strategic sourcing process, keep in mind that companies can often gain a competitive advantage by performing these steps *better* than their competitors do.

Step 1: Assess Opportunities

Spend analysis
The application of quantitative techniques to purchasing data in an effort to better understand spending patterns and identify opportunities for improvement.

While the strategic sourcing process is sometimes kicked off in response to an entirely new need within an organization, in the vast majority of cases, the strategic sourcing process is conducted to improve the performance of a firm's *existing* sourcing activities.

One of the most popular tools firms use to assess sourcing performance is spend analysis. **Spend analysis** is the application of quantitative techniques to purchasing data in an effort to better understand spending patterns and identify opportunities for improvement. Spend

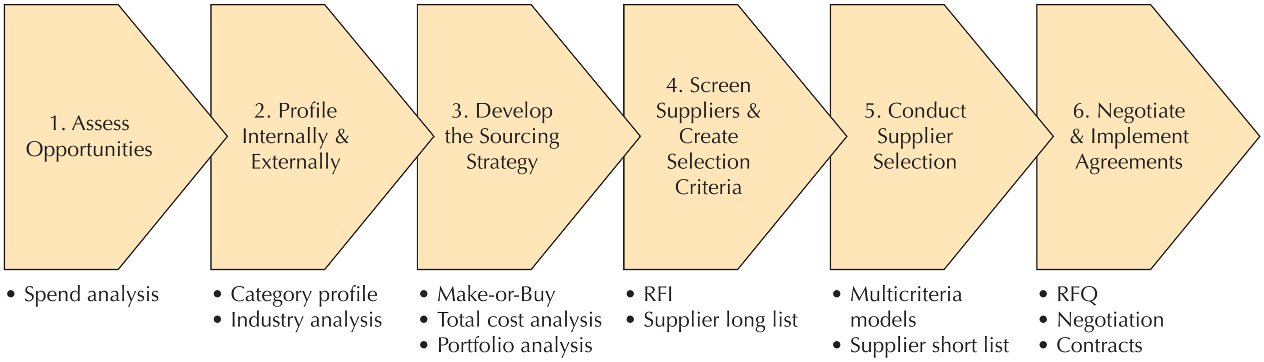

FIGURE 7.1 The Strategic Sourcing Process

analysis can be used to answer a wide variety of questions. For example, management might want to know:

- What categories of products or services make up the bulk of company spending?
- How much are we spending with various suppliers?
- What are our spending patterns like across different locations?

Because the questions can vary so widely, there is no single correct approach to spend analysis. Rather, the approach used will depend on the questions at hand. This means that personnel responsible for spend analysis must have the flexibility and skills needed to analyze large quantities of data. The types of tools used can range from relatively sophisticated statistical techniques, such as regression analysis (Chapter 9), to simple graphing techniques, such as Pareto charts (Chapter 4). Furthermore, some organizations have sophisticated spend analysis applications that draw data from the company's financial and accounting applications, while others depend on simpler Excel spreadsheets or Access databases.

Example 7.3 illustrates how spend analysis might be used to assess the opportunity for a major spend category (office supplies) at El-Way Consultants.

EXAMPLE 7.3

Assessing Sourcing Opportunities at El-Way Consultants

Fred Franklin, a recent graduate in operations and supply chain management, has just been hired as a commodity manager at El-Way Consultants, a consulting firm with offices located in six major cities. The vice president of sourcing tells Fred that no one has ever paid attention to how money is spent on office supplies, and she thinks there may be an opportunity to save the company some money. She asks Fred to assess the opportunity and make recommendations.

To better understand the size of the opportunity, Fred decides to perform some simple spend analysis. First, Fred uses El-Way's available purchasing records to estimate office supply expenditures across El-Way's six locations for the previous year. The results are shown in Table 7.4. Figure 7.2 shows the results Pareto chart form, sorted by location.

TABLE 7.4 Office Supply Spend Analysis for El-Way Consultants, by Location

LOCATION	DOLLARS (000s)	PERCENTAGE
London, UK	$3,105	31%
New York, NY	$2,971	30%
Paris, France	$2,275	23%
San Francisco, CA	$618	6%
Chicago, IL	$545	5%
Atlanta, GA	$486	5%
Totals:	$10,000	100%

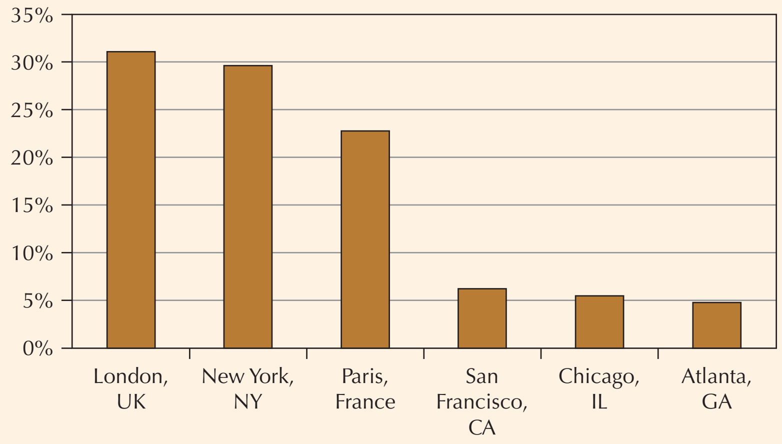

FIGURE 7.2 Office Supply Expenditures for El-Way Consultants, by Location

The spend analysis provides Fred with some useful insights. First, total office supply expenditures for last year were approximately $10 million. If Fred can cut these expenditures by 10% to 20%, he can save El-Way $1,000,000 to $2,000,000 per year. Second, three of El-Way's six locations—London, New York, and Paris—account for 84% of all office supply expenditures. To have a significant financial impact on office supply expenditures, any new sourcing strategy for office supplies will likely need to start with these three locations.

Step 2: Profile Internally and Externally

In the second step of the strategic sourcing process, decision makers often need to develop a more detailed picture, or profile, of the *internal* needs of the organization, as well as the characteristics of the *external* supply base. Two approaches that sourcing managers use to create these profiles are category profiles and industry analysis.

The main objective of a category profile is to understand all aspects of a particular sourcing category that could ultimately have an impact on the sourcing strategy. This might include a breakdown of the total category spend by subcategories, suppliers, and locations. It could also involve understanding how the purchased components or services are used and how demand levels in the organization will change over time. For example, a manufacturer looking at the spend category "purchased components" might break this down into electrical, mechanical, and molded components; components purchased for plants in Asia, the United States, and Canada; components used in production versus those used as spare parts; and components provided from the company's internal sources versus those purchased from external suppliers. Furthermore, discussions with other stakeholders in the firm might indicate that internal demand for molded components is expected to grow at a much higher rate than the other two subcategories. All these factors would affect the manufacturer's sourcing strategy for sourced components.

Industry analysis
Profiles the major forces and trends that are impacting an industry, including pricing, competition, regulatory forces, substitution, technology changes, and supply/demand trends.

While category profiling seeks to provide a better picture of internal needs, **industry analysis** profiles the major forces and trends that are impacting an industry, including pricing, competition, regulatory forces, substitution, technology changes, and supply/demand trends. For example, how many potential suppliers are there? Who are the major suppliers? Is the supply base growing or shrinking? What are the technological trends facing the industry? Where does negotiating power lie—with the suppliers or with the customers?

As you can imagine, industry analysis can require highly specialized knowledge. As a result, buying firms might choose to meet with a key supplier that is an industry expert or hire an external consultant who specializes in studying certain markets (e.g., chemicals, resins, IT providers). Secondary data sources include databases, reports, and Web sites. Examples might be "state of the industry" reports purchased from consulting companies, such as the Harbour Report (**www.theharbourreport.com**), which examines the automotive industry, or publicly available databases, such as those provided by the U.S. Census Bureau or the U.S. Department of Labor Statistics.

Example 7.4 illustrates how category profiling could be used to develop a more detailed understanding of the office supplies category at El-Way Consultants.

EXAMPLE 7.4

Internal Profiling at El-Way Consultants

Fred Franklin's initial assessment indicated that El-Way Consultants is spending approximately \$10 million per year on office supplies. To better understand how this money is being spent, Fred decides to perform a more detailed category profile for office supplies. First, Fred looks at expenditures at each location across five subcategories of office supplies: (1) paper and pads, (2) basic office supplies (such as pens and staplers), (3) ink and toner, (4) mail and shipping supplies, and (5) all other items. The results are shown in Table 7.5 and Figure 7.3. Fred notes that the top two subcategories—paper and pads and basic office supplies—together make up 63% of total office supply expenditures.

TABLE 7.5 Office Supply Category Profile for El-Way Consultants, by Location and Subcategory

	Office Supply Subcategories						
LOCATION	PAPERS & PADS	BASIC OFFICE SUPPLIES	INK & TONER	MAIL & SHIPPING SUPPLIES	OTHER	TOTAL	
London, UK	\$1,280	\$840	\$320	\$200	\$465	\$3,105	31%
New York, NY	\$1,010	\$750	\$450	\$320	\$441	\$2,971	30%
Paris, France	\$740	\$600	\$350	\$130	\$455	\$2,275	23%
San Francisco, CA	\$200	\$180	\$80	\$40	\$118	\$618	6%
Chicago, IL	\$200	\$160	\$60	\$30	\$95	\$545	5%
Atlanta, GA	\$160	\$170	\$70	\$20	\$66	\$486	5%
Totals:	\$3,590	\$2,700	\$1,330	\$740	\$1,640	\$10,000	
	36%	27%	13%	7%	16%		

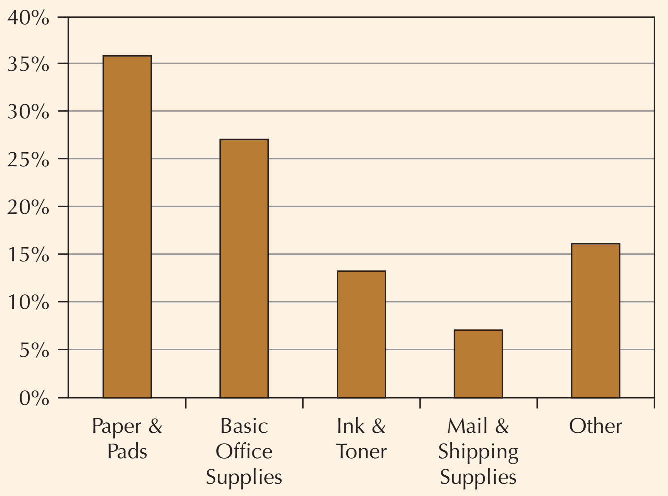

FIGURE 7.3 Office Supply Expenditures for El-Way Consultants, by Subcategory

Next, Fred decides to see which suppliers the various locations are spending their office supply dollars with. In looking through El-Way's purchasing records, Fred learns that in the previous year, El-Way bought office supplies from 150 different vendors; however, the top 7 accounted for 73% of all purchases. The summary results are shown in Table 7.6 and Figure 7.4.

TABLE 7.6 Office Supply Category Profile for El-Way Consultants, by Location and Supplier

	Supplier									
LOCATION	WORLD OFFICE	CLIPS	OPTI-OFFICE	PRINT-MAX	BOUNDARIES	TENDEX	PROTEUS	ALL OTHERS (*n* = 143)		
London, UK	$710	$610	$380	$160	$180	$140	–	$925	$3,105	31%
New York, NY	$580	$740	$640	$440	–	–	–	$571	$2,971	30%
Paris, France	$640	$560	$240	$100	–	–	$60	$665	$2,265	23%
San Francisco, CA	$140	$100	$80	$30	–	–	–	$268	$618	6%
Chicago, IL	$200	$120	$50	$20	–	–	–	$155	$545	5%
Atlanta, GA	$80	$60	$160	$60	–	–	–	$136	$496	5%
Totals:	$2,350	$2,190	$1,550	$810	$810	$140	$60	$2,720	$10,000	
	24%	22%	16%	8%	2%	1%	1%	27%		

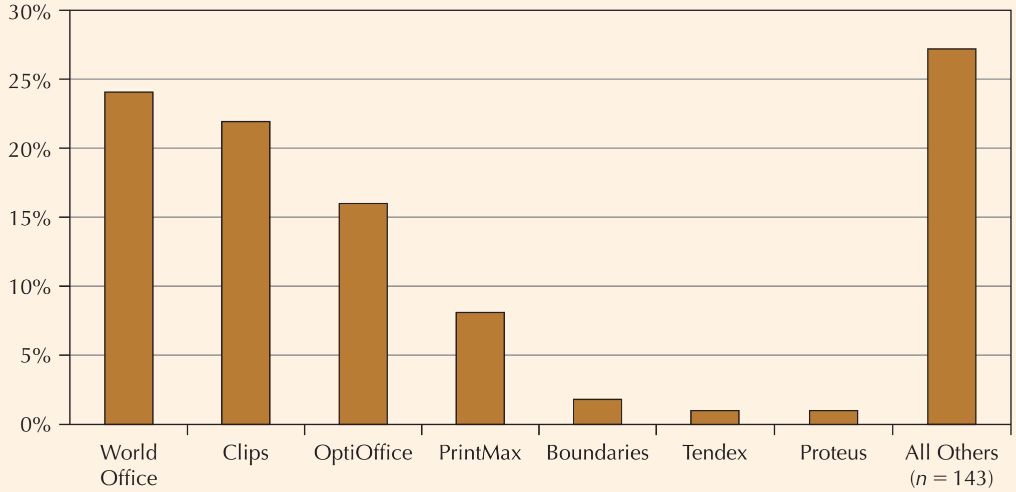

FIGURE 7.4 Office Supply Expenditures for El-Way Consultants, by Supplier

Maverick spending Spending that occurs when internal customers purchase directly from nonqualified suppliers and bypass established purchasing procedures.

Analyzing office supply expenditures by supplier provides Fred with additional insights. First, 62% of El-Way's expenditures are concentrated in three suppliers. In general, Fred considers this a positive result since office supplies are commodity items and spending large amounts with a particular supplier gives El-Way leverage in seeking favorable price discounts and delivery terms. However, 27% of El-Way's office supply expenditures are spread over the bottom 143 suppliers. These purchases provide little opportunity for price discounts, and they also create additional administrative burdens for El-Way, since each supplier represents a new relationship that must be tracked and managed. Furthermore, Fred suspects that many of these smaller purchases result from **maverick spending**—that is, spending that occurs when internal customers purchase directly from nonqualified suppliers and bypass established purchasing procedures.

Step 3: Develop the Sourcing Strategy

The first two steps of the strategic sourcing process—assessing opportunities and profiling internally and externally—provide motivation and information that feed into the third step, developing the sourcing strategy. We divide our discussion of this crucial step into three parts: (1) the make-or-buy decision, (2) total cost analysis, and (3) portfolio analysis.

Insourcing
The use of resources within the firm to provide products or services.

Outsourcing
The use of supply chain partners to provide products or services.

Make-or-buy decision
A high-level, often strategic, decision regarding which products or services will be provided internally and which will be provided by external supply chain partners.

The Make-or-Buy Decision. When developing a sourcing strategy, businesses sometimes face the question of whether to produce some product or service internally (i.e., **insource**) or to source it from an outside supply chain partner (i.e., **outsource**). This is called the **make-or-buy decision.** While nearly every organization depends on sourcing to some extent, the decision to outsource goods or services raises a host of strategic questions, including the following:

- What are the pros and cons of outsourcing?
- Are there suppliers capable of meeting our needs? Which supplier is the "best"?
- How many suppliers should be used to ensure supply continuity, maintain competition, yet achieve the benefits of a solid supply relationship?

Core competencies
Organizational strengths or abilities, developed over a long period, that customers find valuable and competitors find difficult or even impossible to copy.

Advantages and Disadvantages of Insourcing and Outsourcing. Insourcing gives a company a high degree of control over its operations. This is particularly desirable if the company owns proprietary designs or processes. Insourcing can also lower costs but *only* if a company enjoys the business volume necessary to achieve economies of scale. So when a company such as Nike decides to outsource the manufacturing of its running shoes, it also makes a conscious decision to retain the design and marketing of these shoes. Why? Because Nike excels at product innovation and marketing. This example points out an important concept: Companies should try to insource processes that are **core competencies**—organizational strengths or abilities, developed over a long period, that customers find valuable and competitors find difficult or even impossible to copy. Products or processes that could evolve into core competencies are prime candidates for insourcing.

On the downside, insourcing can be risky because it decreases a firm's strategic flexibility. Making a product or providing a service internally often requires a company to make long-term capacity commitments that cannot be easily reversed. Finally, if suppliers can provide a product or service more effectively, managers must decide whether to commit scarce resources to upgrading their processes or to outsource the product or service. Attempting to catch up to suppliers technologically can be an expensive proposition that could restrict a firm's ability to invest in other projects or even threaten its financial viability.

Outsourcing typically increases a firm's flexibility and access to state-of-the-art products and processes. As markets or technologies change, many firms find changing supply chain partners easier than changing internal processes. With outsourcing, less investment is required up front in the resources needed to provide a product or service. The benefits of outsourcing can be significant. For instance, many firms today are outsourcing their logistics capabilities to companies such as FedEx and UPS. Mike Eskew, CEO of UPS, described his organization as an "enabler of global commerce," coordinating the movement of goods from its customers' suppliers to their final destinations and sometimes becoming involved with assembly along the way.[3]

Of course, outsourcing has risks. Suppliers might misstate their capabilities: Their process technology might be obsolete, or their performance might not meet the buyer's expectations. In other cases, the supplier might not have the capability to produce the product to the quality level required.

Control and coordination are also issues in outsourcing. Buying firms may need to create costly safeguards to regulate the quality, availability, confidentiality, or performance of outsourced goods or services. Coordinating the flow of materials across separate organizations can be a major challenge, especially when time zone differences, language barriers, and even differences in information systems come into play.

Companies that outsource also risk losing key skills and technologies that are part of their core competencies. To counteract such threats, many companies oversee key design, operations,

[3]R. Kapadia, "The Brown Revolution," *Smart Money*, November 10, 2005, **www.smartmoney.com/invest/stocks/The-Brown-Revolution-18573/.**