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Operations Management

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Operations Management

Third Edition

Gérard Cachon
The Wharton School, University of Pennsylvania

Christian Terwiesch
The Wharton School, University of Pennsylvania

Mc Graw Hill

OPERATIONS MANAGEMENT, THIRD EDITION

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DEDICATION

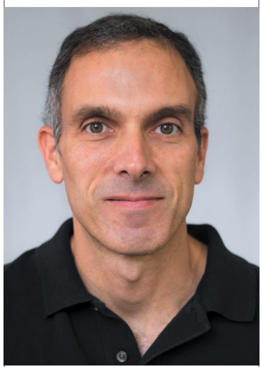
To my core: Beth, Xavier, Quentin, Annick, and Isaac.

—Gérard

To the Terwiesch family—in Germany, Switzerland, and the United States.

—Christian

About the Authors



Gérard Cachon

Gérard Cachon is the Fred R. Sullivan Professor of Operations, Information, and Decisions and a professor of marketing at The Wharton School at the University of Pennsylvania.

Professor Cachon studies operations strategy with a focus on how new technologies transform competitive dynamics through novel business models.

He is an INFORMS Fellow; a Fellow of the Manufacturing and Service Operations Management (MSOM) Society; a former president of MSOM; and a former editor-in-chief of *Management Science* and *Manufacturing & Service Operations Management.*

His articles have appeared in *Harvard Business Review, Management Science, Manufacturing & Service Operations Management, Operations Research, Marketing Science,* and the *Quarterly Journal of Economics,* among others.

At Wharton, he teaches an undergraduate introductory course in operations management, and an MBA and executive MBA course on operations strategy.

Before joining the Wharton School in July 2000, Professor Cachon was on the faculty at the Fuqua School of Business, Duke University. He received a Ph.D. from The Wharton School in 1995.

He is a bike commuter (often alongside Christian) and enjoys photography, hiking, and scuba diving.

Christian Terwiesch

Christian Terwiesch is the Andrew M. Heller Professor at The Wharton School of the University of Pennsylvania. He is a professor in Wharton's Operations, Information, and Decisions department; is co-director of Penn's Mack Institute for Innovation Management; and also holds a faculty appointment in Penn's Perelman School of Medicine.

His research appears in many of the leading academic journals ranging from operations management journals such as *Management Science, Production and Operations Management, Operations Research,* and *The Journal of Operations Management* to medical journals such as *The Journal of General Internal Medicine, Medical Care, Annals of Emergency Medicine,* and *The New England Journal of Medicine.*

Most of Christian's current work relates to using operations management principles to improve health care. This includes the design of patient-centered care processes in the VA hospital system, studying the effects of emergency room crowding at Penn Medicine, and quantifying the benefits of patient portals and remote patient monitoring.

Beyond operations management, Christian is passionate about helping individuals and organizations to become more innovative. Christian's book *Innovation Tournaments* (Harvard Business School Press) proposes a novel, process-based approach to innovation that has led to innovation tournaments in organizations around the world. His latest book, *Connected Strategy* (also published by Harvard Business School Press), was featured by *Business Week* as one of the best business books of 2020.

Christian teaches MBA and executive classes at Wharton. In 2012, he launched the first massive open online course (MOOC) in business on Coursera, which has emerged has one of the largest online business courses ever taught.

Christian holds a doctoral degree from INSEAD (Fontainebleau, France) and a diploma from the University of Mannheim (Germany). He is a cyclist and bike commuter and so, because his commute significantly overlaps the commute of Gérard, many of the topics in this book grew out of discussions that started on the bike.

Preface

This introductory-level operations management title provides the foundations of operations management. The book is inspired by our combined 50 years teaching undergraduate and MBA courses, usually in-person, but also online. Through our experiences, we have learned that the best way to engage and motivate the study of operations is to focus the material on the skills students need to understand and to successfully be a part of (and to create) modern organizations delivering goods and services.

We cannot emphasize enough that students should learn the content they need in today's world, not the world of 30 or 40 years ago. As a result, "services" and "global" are incorporated throughout, rather than confined to dedicated chapters. Manufacturing, of course, cannot be ignored, but again, the emphasis is on contemporary issues that are relevant and accessible to students. For example, any organization can benefit from students who know how to identify the bottleneck in a process and to use the ideas from the Toyota Production System to improve performance. And students should understand why people need to wait for services and how to redesign the process to make them wait less. In sum, we want students to see how operations influence and explain their own experiences, such as the security queue at an airport, the quality of their custom sandwich, or the frustration to find a desired item on backorder.

The skills needed for modern operations also means teaching students much more than how to do math problems. Instead, the emphasis is on the explicit linkages between operations analytics and the strategies organizations use for success. For example, we want students to understand how to manage inventory, but, more importantly, they should understand why Amazon.com is able to provide an enormously broad assortment of products. Students should be able to evaluate the waiting time in a doctor's office, but also understand how assigning patients to specific physicians is likely to influence the service customers receive. In other words, big-picture operations provide students with a new, broader perspective into the organizations and markets they interact with every day.

We firmly believe that operations management is as relevant for a student's future career as any other topic taught in a business school. New companies and business models are created around concepts from operations management. Established organizations live or die based on their ability to manage their resources to match their supply to their demand. One cannot truly understand how business works today without understanding operations management. To be a bit colloquial, this is "neat stuff," and because students will immediately see the importance of operations management, we hope and expect they will be engaged and excited to learn. We have seen this happen with our own students and believe it can happen with any student.

Content Changes in the 3rd Edition

With each edition, we look at every aspect of our text to ensure it is both current and relevant. As we continually seek to improve upon our writing, we take the feedback we receive from our reviewers and users seriously. In this new edition, we have made many changes, including but not limited to the following:

Chapter 1

- New introduction to the concept of sustainability.
- New discussion about how ethical issues can be integrated into the efficiency frontier framework.
- Updated data and more details for the efficiency frontier example in the airline industry.

Chapter 2

- New Connections feature on the application of Little's Law to basketball coaching as an illustration of its wide applicability.

Chapter 5

- New illustration of the concept of yields, based on the case of the recycling process of batteries used for electric vehicles.

Chapter 6

- New data on learning curves in the energy industry, quantifying learning rates for solar electricity, wind electricity, and battery storage.

Chapter 7

- Streamlined explanation and calculations of inventory in a process with setups.
- New Connections feature on how the COVID-19 pandemic influenced product variety decisions.

Chapter 8

- A new discussion of the lean operations and overall equipment effectiveness framework, using data on the efficiency of internal combustion engine vehicles.

- A new illustration of the limitations of just-in-time supply chains, based on the shortages of personal protective equipment (PPE) during the COVID-19 pandemic.

Chapter 10

- New introduction and analogous example from Amazon.
- New example using Kroger and reporting financial data.
- Updated data on U.S. inventory and sales.

Chapter 11

- New Connections feature on reverse supply chains and supply chain sustainability metrics.
- Updated data throughout.
- New example of supply chain disruption.
- Inclusion of the COVID-19 pandemic as a source of variability.

Chapter 12

- Updated data throughout.
- Revised and simplified content on the process to evaluate a quantity discount (Exhibit 12.1).

Chapter 14

- New Connections feature on the impact of the COVID-19 pandemic on automobile inventory.

Chapter 15

- New content on how to deal with extreme events and new scenarios using examples from the COVID-19 pandemic.

Chapter 16

- New illustration on the need for operations to hold excess capacity ("safety capacity") to maintain responsiveness in cases of surging demand.
- New example of how hospitals should be compensated for high demand scenarios as happened during the COVID-19 pandemic.

Chapter 18

- New Connections feature on prioritization in vaccine distribution.

Acknowledgments

This project is the culmination of our many years of learning and teaching operations management. As such, we are grateful for the many, many individuals who have contributed directly and indirectly, in small and large ways, to our exploration and discovery of this wonderful field.

We begin with the thousands of students who we have taught in person and online. It is through them that we see what inspires. Along with our students, we thank our co-teachers who have test piloted our material and provided valuable feedback: Morris Cohen, Marshall Fisher, Ruben Lobel, Simone Marinesi, Nicolas Reinecke, Sergei Savin, Bradley Staats, Xuanming Su, and Senthil Veeraraghavan.

We have benefited substantially from the following careful reviewers: Bernd Terwiesch took on the tedious job of proofreading early drafts of many chapters. Danielle Graham carefully read through all page proofs, still finding more mistakes than we would like to admit. We also thank Kohei Nakazato for double checking hundreds of test bank questions.

"Real operations" can only happen with "real" people. We thank the following who matched supply with demand in practice and were willing to share their experiences with us: Jeff Salomon and his team (Interventional Radiology unit of the Pennsylvania Hospital System), Karl Ulrich (Novacruz), Allan Fromm (Anser), Cherry Chu and John Pope (O'Neill), Frederic Marie and John Grossman (Medtronic), Michael Mayer (Johnson & Johnson), and Brennan Mulligan (Timbuk2).

From McGraw Hill, we thank our long-term friend Colin Kelley, who started us on this path and kept us motivated throughout, and the team of dedicated people who transformed our thoughts into something real: Noelle Bathurst, Harper Christopher, Anne Ehrenworth, Rick Hecker Jr., Jamie Koch, and Sue Nodine.

Finally, we thank our family members. Their contributions cannot be measured, but are deeply felt.

Gérard Cachon
Christian Terwiesch

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Guided Tour

Key Features

Structured with Learning Objectives

Great content is useless unless students are able to learn it. To make it **accessible** to students, it must be highly organized. So, all of the material is tagged by **learning objectives.** Each section has a learning objective, and all practice material is linked to a learning objective.

3 Process Analysis

LEARNING OBJECTIVES

LO3-1 Draw a process flow diagram.

LO3-2 Determine the capacity for a one-step process.

LO3-3 Determine the flow rate, the utilization, and the cycle time of a process.

LO3-4 Find the bottleneck of a multistep process and determine its capacity.

LO3-5 Determine how long it takes to produce a certain order quantity.

CHAPTER OUTLINE

Check Your Understanding 3.2

Question: It takes a color printer 10 seconds to print a large poster. What is the capacity of the printer expressed in posters per hour?

Answer: The capacity of the printer is $\frac{1}{10}$ poster/second, which is 360 posters per hour.

Question: A call center has one operator who answers incoming calls. It takes the operator 6 minutes to answer one call. What is the capacity of the call center expressed in calls per hour?

Answer: The capacity of the call center is $\frac{1}{6}$ calls/minute = 10 calls/hour.

sturti/Getty Images

Check Your Understanding

Given the learning objective structure, it is possible to present the material in **small chunks** that logically follow from each other. And each chunk ends with several straightforward **Check Your Understanding** questions so that students can feel confident that they have absorbed the content.

CONNECTIONS: Amazon

When Jeff Bezos started his company in 1994, he wanted to create the world's largest bookstore in terms of selection. So he named it Amazon.com after the world's largest river system. His initial business model was simple. He would have a single warehouse in Seattle, near a large book distributor. The tech climate of Seattle allowed him to hire the coders he needed, and the time difference with the rest of the country allowed him a few extra hours to package books for shipment to the East Coast. His plan was to offer at least a million titles, substantially more than the typical bookstore with 40,000 or fewer titles. But he didn't want to hold much inventory, in part because, as a startup, he didn't have the

Gregor Schuster/Photographer's Choice/Getty Images

Big-Picture Connections

Each chapter includes several Connections that don't teach new concepts; rather, their role is to intrigue students, to raise their curiosity, and to give a broader understanding of the world around them. For example, we talk about policy issues (emergency room overcrowding), the people who have influenced operations (Agner Erlang), and the companies that have transformed industries (Walmart).

CASE Tesla

The Tesla Model S, one of the most sought-after luxury cars, is produced in Tesla's Freemont factory in California. The production process can be broken up into the following subprocesses.

Stamping: In the stamping process, coils of aluminum are unwound, cut into level pieces of sheet metal, and then inserted into stamping presses that shape the metal according to the geometry of the Model S. The presses can shape a sheet of metal in roughly 6 seconds.

Subassembly: The various pieces of metal are put together using a combination of joining techniques, including welding and adhesion. This creates the body of the vehicle.

Paint: The body of the vehicle is then moved to the paint shop. After painting is completed, the body moves through a 350° oven to cure the paint, followed by a sanding operation that ensures a clean surface.

General assembly: After painting, the vehicle body is moved to the final assembly area. Here, assembly workers and assembly robots insert the various subassemblies, such as the wiring, the dash board, the power train and the motor, the battery pack, and the seats.

Quality testing: Before being shipped to the customer, the now-assembled car is tested for its quality. It is driven on a rolling road, a test station that is basically a treadmill for cars that mimics driving on real streets.

Overall, the process is equipped with 160 robots and 3000 employees. The process produces some 500 vehicles each week. It takes a car about 3–5 days to move from the beginning of the process to the end.

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QUESTIONS

Imagine you could take a tour of the Tesla plant. To prepare for this tour, draw a simple process flow diagram of the operation.

1. What is the cycle time of the process (assume two shifts of 8 hours each and 5 days a week of operation)?
2. What is the flow time?
3. Where in the process do you expect to encounter inventory?
4. How many cars are you likely to encounter as work in progress inventory?

SOURCES

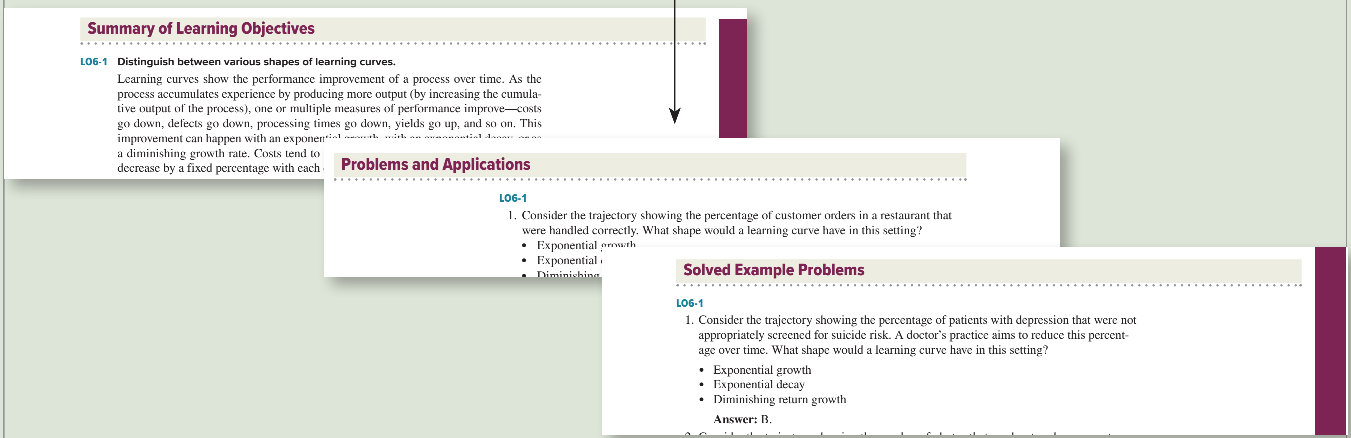
http://www.wired.com/2013/07/tesla-plant-video/
http://www.forbes.com/sites/greatspeculations/2014/09/26/fremont-factory-delays-shouldnt-affect-teslas-sales-this-quarter/

Exercises and Cases

We have an extensive portfolio of exercises and cases. These exercises are entertaining but also illustrate key concepts from the text. Cases bring the "real world" into the classroom so that students appreciate that operations management is much more than just theory.

End-of-Chapter Content

The end of chapter provides students with the resources to reinforce their learning. Conceptual Questions explore their understanding of big-picture operations. Solved Example Problems give step-by-step illustrations into the chapter's analytical tools and Problems and Applications allow students to practice.



Interactive Learning Resources

Students today don't learn by just reading. They expect to learn via multiple modalities. In particular, they like to learn (and in fact do learn) via video tutorials. Each tutorial is targeted to a single learning objective and provides a focused lesson in 1 to 5 minutes. These tutorials provide students with a "safety net" to ensure that they can master even the most challenging material.

Real Operations, Real Solutions, Real Simple

Our chapters are motivated by a diverse set of *real operations*—of companies that students can relate to. They include Subway, Capital One, Medtronic, O'Neill, LVMH, and many more. They are central to the core content of the chapters: We show students how to analyze and improve the operations of these actual companies, in many cases with actual data from the companies, that is, *real solutions.*

Next, *real simple* means that the material is written so that students can actually learn how to implement the techniques of operations management in practice. In particular, we write in a logical, step—by—step manner and include plenty of intuition. We want students to be able to replicate the details of a calculation and also understand how those calculations fit into the overall objectives of what an organization is trying to achieve.

Focus on Process Analysis

All operations management books talk a little bit about process analysis; we believe that not only is process analysis the starting point for operations management, it also is the heart of operations management. Process analysis is at the core of how an organization delivers supply. Hence, students need to understand the key metrics of process analysis (inventory, flow rate, flow time, utilization, labor content, etc.), how they are related, and, most importantly, what the organization can do to improve its processes. Most students will not work in a factory or be in charge of a global supply chain. But all students, no matter where they work or in what industry they work, will be involved in some organizational process. This is why process analysis deserves the prominence it is given in our product.

Written for the Connect Platform

Operations Management has been written specifically for the McGraw Hill Connect platform. Rather than fitting a learning management system to a book, we designed the product and the learning management system jointly. This co-development has the advantage that the test questions map perfectly to the learning objectives. The questions are also concise and can be assessed objectively. It is our experience that open–ended discussion questions ("What are the strengths and weaknesses of the Toyota Production System?") are important in a course. But they make for great discussion questions in the classroom (and we mention such questions in the instructor support material). However, they are frustrating for students as homework assignments, they are difficult to grade, and it is hard to provide the student with feedback on mastery of the topic.

Brief Contents

Contents

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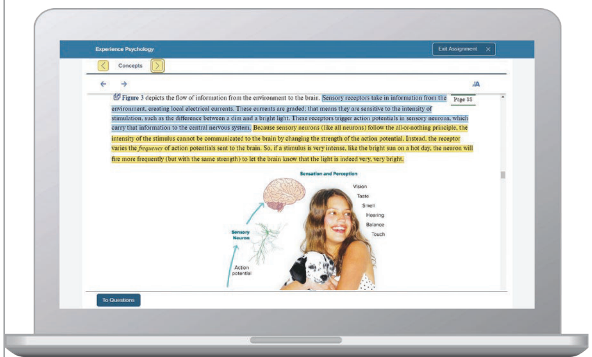

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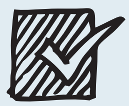

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PART 1: PROCESS ANALYSIS AND IMPROVEMENT

1 Introduction to Operations Management

LEARNING OBJECTIVES

- **LO1-1** Identify the drivers of customer utility.
- **LO1-2** Explain inefficiencies and determine if a firm is on the efficient frontier.
- **LO1-3** Explain the three system inhibitors.
- **LO1-4** Understand how to integrate sustainability and other ethical considerations into the efficient frontier framework.
- **LO1-5** Explain what work in operations management looks like.
- **LO1-6** Articulate the key operational decisions a firm needs to make to match supply with demand.

CHAPTER OUTLINE

Introduction

As a business (or nonprofit organization), we offer products or services to our customers. These products or services are called our **supply**. We provide rental cars, we sell clothes, or we perform medical procedures. Demand is created by our customers—**demand** is simply the set of products and services our customers want. Our customers may want a rental car to travel from A to B, or a black suit in size 34, or to get rid of an annoying cough.

To be successful in business, we have to offer our customers what they want. If Mr. Jamison wants a midsize sedan from Tuesday to Friday to be picked up at Chicago O'Hare International Airport (demand), our job is to supply Mr. Jamison exactly that—we need to make sure we have a midsize sedan (not a minivan) ready on Tuesday (not on Wednesday) at O'Hare (not in New York) and we need to hand it over to Mr. Jamison (not another traveler).

If on Saturday Sandy wants a green dress in size M in our retail outlet in Los Angeles, our job is to get her exactly that—we need to make sure we have a green dress in size M (not in red or in size L) in the Los Angeles store (not in San Francisco) on Saturday (not on Friday of last week).

And if Terrance injures his left knee in a soccer game and now needs to have a 45-minute meniscus surgery in Philadelphia tomorrow, our job is to supply Terrance exactly that—we need to make sure we reserve 45 minutes in the operating room (not 30 minutes), we need to have an orthopedic surgeon and an anesthesiologist (not a dentist and a cardiologist) ready tomorrow (not in 6 weeks), and the surgeon definitely must operate on the left knee (not the right one).

Photodisc/Getty Images

Supply Products or services a business offers to its customers.

Demand Simply, the set of products and services our customers want.

Another way of saying "we offer customers what they want" is to say, "we match supply with demand"! Matching supply with demand means providing customers what they want, while also making a profit. Matching supply with demand is the goal of operations management.

This book is about how to design operations to better match supply with demand. It thus is a book about getting customers what they want. Our motivation is simply stated: By better matching supply with demand, a firm is able to gain a significant competitive advantage over its rivals. A firm can achieve this better match through the implementation of the rigorous models and the operational strategies we outline in this book.

In this introductory chapter, we outline the basic challenges of matching supply with demand. This first requires us to think about demand—what do customers want? Once we understand demand, we then take the perspective of a firm attempting to serve the demand—we look at the supply process. We then discuss the operational decisions a firm has to make to provide customers with what they want at a low cost. Now, typically, customers want better products for lower prices. But, in reality, this might not always be simple to achieve. So, a subsequent section in this chapter talks about overcoming three inhibitors that keep the operation from delivering great products at low prices. Beyond overcoming these inhibitors, the operation also needs to make trade-offs and balance multiple, potentially conflicting objectives. We conclude this chapter by explaining what jobs related to operations management look like and by providing a brief overview of operations management in the remainder of the book.

1.1 The Customer's View of the World

You are hungry. You have nothing left in the fridge and so you decide to go out and grab a bite to eat. Where will you go? The McDonald's down the street from you is cheap and you know you can be in and out within a matter of minutes. There is a Subway restaurant at the other end of town as well—they make an array of sandwiches and they make them to your order—they even let you have an Italian sausage on a vegetarian sandwich. And then there is a new organic restaurant with great food, though somewhat expensive, and the last time you ate there you had to wait 15 minutes before being served your food. So where would you go?

John Flournoy/McGraw Hill

Economic theory suggests that you make this choice based on where you expect to obtain the highest **utility**. Your utility associated with each of the eating options measures the strength of your preferences for the restaurant choices available. The utility measures your desire for a product or service.

Now, why would your utility associated with the various restaurant options vary across restaurants? We can think about your utility being composed of three components: consumption utility, price, and inconvenience.

Consider each of these three components in further detail. Let us start with **consumption utility**. Your consumption utility measures how much you like a product or service, ignoring the effects of price (imagine somebody would invite you to the restaurant) and ignoring the inconvenience of obtaining the product or service (imagine you would get the food right away and the restaurant would be just across the street from you). Consumption utility comes from various attributes of a product or service; for example, "saltiness" (for food), "funniness" (for movies), "weight" (for bicycles), "pixel count" (for cameras), "softness" (for clothing), and "empathy" (for physicians). There are clearly many attributes and the relevant attributes depend on the particular product or service we consider. However, we can take the set of all possible attributes and divide them into two sets: performance and fit. These sets allow us to divide consumption utility into two subcomponents:

- **Performance.** Performance attributes are features of the product or service that most (if not all) people agree are more desirable. For example, consumers prefer roasted salmon cooked to perfection by a world-class chef over a previously frozen salmon steak cooked in a microwave. In the same way, consumers tend to prefer the latest iPhone over an old iPod, and they are likely to prefer a flight in first class over a flight in economy class. In other words, in terms of performance, consumers have the same ranking of products—we all prefer "cleaner," "more durable," "friendlier," "more memory," "roomier," and "more efficient."
- **Fit.** With some attributes, customers do not all agree on what is best. Roasted salmon sounds good to us, but that is because we are not vegetarian. Customers vary widely in the utility derived from products and services (we say that they have **heterogeneous preferences**), which is the reason you see 20 different flavors of cereals in the supermarket aisles, hundreds of ties in apparel stores, and millions of songs on iTunes. Typically, heterogeneous preferences come from differences across customers in taste, color, or size, though there are many other sources for them.

The second component of the customer's utility is **price**. Price is meant to include the total cost of owning the product or receiving the service. Thus, price has to include expenses such as shipping or financing and other price-related variables such as discounts. To state the obvious, holding everything else constant, customers prefer to pay less rather than paying more.

The third and final component of the customer's utility function is the **inconvenience** of obtaining the product or receiving the service. Economists often refer to this component as **transaction costs**. Everything else being equal, you prefer your food here (as opposed to three miles away) and now (as opposed to enduring a 30-minute wait). The following are the two major subcomponents of inconvenience:

- **Location.** There are 12,800 McDonald's restaurants in the United States (but only 326 in China), so no matter where you live in the United States, chances are that there is one near you. McDonald's (and many other restaurants for that matter) wants to be near you to make it easy for you to get its food. The further you have to drive, bike, or walk, the more inconvenient it is for you.
- **Timing.** Once you are at the restaurant, you have to wait for your food. And even if you want fast food, you still have to wait for it. A recent study of drive-through restaurants in the United States found that the average customer waits for 2 minutes and 9 seconds at Wendy's, 3 minutes and 8 seconds at McDonald's, and 3 minutes and 20 seconds at Burger King. All three of those restaurants are much faster than the 20 minutes you have to wait for the previously mentioned roasted salmon (though the authors think that this is well worth the wait).

LO1-1 Identify the drivers of customer utility.

Utility A measure of the strength of customer preferences for a given product or service. Customers buy the product or service that maximizes their utility.

Consumption utility A measure of how much you like a product or service, ignoring the effects of price and of the inconvenience of obtaining the product or service.

Performance A subcomponent of the consumption utility that captures how much an average consumer desires a product or service.

Fit A subcomponent of the consumption utility that captures how well the product or service matches with the unique characteristics of a given consumer.

Heterogeneous preferences The fact that not all consumers have the same utility function.

Price The total cost of owning the product or receiving the service.

Inconvenience The reduction in utility that results from the effort of obtaining the product or service.

Transaction costs Another term for the inconvenience of obtaining a product or service.

Location The place where a consumer can obtain a product or service.

Timing The amount of time that passes between the consumer ordering a product or service and the consumer obtaining the product or service.

Figure 1.1
Consumer utility and its components and subcomponents

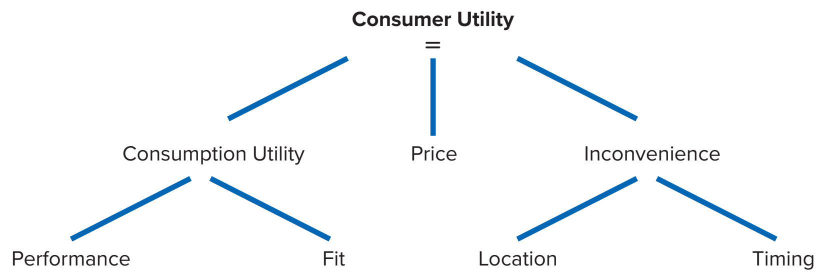


Figure 1.1 summarizes the three components of a consumer's utility for a product or service along with their subcomponents.

Customers buy the products or services that maximize their utility. They look at the set of options available to them, including the option of doing nothing (make their own lunch or stay hungry). The products or services that are maximizing the utility of our customers is thus the demand for our business as we defined in the previous section. So, our demand is driven by the consumption utility of our product or service, its price, and the associated inconvenience for our customers. In the case of a McDonald's restaurant, on any given day the demand for that restaurant corresponds to those customers who, after considering their consumption utility, the price, and the inconvenience, find that McDonald's restaurant is their best choice. Because we most likely have multiple customers, our demand corresponds to a total quantity: 190 cheeseburgers are demanded in Miami on Tuesday at lunch.

Understanding how customers derive utility from products or services is at the heart of **marketing**. Marketers typically think of products or services similar to our previous discussion in conjunction with Figure 1.1. As a business, however, it is not enough to just understand our customers; we also have to provide them the goods and services they want.

Marketing The academic discipline that is about understanding and influencing how customers derive utility from products or services.

Check Your Understanding 1.1


Exactostock/Digital Vision/SuperStock

Question: What drives your utility in terms of choosing a hotel room in San Francisco?

Answer: Consider each of these items:

- Performance attributes of consumption include the number of amenities and the size of the room (think two-star versus five-star hotel). Fit attributes are driven by personal preferences. For example, some like classic décor, while others like modern styling, and some like a noisy, busy atmosphere, while others prefer a subdued, quiet ambience.
- Price is simply the price you have to pay to the hotel.
- Inconvenience is driven by the availability of the hotel relative to your travel plans. You might be off from work or study in July, but the hotel might only have rooms available in March. This is the timing piece of inconvenience. Inconvenience can also relate to location. If you want to go sightseeing, chances are you would prefer a hotel in the Fisherman's Wharf area of San Francisco over one next to the airport.

Therefore, the utility is driven by the utility of consumption, price, and inconvenience.

1.2 A Firm's Strategic Trade-Offs

In a perfect world, we would provide outstanding products and services to all our customers, we would tailor them to the heterogeneous needs of every single one of our customers, we would deliver them consistently where and when the customer wants, and we would offer all of that at very little cost.

Unfortunately, this rarely works in practice. In sports, it is unlikely that you will excel in swimming, gymnastics, running, fencing, golf, and horse jumping. The same applies to companies—they cannot be good at everything. Companies have **capabilities** that allow them to do well on some but not all of the subcomponents making up the customer utility function. We define a firm's capabilities as the dimensions of the customer's utility function it is able to satisfy.

Consider the following examples from the food and hospitality industry:

- McDonald's is able to serve customers in a matter of 3 minutes (see the previous section). One reason for this is that they make the burgers before customers ask for them. This keeps costs low (you can make many burgers at once) and waiting times short. But because McDonald's makes the burger before you ask for it, you cannot have the food your way.
- Subway, in contrast, is able to charge a small premium and has customers willing to wait a little longer because they appreciate having sandwiches made to their order. This approach works well with ingredients that can be prepared ahead of time (precut vegetables, cheeses, meats, etc.) but would not work as well for grilled meat such as a hamburger.
- Starbucks provides a fancy ambiance in its outlets, making it a preferred place for many students to study. It also provides a wide array of coffee-related choices that can be further customized to individual preferences. It does, however, charge a very substantial price premium compared to a coffee at McDonald's.

So companies cannot be good at everything; they face **trade-offs** in their business. For example, they trade off consumption utility and the costs of providing the products or services. Similarly, they trade off the inconvenience of obtaining their products or services with the costs of providing them; as the McDonald's versus Subway example illustrated, they even face trade-offs among non-cost-related subcomponents of the utility function (fit—the sandwich made for you—versus wait times).

Such trade-offs can be illustrated graphically, as shown in Figure 1.2. Figure 1.2 shows two fast-food restaurants and compares them along two dimensions that are important to us

Capabilities The dimensions of the customer's utility function a firm is able to satisfy.

Trade-offs The need to sacrifice one capability in order to increase another one.

Figure 1.2
The strategic trade-off between responsiveness and productivity

as potential customers hunting for food. The *y*-axis shows how responsive the restaurant is to our food order—high responsiveness (short wait time) is at the top, while low responsiveness (long wait time) is at the bottom. Another dimension that customers care about is the price of the food. High prices are, of course, undesirable for customers. We assume for now that the restaurants have the same profit per unit. For the sake of argument, assume they charge customers a price of $2 above costs, leaving them with $2 of profit per customer. So, instead of showing price, the *x*-axis in Figure 1.2 shows cost efficiency—how much it costs a restaurant to serve one customer. Cost performance increases along the *x*-axis.

Consider restaurant A first. It costs the restaurant an average of $4 for a meal. Customers have to wait for 10 minutes to get their food at restaurant A, and restaurant A charges $6 to its customers for an average meal ($4 cost plus $2 profit).

Restaurant B, in contrast, is able to serve customers during a 5-minute wait time. To be able to respond to customers that quickly, the restaurant has invested in additional resources—they always have extra staff in case things get busy and they have very powerful cooking equipment. Because staffing the kitchen with extra workers and obtaining the expensive equipment creates extra expenses, restaurant B has higher average costs per customer (a lower cost performance). Say their average costs are $5 per customer. Because they have the same $2 profit as restaurant A, they would charge their customers $7.

Assuming the restaurants are identical on all other dimensions of your utility function (e.g., cooking skills, food selection, location, ambience of the restaurant, etc.), which restaurant would you prefer as a customer? This clearly depends on how much money you have available and how desperate you are for food at the moment. The important thing is that both restaurants will attract some customers.

Figure 1.2 illustrates a key trade-off that our two restaurants face. Better responsiveness to the needs of hungry customers requires more resources (extra staff and special equipment), which is associated with higher costs. Most likely, restaurant B is occasionally considering cutting costs by reducing the number of staff in the kitchen, but this would make them less responsive. Similarly, restaurant A is likely to also investigate if it should staff extra workers in the kitchen and invest in better equipment, because that would allow it to charge higher prices. We refer to trade-offs such as the one between responsiveness and costs as a **strategic trade-off**—when selecting inputs and resources, the firm must choose between a set that excels in one dimension of customer utility or another, but no single set of inputs and resources can excel in all dimensions.

Considering restaurants A and B, which one will be more successful? Low cost (and low price) with poor responsiveness or higher costs (higher prices) with good responsiveness? Again, assuming the two restaurants are identical in all other aspects of their business, we first observe that neither restaurant is better on both dimensions of performance. From the customer's perspective, there exists no dominant choice. As discussed earlier, some customers prefer the fast service and are willing to pay a premium for that. Other customers cannot afford or do not want to pay that premium and so they wait. As a result of this, we have two different **market segments** of consumers in the industry. Which restaurant does better financially? The answer to that question strongly depends on the size and dynamics of these market segments. In some areas, the segment served by restaurant A is very attractive (maybe in an area with many budget-conscious students). In other regions (maybe in an office building with highly paid bankers or lawyers), the segment served by restaurant B is more attractive.

Now, consider restaurant C, shown in Figure 1.3. Restaurant C has its customers wait for 15 minutes for a meal and its costs are $6 for the average customer (so the meals are priced at $8). The restaurant seems to be slower (lower responsiveness; i.e., longer waits) and have higher costs. We don't know why restaurant C performs as it does, but (again, assuming everything else is held constant) most of us would refer to the restaurant as underperforming and go to either restaurant A or B when we are hungry.

As we look at restaurant C, we don't see a rosy future simply because restaurants A and B can provide a better customer experience (faster responsiveness) for a lower price. Why would any customer want to go to restaurant C? Restaurant C is **Pareto dominated** by restaurants A

Market segment A set of customers who have similar utility functions.

Pareto dominated Means that a firm's product or service is inferior to one or multiple competitors on all dimensions of the customer utility function.

Figure 1.3
An underperforming operation (restaurant C)

and B. They perform equally or better on all attributes of the customer's utility function. Or, put casually, they are simply *better.*

We define the **efficient frontier** in an industry as the set of firms in the industry that are not Pareto dominated. In other words, firms that are on the efficient frontier have no firms in the industry to their upper right (i.e., are better on all dimensions). In Figure 1.3, the efficient frontier consists of restaurants A and B. Restaurants on the frontier have made different strategic trade-offs and thus focus on different market segments, but no single firm on the frontier Pareto dominates another.

Some firms, in our case restaurant C, are not on the frontier. The fact that others can provide better (equal) customer utility at equal (lower) costs suggests that restaurant C is **inefficient**. We can visualize inefficiency as the gap between the firm's current position and the efficient frontier. Figure 1.4 helps illustrate this definition of the efficient frontier.

Figures 1.2 and 1.3 illustrate two ways operations management achieves the goal of "matching supply with demand." First, operations management designs the operations that match the demand of a market segment with the supply of products and services appropriate for that segment. The management of the restaurant achieves this by making a strategic trade-off—does it want to be like restaurant A or like restaurant B? Operations management helps to execute on that strategy by building an operation appropriate for that market segment.

Second, operations management seeks to utilize inputs and resources to their fullest potential. Restaurant C is not doing this simply because restaurants A and B can provide a better customer experience (fast responsiveness) for a lower price. Applying operations management to restaurant C means figuring out how to eliminate inefficiencies (and thereby move the firm to the efficient frontier). This might mean changing the inputs and resources it currently has, or it might mean managing those inputs and resources more effectively.

But there is a third, and very crucial, way that operations management achieves the goal of "matching supply with demand." To explain, consider restaurant D, as shown in Figure 1.5. Restaurant D offers a meal within three minutes and operates with an average cost of $3 per customer (so the price is $5). The restaurant is faster (higher responsiveness) and has lower costs! It is able to get more out of its resources along all dimensions relative to the other firms in the industry. It must be doing something smarter. For example, restaurant D might have found a way to make the same food with fewer worker hours. One of the first innovations at McDonald's on its journey from a small restaurant to a multibillion-dollar company was the invention of a sauce dispenser that allowed for consistent portion sizing even when operated by an unskilled worker at high speed—one of many innovations that led it to continuously increase the output it was able to achieve with its resources.

Assuming everything else is constant across the restaurants, most of us would make restaurant D our preferred choice when hunting for food. And that bodes well for its future and

Efficient frontier The set of firms that are not Pareto dominated.

Inefficiency The gap between a firm and the efficient frontier.

LO1-2 Explain inefficiencies and determine if a firm is on the efficient frontier.

Figure 1.4
The definition of the efficient frontier

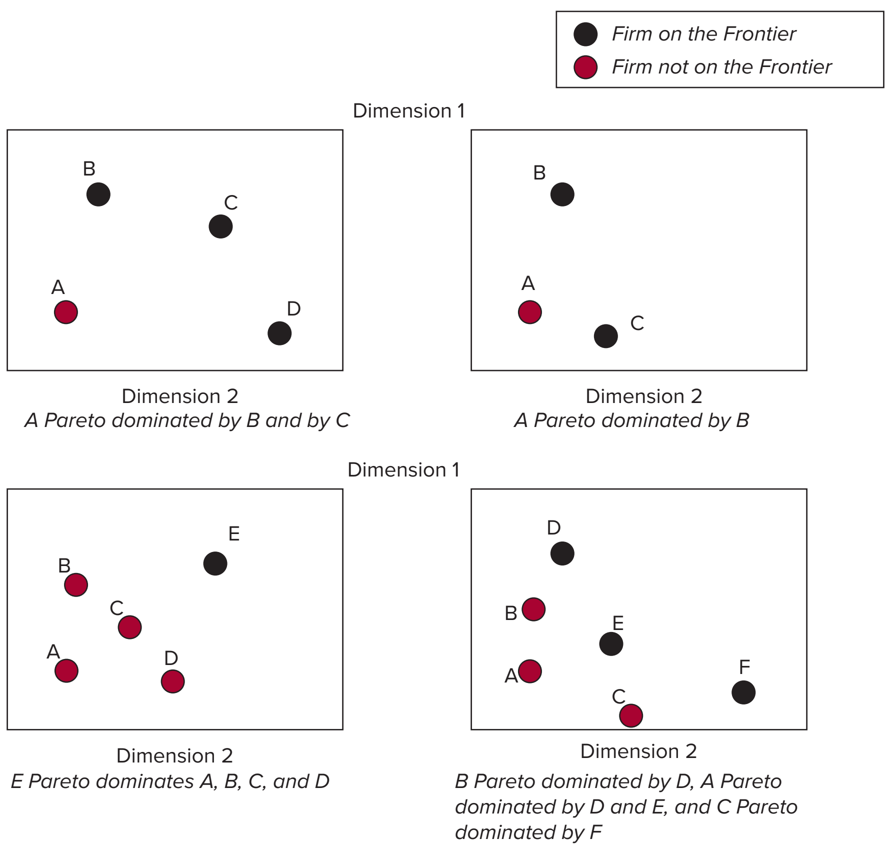
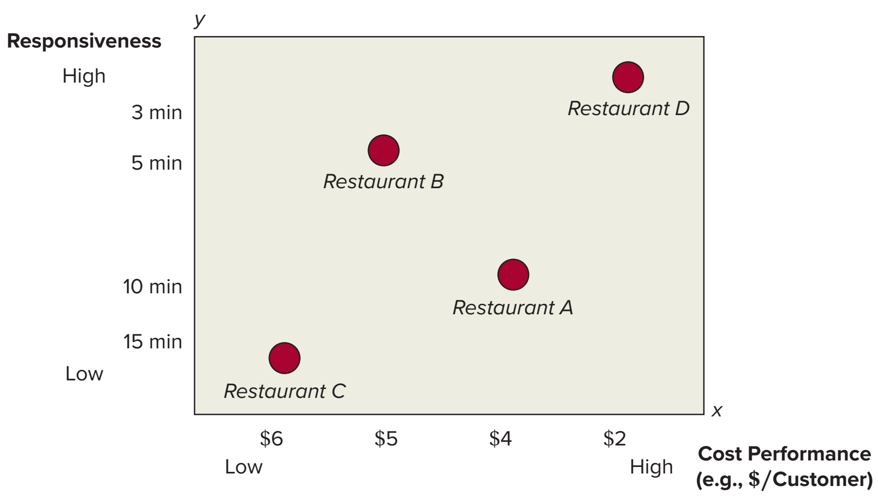


Figure 1.5
A high-performing operation (restaurant D) enters the market



profits. So the third way operations management achieves the goal of "matching supply with demand" is to keep innovating to shift the efficient frontier. Restaurant D must have gone beyond just eliminating inefficiencies and moving toward the frontier. Instead, it broke the existing cost–responsiveness trade-off.

So, great operations never rest on their laurels. Operations management is not just about executing the current way of doing things but about constantly improving and looking for new ways of doing business. Such innovations might be incremental, such as McDonald's sauce

Check Your Understanding 1.2

Question: **There are four automotive companies competing with otherwise very similar products on the dimensions of fuel economy (measured in miles per gallon, mpg) and price.**

- Company A: price = $40,000; mpg = 50
- Company B: price = $50,000; mpg = 60
- Company C: price = $30,000; mpg = 40
- Company D: price = $45,000; mpg = 45

Which of these companies are on the efficient frontier?

Answer: The only company that is Pareto dominated is company D; all others are on the efficient frontier. Company D is Pareto dominated by company A, because A is both cheaper ($40,000 instead of $45,000) and more fuel efficient (50 instead of 45 mpg).

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CONNECTIONS: Airlines

Bertlmann/Getty Images

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A passenger flying Economy class on Delta Airlines, be it within the United States or internationally, gets 558 square inches of space. This is roughly in line with what is offered by American Airlines (516 square inches domestic, 527 square inches international) and United (533 square inches domestic, 527 square inches international).

Things are different in First or Business Class. For domestic flights, Delta provides passengers with 756 square inches of space (American offers 777 and United offers 789 square inches). For international flights (believe it or not), passengers get 1672 square inches on Delta, 1538 on American and 1607 on United. As one might expect, this increased luxury comes at a hefty price with typical first class tickets being priced 214% higher domestically and 434% higher internationally compared to Economy class. [Source: *Wall Street Journal* (April 24, 2019)]

These "real estate prices" in an aircraft illustrate the basic trade-off faced by airline executives. Airlines can either provide a delightful travel experience (did you know that Singapore Airlines provides its first class passengers traveling on the Airbus 380 something that best could be described a private room?) and charge a premium price. Or, they can squeeze costs (and thus legroom), improving operating efficiency, which allows them to be profitable at very low prices.

This trade-off between operating efficiency and ticket prices can also be seen when looking at revenue and cost data across airlines. Consider Figure 1.6, which is based on

Continued

data from the MIT Airline Data Project and Airlines' Annual Reports. The *y*-axis in the figure corresponds to how much money a passenger pays per mile of travel, and the *x*-axis corresponds to how much it costs the airline to provide that mile. The German airline Lufthansa is able to obtain almost triple the price per mile compared to the British airline Ryanair. This pricing power, however, is also reflected in the operating cost. For $1 of operating cost, Lufthansa cannot even produce 5 miles of passenger travel. Ryanair, in contrast, can transport its passengers for about 17 miles. The figure illustrates the concept of the efficient frontier: Is Lufthansa a better airline than Ryanair? Clearly, neither one Pareto dominates the other. So, while a Lufthansa flight might be more enjoyable, there are good reasons to consider an alternative, especially if paying for the ticket oneself.

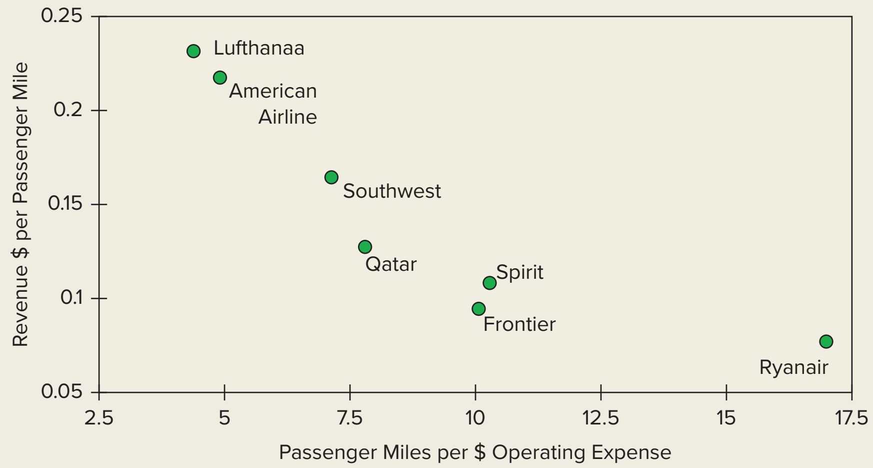

Figure 1.6 Relationship between revenue per mile and cost per mile in the airline industry

Source: Based on MIT data and financial reports

dispenser, or they might be more radical. Either way, such innovations make a firm more competitive in the marketplace.

In sum, you can think about three ways in which operations management can improve a business as it seeks to match supply with demand:

- Make trade-offs among the dimensions of performance.
- Reduce inefficiencies so that the business does not have to sacrifice one performance dimension versus another, thereby moving toward the efficient frontier.
- Innovate and improve the operations, corresponding to a shift in the efficient frontier.

1.3 Overcoming Inefficiencies: The Three System Inhibitors

LO1-3 Explain the three system inhibitors.

A company can only be successful if its customers are willing to pay a sufficiently high price to cover the cost of the product or service it offers. The difference between the revenue it earns and the costs it incurs is its **profit.** There are two types of costs:

- **Costs for inputs:** Inputs are the things that a business purchases. A fast-food restaurant has to purchase meat, salad, buns, soda, etc. Car manufacturers have to buy steel, seats, and tires; computer makers have to buy displays, chips, and power supplies. And hospitals have to purchase medications, bandages, and food.
- **Costs for resources:** Resources are the things in a business that help transform input into output and thereby help provide supply for what customers demand. In a fast-food restaurant, the resources are the cooking equipment, the real estate of the restaurants, and the employees, among others. Car manufacturers and computer makers have

plants, warehouses, and employees. And hospitals have to pay for doctors, nurses, and their building.

As a firm reduces inefficiencies (moves toward the efficient frontier), it increases the customer's utility (and thus is able to charge a higher price) or it decreases the cost of serving the customer. Sometimes, reducing inefficiencies allows a firm to simultaneously increase price and decrease costs. Either way, reducing inefficiencies will increase the firm's profitability.

But why aren't all firms in the upper right corner? Why would a company ever carry out its operations inefficiently and be Pareto dominated? And, from a practical perspective, what do such inefficiencies look like?

Let's tackle the last question first. Imagine you spent a day at Subway or McDonald's in order to identify inefficiencies. We have to confess that our previous definition of inefficiency being the gap between the firm's current position and the efficient frontier is rather abstract.

We find it helpful to think of inefficiencies as a combination of three forces: *waste, variability,* and *inflexibility.* We refer to these three forces as the **three system inhibitors.** Let's define the three system inhibitors one by one.

Waste corresponds to all the consumption of inputs and resources that do not add value to the customers. Because waste consumes inputs and resources, waste is costly. But because it does not add value to the customer, the customer is not willing to pay for this. We have extensive discussions of waste in subsequent chapters of this book. But, for now, look at the following examples from the restaurant industry:

- Restaurants have to dispose of food that has been purchased but has not been used before its expiration date. Even worse, oftentimes, food is prepared but then not sold (think of leftover beef patties), costing the restaurant inputs (the beef) and resources (the time and energy to cook).
- Just as they waste food, restaurants also can waste the time of their employees. We already mentioned the sauce dispenser at McDonald's. If you would measure the time it takes a McDonald's employee to prepare a burger and you compared it with the preparation of a burger at a small local diner, you would see a significant difference in speed. Similarly, restaurants vary in their layout. In some restaurants, employees need to run around from one corner to the other, which again constitutes mere waste.
- Another form of waste is giving customers something they don't value. What is the point of having a long menu of side dishes if almost all of your customers want fries? And why pay a waiter for bringing food to the customer if the customer is perfectly willing to pick up the food herself. Take the case of Chipotle, a restaurant chain that recently has been very successful. Chipotle customers pay around $10 for a burrito and a drink, but they are perfectly happy having few choices and picking up the food themselves.

We will see various other sources of waste throughout the subsequent chapters. In particular, we have an entire chapter on lean operations, which is all about waste reduction.

The second system inhibitor is variability. **Variability** corresponds to changes in either demand or supply over time. Consider the variability associated with customer demand first. We can distinguish between the following forms of demand variability:

- *Customer arrivals:* Customers come at very different times of the day. Some of this variability is predictable. A restaurant has more demand at noon than at 3 p.m. However, every day is somewhat different and we can never perfectly plan in advance.
- *Customer requests:* Not only is the number of customers requiring food on a given day unknown to us, we also don't know what particular menu item a customer wants to order.
- *Customer behavior:* Imagine two customers coming at the same time and both ordering a chicken salad sandwich. Same time, same order—both customers will cost us the same to serve, right? But what if one customer spends one minute at the checkout looking for his credit card? What if one customer has a ton of questions about other menu items before placing the order? And what if one customer expects a culinary delight from the fast-food restaurant and now decides to complain to the manager?

Waste The consumption of inputs and resources that do not add value to the customer.

Variability Predictable or unpredictable changes in the demand or the supply process.

Companies also face variability in their supply. This is variability internal to their operation and could take the following forms:

- *Time to serve a customer:* Just like how customers differ from one another (see earlier), so do employees. Some employees are faster; others are slower. Even our fast employees will have times when they slow down a bit, be it because of fatigue or distraction. Human beings are not robots and so we always will have some variation coming from our workforce.
- *Disruptions:* Sometimes a worker is faster; sometimes he is slower. And sometimes he does not show up. Sickness, bad weather, poor motivation—there are many reasons why workers might be absent. Similarly, equipment can break and computer systems might run slowly or require a reboot.
- *Defects:* Things go wrong in a business. Waiters enter the wrong order, food gets overcooked, and bills can get messed up. Again, all of this leads to more variability in the process.

Given the variability that exists in an operation, it would be wonderful if we would be able to react to it. It would be nice if we could double the size of the restaurant at noon so that we can serve more customers, only to then have it contract to its usual size in the afternoon so we don't have to pay too much rent. It would also be great if our waiter could cook, too, especially on days when our cook is sick. And, even better still, it would be great if our beef patty could become a salmon—say, if we have extra beef but a customer wants a fish dish. We define **flexibility** as an operation's ability to react to variability. **Inflexibility**, which is our third process inhibitor, is thus the inability of an operation to quickly and cheaply change in response to new information.

So, inefficiencies result from the three system inhibitors: waste, variability, and inflexibility. Fighting these three system inhibitors is an ongoing process. Just as a one-time visit to the gym will not turn you into an amazing athlete, reducing the negative impacts of waste, variability, and inflexibility is an ongoing process. And just as some athletes outperform their peers, some operations are better in their battle against the three system inhibitors than others. Table 1.1 shows examples for the three system inhibitors.

Inflexibility The inability to adjust to either changes in the supply process or changes in customer demand.

TABLE 1.1 Examples of Demand–Supply Mismatches

	Fast-Food Restaurant	Rental Cars	Fashion Retailer	Emergency Room
Waste	Leftover food	Cars sitting in the parking lot	Items that stay in the store all season	Time spent on patients who could have been seen in primary care
Variability	Swings in customer demand	Bad weather conditions delaying the arrival of cars	Consumer demand driven by fashion	Sudden increases in patient volume due to the flu season
Inflexibility	Rigid staffing levels	Inability to move vehicles across rental centers	Long times to replenish items from overseas	Inability to admit patients due to a lack of inpatient beds

Check Your Understanding 1.3

Rubberball/Getty Images

Question: **Recall the last time you were standing in line at the checkout of the grocery store. Where did you see signs of the system inhibitors?**

Answer: The following provide some examples for the three system inhibitors.

- **Waste:** employees being idle; fresh food needing to be trashed because of reaching its expiration date; employees moving back and forth to replenish items in the shelves from the back of the store.
- **Variability:** long lines form before the holidays.
- **Inflexibility:** inability to move employees from being cashiers to replenishing shelves.

1.4 Additional Dimensions in the Efficient Frontier

LO1-4 Understand how to integrate sustainability and other ethical considerations into the efficient frontier framework.

When we draw the efficient frontier in ways similar to what is shown in Figure 1.5, the vertical axis (*y*-axis) captures the utility to the customer consuming the product or service, including consumption utility and transaction costs. On the horizontal axis (*x*-axis), we plot the efficiency of the organization providing the product or service, typically measured as a cost per unit. Recall that higher efficiency, and thus lower unit costs, are to the right of the figure. If those were the only two dimensions that mattered, firms should always aspire to move to the upper right in this two-dimensional plot, which is why we define the efficient frontier as the set of firms that are not Pareto dominated.

But, what if there are other variables that matter which are not captured in this two dimensional framework? What if we could reduce costs and provide a higher utility to the consumer, but we would have to rely on child labor or engage in other labor practices that would either be illegal or immoral? What if one firm Pareto dominates another firm along our two dimensions of customer utility and efficiency but does so at the expense of the environment?

One such variable that presently (and rightfully) receives a lot of attention beyond customer utility and costs relates to the impact that a firm's operation has on the environment by depleting natural resources such as clean air, water, or biodiversity. Because natural resources on our planet are finite, nations, firms, or consumers cannot maintain a life in which these resources are depleted indefinitely. The goal of sustainable operations is to maintain an ecological balance by not depleting those finite natural resources.

How can we integrate the additional dimension of "sustainability" into our two-dimensional efficiency frontier framework? Note that some variables related to sustainability can directly impact either customer utility or operational efficiency. For example:

- Customers might prefer to consume products that are produced through sustainable operations (they might prefer milk from grass-fed cows, or they might prefer to drive a vehicle with low emissions). In this case, their consumption utility goes up and the firm can ask for higher prices.
- Firms might be saving operating costs by not wasting natural resources (they might save by using an advanced air conditioning system in their office building, or they might reduce their energy consumption of a chemical reaction process by reducing the amount of wasted heat). In this case, the efficiency improves.

Other variables might not be captured in the trade-off between customer utility and operational efficiency. Though the idea of Pareto dominance (and thus the concept of an efficiency frontier) still applies, we now have to think about an additional dimension. As much as we would like to say that what is good for the environment is also good for the operations of a firm, sometimes a firm has to make trade-offs. Like in many parts of business, operations management requires dealing with ethical dilemmas, and you might be facing choices that cannot be put into customer utility or efficiency.

1.5 Operations Management at Work

You are reading an operations management book. Why? Why learn something about operations management? What does a (paid) job in operations look like? And where are these jobs?

Before we answer these questions, let us make a rather broad statement. Every work requires operations. The word *operations* comes from the Latin word *opus,* and *opus* means "work." So, by definition, operations is about work.

If "operations" is about work, "operations management" is about improving the way we and/or others do their work. At Toyota, a company that is often associated with great operations (and a company we will study in greater detail throughout the book), it is often said that "Everybody has two jobs: (1) do their work and (2) improve their work."

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So, if we think about the importance of operations management for your future professional career, we have to distinguish between two cases. First (and, empirically, most likely), you will not work in operations management. You might become a software developer, a doctor, a lawyer, an accountant, a technician—your job description does not mention the word *operations*. In this case, you will need other academic and nonacademic training to *do* your work (go to medical school, do an internship, learn a programming language). However, this does not mean that operations management is not important for your work. After all, you will have two jobs: *do* your work and *improve* your work. We argue that the tools you will learn in this book will help you improve your work.

LO1-5 Explain what work in operations management looks like.

Second, some jobs are all about operations management. Broadly speaking, these jobs can be divided up into two groups:

- Companies have employee and management positions that are in charge of acquiring the inputs and managing the resources they need to serve their customers. This includes managing a fleet of rental cars, determining the right staffing level in a call center, ensuring the quality of a manufacturing process, or designing new products and services.
- Oftentimes, companies seek external help when it comes to improving the way they work. This help is offered by consulting companies. There exist hundreds of consulting companies that work in operations management, ranging from one-person boutique consulting companies to global service providers such as Deloitte and McKinsey & Co.

Thus, outside of you being a doctor or a management consultant, you get paid to improve the way you or somebody else works. How do you do this? You do this by overcoming the three system inhibitors we described earlier: You eliminate waste, reduce variability, and try to overcome inflexibility. You are permanently on the lookout for operations that could benefit from further improvement. Poor quality, customers waiting in line, idle resources, or piles of inventory are for you what an open wound is for a doctor—the opportunity to make something better. That is why the largest professional organization of operations management defines *operations management* simply as "The Science for the Better."

1.6 Operations Management: An Overview of the Book

LO1-6 Articulate the key operational decisions a firm needs to make to match supply with demand.

So, at the 30,000-foot level, operations management is about matching supply with demand—providing the goods and services that customers want while making a profit. Matching supply with demand while making a profit is complicated by the fact that we face the three system inhibitors. We waste our inputs and resources (our supply). Variability in supply and demand makes matching supply with demand difficult. And, while demand is variable, supply oftentimes is inflexible, which again prevents us from matching supply with demand.

There does not exist a single magic formula we could teach you that you could apply to solve all operations problems you might encounter. Instead, matching supply with demand needs to happen at many levels and in many areas of a business. We will have to confront the three system inhibitors in any one of these areas, but waste, variability, and inflexibility will take different forms depending on the type of problem you face. Consequently, operations management requires knowing how to use an entire assortment of tools, rather than just one. The chapters in this book can address four themes corresponding to four operational problems you might encounter in practice. This categorization is not perfect, but should give you a good sense of the "big picture". We will refer to these four categories as modules though this might sound more technical than it needs to:

- Process Analysis and Improvement
- Process Productivity and Quality
- Anticipate Customer Demand
- Respond to Customer Demand

These four modules will support you in answering a set of managerial questions that help you match supply with demand and thus overcome its own sort of inefficiencies. The modules are relatively independent ("modular") of each other. With few exceptions, this is also true for the chapters within a module; that is, most chapters stand on their own as opposed to requiring you to have read the previous chapters.

Consider each of these modules in turn. The first module is entitled "Process Analysis and Improvement." In the module, you will learn to address the following questions:

- *How should we produce the products or services we provide to our customers?* You probably know how to cook and you might have made sandwiches for you, your family, and your friends. But a McDonald's restaurant oftentimes serves over 1000 burgers per day, and all McDonald's restaurants combined make dozens of burgers every second. Moving from the craftsmanship associated with making a handful of products to creating operations based on processes is at the heart of this module.
- *How can we improve our processes?* Having a process is one thing; having a *good* process is another. Because customers don't like to pay high prices and because at least some of our competitors will try to undercut our prices, we have to be able to improve our processes.

The second module in this book is entitled "Process Productivity and Quality." Lean operations is a central theme of this module. Lean, as we will see, is the response to the three system inhibitors we introduced earlier. We have a dedicated "lean chapter" in this module, but the concept of "lean" is really central to this entire module and, in fact, to the entire book. Specifically, the second module will help you answer questions such as these:

- *How do we improve the productivity of the process?* Some companies are able to provide the same utility to the customer at lower costs. Other companies are held back by their inefficiencies. The difference between these companies is their ability to make productive use of their resources.
- *How do we respond to the heterogeneous preferences of our customers without sacrificing too much productivity?* Once you start making something in large quantities,

you will find it easier to keep everything the same. McDonald's does not ask their customers if they want their burger to be grilled "medium rare" or "well done." Why not? Because it is a lot easier to make one type of Big Mac rather than making 10 types. Accommodating a variety of options to respond to the fit subcomponent in the customer utility function (Figure 1.1) often causes an increase in variability.

- *How can we consistently deliver the products and services?* Car companies like Volkswagen, GM, and Toyota produce many millions of vehicles per year and fast-food restaurants service millions of customers per day. To provide high-quality products to the customer, it is thus critical that a company performs its operations as consistently as possible.

McDonald's has to prepare food and make some purchasing decisions before the customer even places an order. Each McDonald's restaurant must purchase ingredients, and its employees must prepare some food—all without knowing how many burgers it will exactly sell. If too much food is prepared, McDonald's risks spoilage; if too little food is prepared, McDonald's faces hungry customers who might take their business elsewhere. Central to this decision is the management of inventory. Thus, we start the third module, "Anticipate Customer Demand," by talking about inventory management. We then address questions such as these:

- *How much of the products should we produce and how many customers should we serve?* Producing without having a customer order in your hand is risky; after all, you might prepare a burger that never sells. Vice versa, you might not have enough food prepared, leading to lost sales and unhappy customers.
- *How do we design a supply chain and distribution system?* Modern operations are complex, involving entire networks of operations, potentially including warehouses, suppliers, and sub-suppliers.
- *How can we predict demand?* Perfectly knowing demand ahead of time is rare in a world of variability. But we can try to predict it, which is the topic of a chapter on forecasting.

The management of inventory is at the heart of the third module. You forecast demand, you produce some inventory, and then you sell it. However, this approach to producing before having the actual demand does not work in many settings, including most of the service sector. After all, you cannot operate on a patient's broken leg before the patient has had the corresponding accident leading to the broken leg. So, the fourth and final module is about responding to customer demand. This includes the following questions:

- *How can we quickly respond to the customer demand of one customer?* Imagine the president of the United States (or the queen of England) walks into a Subway store (admittedly, a somewhat odd example). It seems like a safe assumption that the employees there would be willing to do everything possible to give him/her a customized sandwich as soon as possible. How long would it take? Even with just one single customer, the supply process is not instantaneous. Even if your customer is the president or the queen, you still need to cut the bread, put it in the toaster, and put on the ingredients. Project management is about planning the work for a single, unique job.
- *How can we quickly respond to the customer demand of many customers?* Subway takes about 2.5 minutes to take an order, make a sandwich, and ring up the customer. However, unless you are the president or the queen, you most likely will spend a longer time in the restaurant; you wait until it is your turn. We discuss models that explain how long customers have to wait (and how they react to that waiting).
- *What products and services best meet the needs of our customers?* Be it the recipe for a hamburger at McDonald's, the specifications of a BMW sports car, or the service

standards in a call center or hospital, a firm needs to decide how it will address the needs of the customer.

Matching supply with demand is the theme that is common across all chapters. And this requires overcoming the three system inhibitors of waste, variability, and inflexibility. Throughout the book, we use examples from many different industries, ranging from hospitals to scooter plants, from banks to automotive companies, and from fast-food to fashion apparel. All examples are based on real operations.

While we cannot possibly cover all industries, companies, and examples, the operational questions, techniques, and strategies covered in this book are applicable broadly. At the risk of offending doctors and nurses in the readership, the challenges of managing an emergency room in a hospital have a lot in common with managing a fast-food restaurant. Recall from earlier: The tools and training for "doing the work" will certainly differ between cook and doctor, but the tools for improving the operations are remarkably similar. Patients want the care that is right for them, they want it delivered nearby, they don't want to wait in the waiting room, and they or their insurance company do not want to pay too much, just as hungry students want food that is right for them, delivered or served nearby, without too much of a wait at an affordable price.

Table 1.2 summarizes the operational decisions of a firm and groups them by the components of the customer utility function discussed at the beginning of the chapter. The first two rows correspond to the consumption utility, the next two rows to price (and cost), and the last two rows to convenience. The table illustrates the decisions for a restaurant chain, a rental car agency, a fashion retailer, and an emergency room.

TABLE 1.2 Key questions in operations management

	Fast-Food Restaurant	Rental Cars	Fashion Retailer	Emergency Room
What is the product or service?	Define the recipes and the cooking instructions	Pick vehicles for the fleet	Choose an assortment of attractive apparel	Create a care path for a specific procedure
Who are the customers and what are their heterogeneous needs?	Let customers choose from a menu; potentially allow for special requests	Choose different car types	Determine sizes and colors	Diagnose the unique medical needs of each patient and deliver the appropriate care
How much do we charge?	Pricing for the various items on the menu	Pricing for the vehicles; potentially advance booking discount	Pricing; potentially discounts at the end of season	Reimbursement rates
How efficiently are the products or services delivered?	Decide on how much equipment to buy, how much staff to hire, and how to organize cooking and the cash register	Make sure to not have too many or too few vehicles in the parking lot	Make sure to not have too many or too few items of a particular piece of clothing	Determine staffing plans for doctors and nurses and organize the flow of patients through the ER
Where will the demand be fulfilled?	Location of restaurants; potentially take-out or home delivery services	Location of rental stations; potentially pick up customer from home	Store locations	Location of hospitals; potentially provide some care in outpatient clinics
When will the demand be fulfilled?	Decide if you prepare the food ahead of the customer order; ensure fast service	Right level of staff enabling fast service	Avoid long lines at checkout	Ensure short wait times, especially for high acuity patients; decide on triage process

Dougal Waters/Photodisc/Getty Images

Check Your Understanding 1.4

Question: You and a group of fellow students are starting a new venture providing tutoring services for high school kids in your neighborhood preparing them for the SAT and ACT. What type of operational decisions do you have to make?

Answer:

- **What** is the product or service? Do we offer SAT and ACT? Do we help with subject SATs?
- **Who** are the customers and what are their heterogeneous needs? Do we cater to all students or only students who are aiming for very high scores? How do we deal with customers who are struggling?
- **How much** do we charge? What is the price for our preparation?
- **How efficiently** are the products or services delivered? How many tutors do we hire? Do we operate our own building? What are class sizes? Is there any online work that is automated?
- **Where** will the demand be fulfilled? Are students coming to us or are we coming to the students?
- **When** will the demand be fulfilled? Are we operating on a fixed schedule or whenever a customer needs our service?

Conclusion

Operations management is about giving customers what they want while making good use of inputs and resources so that costs are low enough to yield a profit. Matching supply with demand while making a profit is complicated by the fact that we face the three system inhibitors. As you read through other chapters in this book, keep this basic framework in mind. Always ask yourself what the customer really wants and what keeps us from matching this demand with a supply that we can provide at sufficiently low cost to still make a profit.

Summary of Learning Objectives

LO1-1 Identify the drivers of customer utility.

Customer utility is driven by the consumption utility, the price, and the inconvenience. The consumption utility depends on the absolute performance and the fit to a given customer. The price includes all costs associated with the product or service. Inconvenience, also called transaction cost, is driven by time and location.

LO1-2 Explain inefficiencies and determine if a firm is on the efficient frontier.

The efficient frontier consists of all firms that are not Pareto dominated. *Pareto dominated* means that a firm's product or service is inferior to that of one or multiple competitors on all dimensions of the customer utility function.

LO1-3 Explain the three system inhibitors.

The gap between our current performance and the efficient frontier is our inefficiency. This inefficiency results from a combination of the three system inhibitors: waste, variability, and inflexibility.

LO1-4 Understand how to integrate sustainability and other ethical considerations into the efficient frontier framework.

As much as we like to improve the quality of our products and services while also having an eye on costs, we need to be careful and remember to also consider how our operations impact the world around us, including environmental damages or questionable labor practices.

LO1-5 Explain what work in operations management looks like.

Operations comes from the Latin word *opus,* which means "work." Operations management is about helping people do their work. But it is also about helping people to improve the way that they work by overcoming the inefficiencies that they face.

LO1-6 Articulate the key operational decisions a firm needs to make to match supply with demand.

A firm or company needs to make a number of operational decisions. This includes answering the following questions: (a) **What** is the product or service? (b) **Who** are the customers? (c) **How much** do we charge? (d) **How efficiently** are the products or services delivered? (e) **Where** will the demand be fulfilled? (f) **When** will the demand be fulfilled?

Key Terms

Introduction

Supply Products or services a business offers to its customers.

Demand Simply, the set of products and services our customers want.

1.1 The Customer's View of the World

Utility A measure of the strength of customer preferences for a given product or service. Customers buy the product or service that maximizes their utility.

Consumption utility A measure of how much you like a product or service, ignoring the effects of price and of the inconvenience of obtaining the product or service.

Performance A subcomponent of the consumption utility that captures how much an average consumer desires a product or service.

Fit A subcomponent of the consumption utility that captures how well the product or service matches with the unique characteristics of a given consumer.

Heterogeneous preferences The fact that not all consumers have the same utility function.

Price The total cost of owning the product or receiving the service.

Inconvenience The reduction in utility that results from the effort of obtaining the product or service.

Transaction costs Another term for the inconvenience of obtaining a product or service.

Location The place where a consumer can obtain a product or service.

Timing The amount of time that passes between the consumer ordering a product or service and the consumer obtaining the product or service.

Marketing The academic discipline that is about understanding and influencing how customers derive utility from products or services.

1.2 A Firm's Strategic Trade-Offs

Capabilities The dimensions of the customer's utility function a firm is able to satisfy.

Trade-offs The need to sacrifice one capability in order to increase another one.

Market segments A set of customers who have similar utility functions.

Pareto dominated Means that a firm's product or service is inferior to one or multiple competitors on all dimensions of the customer utility function.

Efficient frontier The set of firms that are not Pareto dominated.

Inefficiency The gap between a firm and the efficient frontier.

1.3 Overcoming Inefficiencies: The Three System Inhibitors

Waste The consumption of inputs and resources that do not add value to the customer.

Variability Predictable or unpredictable changes in the demand or the supply process.

Inflexibility The inability to adjust to either changes in the supply process or changes in customer demand.

Conceptual Questions

LO 1-1

1. Below are a number of slogans used for advertisement. Which dimensions of customer utility do the slogans emphasize?
   a. We build lenses uniquely to the needs of your eyes.
   b. Get your burger in 1 minute or less—otherwise, you eat free.
   c. We match any price in town.
   d. Our dealership network provides service, wherever in the country you may be.
   e. The fastest Internet in the nation.
2. Which of the following is not a dimension or subdimension in a customer's utility function?
   a. Convenience
   b. Price
   c. Location
   d. Customer satisfaction
   e. Performance

LO 1-2

3. The efficient frontier is given by the cheapest company in the industry. True or false?
4. There can be no more than two firms on the efficient frontier. True or false?
5. Two retailers compete on costs and the ambience of their retail stores. They are identical in all other dimensions of customer utility. Retailer A is cheaper than retailer B. Retailer A also has the better ambience. Does this mean that retailer A is on the efficient frontier? Yes or no?

LO 1-3

6. Which of the following is NOT one of the three system inhibitors?
   a. Waste
   b. Variability
   c. Fatigue
   d. Inflexibility
7. Which of the following is an example of a system inhibitor?
   a. A customer adds extra weatherproofing to a new truck purchase.
   b. An emergency room doctor has no patients at the moment.
   c. A financial advisor spends time with a client explaining retirement options.
   d. A vacation home is cleaned for the next guests.

LO 1-6

8. Which of the following questions is NOT related to operations management?
   a. **When** will the demand be fulfilled?
   b. **How much** will the CEO be paid?
   c. **Who** are the customers?
   d. **How efficiently** are the products or services delivered?
   e. **Where** will the demand be fulfilled?
   f. **What** is the product or service?
9. Which of the following is most related to the operations management of an organic sheep farm?
   a. The amount of land they rent for grazing sheep.
   b. The amount borrowed from a bank.
   c. The legal structure selected for the owners.
   d. The color of their brand logo.

Solved Example Problems

LO 1-1

1. The following is a list of customer complaints. To which dimension of customer utility do the complaints relate?
   a. I had to spend 27 minutes on hold before talking to an agent.
   b. This car is not fuel-efficient at all.
   c. When I needed a restroom in the amusement park, I had to walk almost a mile.
   d. I had this suit tailored for me, but now I realize that the shoulders are too wide.

   Answer: The complaints relate to

   - Timing
   - Performance
   - Location
   - Fit

LO 1-2

2. There are four cab companies in a large urban area. Prices are identical across the four companies, and so the companies compete on (a) the response time it takes between receiving a call requesting a cab and the arrival of the cab, and (b) the cleanliness of the cab and the courtesy of the driver. The following table lists past performance data.

Cab Company	Response Time	Courtesy (1: very low … 5: very high)
1	6 min	3
2	9 min	5
3	3 min	2
4	11 min	2

   Which of these companies are NOT on the efficient frontier?

   Answer: We observe that company 4 is Pareto dominated by companies 1 and 2; none of the other companies are Pareto dominated.

3. You have a choice between five restaurants that differ from each other with respect to their food quality [as measured by the number of stars (*) the restaurant received in customer reviews; this ranges from one to five stars, with five being the best] as well as their price.

Restaurant	Quality	Price
1	***	$30
2	**	$25
3	*****	$50
4	***	$20
5	*	$5

   Which of these restaurants are on the efficient frontier?

   Answer: Restaurants 3, 4, and 5 are on the efficient frontier. Restaurant 4 Pareto dominates both 1 and 2.

LO 1-3

4. You are organizing a pizza night with your friends. You expect somewhere between 10 and 20 guests, so you decide to order food for 15. What mismatches between supply and demand can you envision? What would be costs related to these mismatches?

   Answer: Depending on how many guests show up and how much they want to eat, we can end up in one of two cases:

   - *Too much demand:* This corresponds to more guests than you have expected showing up; in this case, some guests will not get to eat. They might be mad at you as the host. Or you might have to run and order more food, leading to waiting time and probably also worse food.
   - *Too much supply:* This corresponds to you ordering more food than your guests want to eat. In this case, you will have leftover food—food that you paid for but really don't need.

5. What are supply–demand mismatches for the operator of a fleet of ambulances? What economic and social costs could you envision?

   Answer: At any given time, there are either too many ambulances (with the associated costs of resources) or too few ambulances (with the tragic costs of patients having to wait for an ambulance, putting them at an increased medical risk).

LO 1-2

6. Lunch@Work is a student-initiated venture that provides office workers with lunch brought right to their desks. What operational decisions will the venture have to make?

   Answer: The questions include the following:

   - *What is the service?* Determine what food you provide.
   - *Who are the customers?* Determine if there are any dietary restrictions and how you deal with those.
   - *How much do we charge?* Determine the price.
   - *How efficiently is the service delivered?* Decide how many people make the food, how to run the kitchen operations, and how to distribute the food to the offices.
   - *Where will the demand be fulfilled?* Determine where you would ship to (which zip codes, where in the building).
   - *When will demand be fulfilled?* Ensure that waiting times are not too long.

Problems and Applications

LO 1-1

1. What are the subcomponents of inconvenience in a customer utility function?
   a. Location and price
   b. Price and volume
   c. Location and time
   d. Time and performance
2. Custom-built windows are designed and produced for the unique needs of a particular building. Which dimension of the customer utility function is particularly emphasized with the concept of "custom built"?
   a. Performance
   b. Fit
   c. Price
   d. Location
3. Which of the following characteristics is a subcomponent of the consumption utility in a customer utility function?
   a. Performance
   b. Location

c. Timing
d. Price

4. A national restaurant chain has just opened a sit-down location at Chicago's O'Hare International Airport. Next to the sit-down location, it has also established a "to-go" section where travelers can purchase pre-made sandwiches and salads, as well as drinks and snacks. Which dimension of the customer utility function is particularly emphasized with the "to-go" section?
   a. Performance
   b. Fit
   c. Price
   d. Timing
5. A car manufacturer has designed a "special edition" version of its popular two-door coupe. This special edition has increased horsepower compared to the standard model and a sports suspension. Which dimension of the customer utility function is particularly emphasized with the special edition coupe?
   a. Performance
   b. Fit
   c. Price
   d. Timing
6. There are four hotels competing with otherwise very similar products on the dimensions of price ($ per night) and amenities (measured by the number of *s awarded by customer reviews).
   Hotel A: price = $200 per night; rating: ***
   Hotel B: price = $150 per night; rating: ****
   Hotel C: price = $300 per night; rating *****
   Hotel D: price = $80 per night; rating **

   Which of these hotels are on the efficient frontier? You may select more than one answer.

LO 1-2

7. Four regional less-than-truckload (LTL) carriers handle shipments traveling from Lexington, Kentucky, to Springfield, Illinois. All four companies say that their normal service time to deliver these shipments is 2 business days. The four carriers compete with each other on the basis of price and service quality rating, as shown in the following table. The price reported in the table is the (nondiscounted) cost per hundredweight (cwt) of sending a 600-pound shipment from Lexington to Springfield at freight class 70. The service quality rating measures a carrier's loss and damage record and goes from 0 (poor quality) to 100 (high quality).

Carrier	Price	Service Quality Rating
A	$103.90	95
B	$98.50	91
C	$127.20	98
D	$111.40	94

   Which of these LTL carriers are on the efficient frontier?
8. A suburb of Dayton, Ohio, has four local dry cleaners that compete with each other on the basis of price and service speed. Each of them can perform the same basic services at the same level of quality. The following table provides the price that each dry cleaner charges to clean a two-piece suit, as well as the quoted number of days that the service will take.

Dry Cleaner	Price	Number of Days
A	$8.00	3
B	$9.50	3
C	$9.00	2
D	$7.50	4

Which of these dry cleaners are NOT on the efficient frontier?

LO 1-3

9. Which of the following items would be considered an input in the operations of a soft drink manufacturer?
   a. Brand image
   b. Bottling machines
   c. Empty bottles
   d. Workers
10. Which of the following items would be considered a resource in the operations of a soft drink manufacturer?
   a. Water
   b. Bottling machines
   c. Empty bottles
   d. Sugar and/or concentrate
11. Which of the following items would be considered an input in the operations of a doctor's office?
   a. Examination table
   b. Nurse
   c. Needle
   d. Stethoscope
12. Which of the following items would be considered a resource in the operations of a movie theater?
   a. Popcorn
   b. Projector
   c. Printer ink
   d. Soda
13. Which of the following inefficiencies in a grocery store's operations results from inflexibility?
   a. Leftover fruits and vegetables
   b. Delivery delays from the warehouse
   c. A surge in customer arrivals at one time
   d. Employee work schedules set a week in advance
14. Which of the following inefficiencies in a bank's operations results from variability?
   a. Employees entering the same information twice
   b. Associates reading the terms and conditions of each account to the customer
   c. Customers incorrectly listing information on forms
   d. Employee work schedules set a week in advance

LO 1-6

15. Which of the following operational decisions correspond(s) to the convenience component of the consumer utility function?

   Instructions: You may select more than one answer.
   a. When will the demand be fulfilled?
   b. How efficiently will the products or the services be delivered?
   c. What is the product or service to be delivered?
   d. Where will the demand be fulfilled?

16. Which of the following operational decisions correspond(s) to the price component of the consumer utility function?

    Instructions: You may select more than one answer.

    a. When will the demand be fulfilled?
    b. What are the shipping charges to the customer?
    c. What is the product or service to be delivered?
    d. Where will the demand be fulfilled?

17. Which of the following operational decisions correspond(s) to the consumption utility component of the consumer utility function?

    Instructions: You may select more than one answer.

    a. When will the demand be fulfilled?
    b. How efficiently will the products or the services be delivered?
    c. What is the product or service to be delivered?
    d. Where will the demand be fulfilled?

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2 Introduction to Processes

LEARNING OBJECTIVES

LO2-1 Identify an appropriate flow unit for a process.

LO2-2 Distinguish among the three key process metrics (flow rate, flow time, and inventory) and evaluate average flow rate and flow time from departure and arrival data.

LO2-3 Use Little's Law to evaluate the three key process metrics.

CHAPTER OUTLINE

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Introduction

We live our lives from one process to another—there is a process for getting a driver's license, a process for completing a college degree, a process for talking to a doctor, and on and on. In those cases, and in many others, we take the perspective of a customer—we participate in the process to receive a good or service. But there is another perspective, the view of a process observer—not the view of somebody in the process or receiving the process, but rather the view of somebody watching or managing the process. That is the view we take in this chapter and throughout this book.

There are two key questions the manager of a process should ask: (1) Is the process performing well? (2) How can we make the process better? In some sense, the operations manager is very much like the coach on a sports team. The coach must first decide how to measure the performance of the players. For example, a basketball coach might want to track the number of shots attempted, the number of assists, and the number of points scored per game. Next, the coach needs to figure out how to make each player better and especially how to make the team better. The first step (measure the process) is critical for the second (improve the process)—if you do not know how to measure a process, then it is difficult to know how to improve it (or even to know if you have improved it).

In this chapter, we focus on the manager's first question—what should the operations manager measure to determine if the process is performing well? The second question (How to improve the process?) is discussed extensively in the subsequent chapters. Through an example from our health care system, we show that there are three key measures of a process. We identify these measures and show how they are linked together through Little's Law. Finally, we explain why these measures are important to an organization.

2.1 Process Definition, Scope, and Flow Units

A **process** is a set of activities that takes a collection of inputs, performs some work or activities with those inputs, and then yields a set of outputs. For example, interventional radiology at Presbyterian Hospital in Philadelphia accepts patients (inputs); performs minimally invasive advanced imaging techniques like real-time X-ray, ultrasound, computer tomography, and magnetic resonance imaging; and then sends patients home (output), hopefully with better health or at least with the information needed to improve their care. This can seem like a very complex process. There are many people involved, such as patients, receptionists, nurses, physicians, and lab technicians. There are numerous pieces of complicated equipment and there are multiple rooms, including a waiting area and procedure rooms. Despite the complexity of an interventional radiology unit, if we step back a bit, the complexity can be boiled down to the simple picture shown in Figure 2.1.

Javier Larrea/Pixtal/AGE Fotostock

Figure 2.1 is called a **process flow diagram** because it provides a graphical representation of the process. It has several components. The inputs to the process are indicated with arrows flowing into the process and outputs are indicated with arrows flowing out of the process. Boxes within the process flow diagram represent **resources**—a resource is a group of people and/or equipment that transforms inputs into outputs. In Figure 2.1, there is a single resource, the radiology unit, but as we later see, process flow diagrams can have multiple resources with the output of some resources used as the inputs to other resources.

So at a basic level, the interventional radiology unit takes in patients as inputs, the unit then performs some tasks on them when they are in the unit, and then treated patients

Process A set of activities that take a collection of inputs, perform some work or activities with those inputs, and then yield a set of outputs.

Process flow diagram A graphical way to describe the process. It uses boxes to depict resources, arrows to depict flows, and triangles to depict inventory location.

Resource A group of people and/or equipment that transforms inputs into outputs.

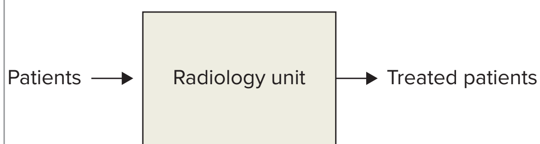


Figure 2.1
A simple process flow diagram of the radiology unit at Presbyterian Hospital

Figure 2.2
A process flow diagram for just real-time X-rays within the radiology unit

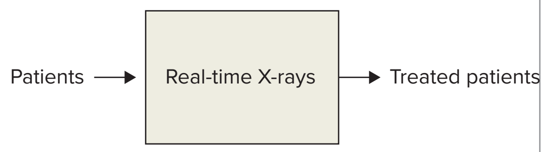
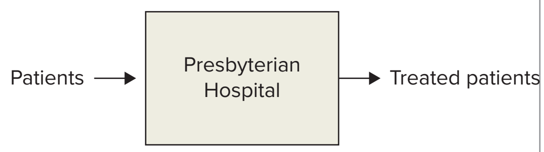


Figure 2.3
A process flow diagram for all of Presbyterian Hospital



Process scope The set of activities and processes included in the process.

Flow unit The unit of analysis that we consider in a process analysis; for example, patients in a hospital, scooters in a kick-scooter plant, and calls in a call center.

leave as the outputs. This describes the radiology unit's **process scope**—the set of activities included in the process.

We have defined the scope of this process to include the entire interventional radiology unit. This is appropriate if we are responsible for the entire unit and we want to keep track of how the entire unit is doing. But other scopes are certainly reasonable, depending on your perspective. For example, if you are a technician who assists with real-time X-rays, you might only be interested in the portion of the unit that performs real-time X-rays. In that case, your process flow diagram might look like Figure 2.2.

We have retained the same inputs and outputs, but our scope has narrowed to just a single type of procedure.

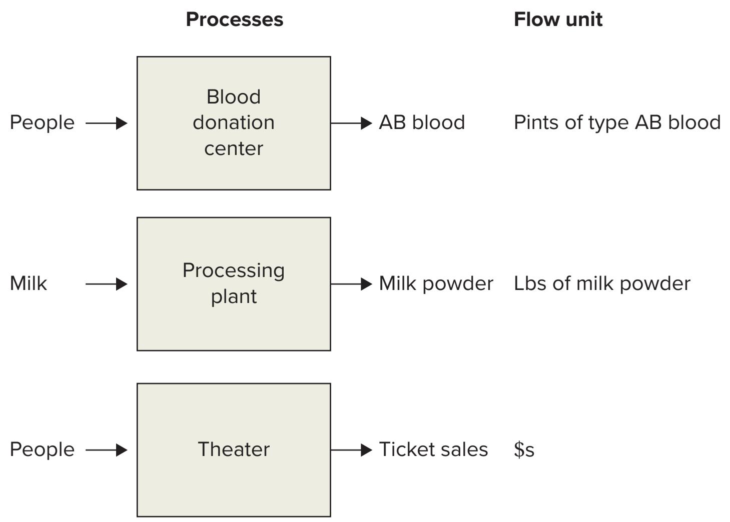
If our scope can narrow, it can also expand. For instance, say you are the CEO of Presbyterian Hospital. Then your process could be described with the "high-level" picture displayed in Figure 2.3.

LO2-1 Identify an appropriate flow unit for a process.

In addition to the process scope, to begin to understand and analyze a process, we must define a flow unit. The **flow unit** is the basic unit that moves through a process. It is generally associated with the outputs of a process. In the case of the interventional radiology unit, a natural flow unit is a "patient" because the purpose of the interventional radiology unit is to provide care to patients.

Figure 2.4 illustrates three other processes and possible flow units. In each case, it is not hard to imagine that the flow unit could be something different than what is listed. For example,

Figure 2.4
An illustration of three other processes and possible flow units



Check Your Understanding 2.1

Question: Which of the following is an appropriate flow unit for a roller coaster at an amusement park?

a. Seats on the roller coaster
b. Riders
c. Employees
d. Miles per hour (as in the speed of the roller coaster)
e. Operating time (as in the number of hours operated per day)

Answer: The roller coaster is a process that takes in riders and provides them with an exciting ride. The riders are the ones who receive this service, not the seats or the employees. While speed (miles per hour) and operating time are relevant to understanding how the process works, they are neither the input nor the output of the process per se. The correct answer is b.

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the flow unit in a blood donation center could be a "blood donor," but "pints of AB blood" is better if your interest is specifically on the output of AB blood. The processing plant could use "gallon of milk" as the flow unit, but generally it makes more sense to define the flow unit in terms of output rather than input. And while entertained "people" certainly flow through a theater, the theater may more directly be concerned with the output of revenue in terms of "$s."

To summarize, there are several important rules with respect to defining the flow unit:

1. Choose a flow unit that corresponds to what you want to track and measure with respect to the process.
2. Stick with the flow unit you defined. Don't measure some aspects of the dairy process using a "gallon of milk" as the flow unit and then switch to "pounds of milk powder." It makes no sense to combine things in different units.
3. Choose a flow unit that can be used to measure and describe all of the activities within the process. To use an exercise example, "distance traveled" might not be the best measure of all activities for a triathlete who must swim, bike, and run because people generally bike much further than they swim. A more unifying flow unit could be "minutes of workout" or, to be even more sophisticated, "calories burned" (or some other measure of power). In business, a currency (such as a euro, dollar, or yen) is a common flow unit that can be used to span all of the things and activities in a process.

Once you have defined the scope of the process and its flow unit, you are ready to start analyzing and measuring some key performance variables for the process.

2.2 Three Key Process Metrics: Inventory, Flow Rate, and Flow Time

A **process metric** is something we can measure that informs us about the performance and capability of a process. For a process observer or designer, there are three key process metrics:

- **Inventory** is the number of flow units within a process. For example, "dollars" in process, "kilograms" in process, or "people" in process.
- **Flow rate** is the rate at which flow units travel through a process. As a rate, it is measured in "flow units per unit of time"; for example, "dollars per week," "kilograms per hour," or "people per month." The key feature of a rate is that it is always expressed in terms of some unit (e.g., boxes or dollars) *per unit of time.* If the "per unit of time" is missing, then it is just inventory.
- **Flow time** is the time a flow unit spends in a process, from start to finish. Typical units for this measure are minutes, hours, days, weeks, months, or years.

Process metric A scale or measure of process performance and capability.

Inventory The number of flow units within the process.

Flow rate The rate at which flow units travel through a process.

Flow time The time a flow unit spends in a process, from start to finish.

LO2-2 Distinguish among the three key process metrics (flow rate, flow time, and inventory) and evaluate average flow rate and flow time from departure and arrival data.

Inventory tells us how much "stuff" is in the process. This is useful to know because inventory generally takes up space and may cost money. For example, if the average inventory of people in the radiology unit increases, then the radiology unit might eventually need a bigger building, which comes with a cost. If a retailer needs to increase the number of items in the store, then it might need a bigger store (which means higher rent) and it needs to have more cash to buy that inventory.

Flow rate tells us how much stuff moves through the process per unit of time. More units flowing through a process is generally desirable because the point of the process is to produce output.

Flow time tells us how much time stuff spends in the process. If you are a patient in the radiology unit, then you surely care about your flow time. The manager of the radiology unit is therefore interested in flow time because it influences the satisfaction of its patients.

To see how these process metrics can be evaluated for the interventional radiology unit, we can collect data on when patients arrive and depart our process, like those reported in Table 2.1. Over the course of the day, the table reports that there were 11 patients. Using these data, among our three process metrics, it is probably easiest to evaluate the flow time for each patient. To do so, we simply subtract the patient's departure time from his or her arrival time. According to the table, the flow times varied from a short 15 minutes to a maximum of 220 minutes. The average of the patients' flow times is 125 minutes, which is 2.08 hours.

The next easiest process metric to evaluate is flow rate. The first patient arrives at 7:35 a.m. and the last patient leaves at 18:10, or 6:10 p.m. The interval of time between those two events is 635 minutes, or 10.58 hours. During the day there are 11 patients. So the average flow rate is 11 patients/10.58 hours = 1.04 patients per hour. This flow rate applies throughout the process. For example, patients enter the process at the rate of 1.04 patients per hour and patients exit the process at the rate of 1.04 patients per hour. The entry rate and the exit rate do not have to match at every moment (e.g., in the morning more patients are entering than exiting), but they do have to match on average over the long run. This is simply a reflection of the fact that "what goes in must come out."

Finally, using the data from Table 2.1, we can also evaluate the inventory of patients at any time in the radiology unit. For example, there is one patient from 7:35 to 7:45, then two patients from 7:45 to 8:10. The third patient arrives at 8:10, but our inventory of patients drops back down to two at 8:50 because that is when the first patient departs. Figure 2.5

TABLE 2.1 Arrivals and Departures to the Interventional Radiology Unit over the Course of a Day

Patient	Arrival	Departure	Flow Time (min)
1	7:35	8:50	75
2	7:45	10:05	140
3	8:10	10:10	120
4	9:30	11:15	105
5	10:15	10:30	15
6	10:30	13:35	185
7	11:05	13:15	130
8	12:35	15:05	150
9	14:30	18:10	220
10	14:35	15:45	70
11	14:40	17:20	160
Average			125

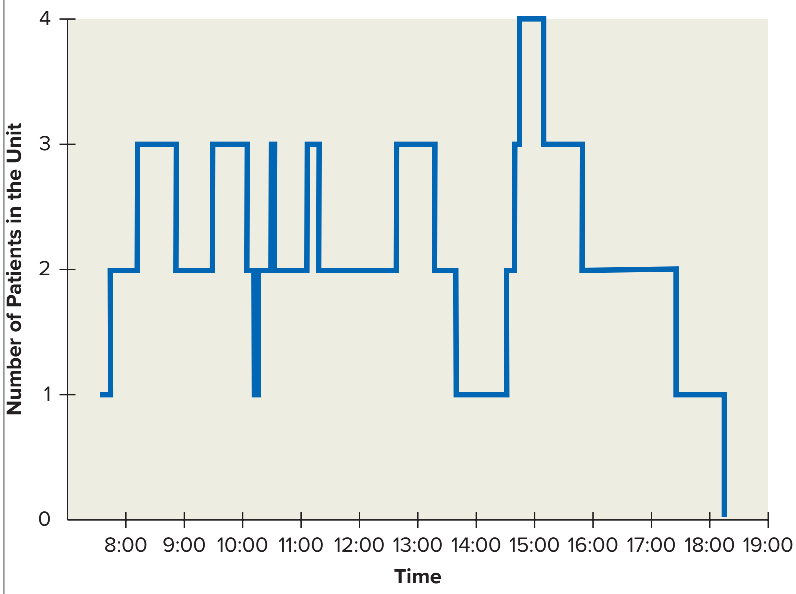

Figure 2.5
Inventory of patients in the interventional radiology unit throughout the day

Check Your Understanding 2.2

DC Studio/Shutterstock

Question: Over the course of an 8-hour day, a dentist's office treats 24 patients. What is the flow rate of patients in this dentist's office per hour?

Answer: Flow rate = 24 patients/8 hours = 3 patients per hour

Question: From 5 a.m. to 6 a.m., four callers contact a help desk. The callers spend 2, 5, 3, and 10 minutes on their calls. What is the average flow time of a caller at this help desk?

Answer: The average time for these callers is (2 + 5 + 3 + 10)/4 = 5 minutes.

plots these ups and downs in our inventory. While it is relatively straightforward to calculate the average flow time and average flow rate, the calculation of the average inventory is clearly more involved. Although it is apparent from Figure 2.5 that on average there are about two patients in the unit at any given time, it is not obvious how to evaluate the exact average inventory of patients. Fortunately, there indeed exists a very simple method, as we are about to describe.

2.3 Little's Law—Linking Process Metrics Together

LO2-3 Use Little's Law to evaluate the three key process metrics.

Within any process, the three key process metrics are related to each other in the following way, known as **Little's Law**:

$$\text{Inventory} = \text{Flow rate} \times \text{Flow time}$$

This relationship is so central to process analysis that it is often described in its shorthand version:

$$I = R \times T$$

Little's Law The law that describes the relationship between three key process metrics: inventory, flow rate, and flow time.

Little's Law is deceptively simple, but at the same time it is also remarkably powerful. It tells us that if we know any two of the process metrics, we can know, or derive, the third. In addition, it means that if by changing our process we modify one of the metrics while holding a second one constant, then we can determine how the third one changes.

Let's apply Little's Law to the radiology unit. Based on the data in Table 2.1, the flow time is $T = 2.08$ hours and the flow rate is $R = 1.04$ patients/hour. Thus, according to Little's Law, the average inventory of patients throughout the day is

$$I = 1.04\,\frac{\text{patients}}{\text{hr}} \times 2.08\text{ hr} = 2.16\text{ patients}$$

The beauty of Little's Law is that it works for any process. For example, suppose we watch people (our flow unit) loading onto the escalator in the Vastraskogen subway station in Stockholm, which is 220 feet (67 meters) long. It is a busy time of the day and we observe that the flow rate of people onto the escalator is 2.5 people per second, $R = 2.5$ people per second. We then hop on the escalator ourselves and record that the flow time from bottom to top is 88 seconds, $T = 88$ seconds. While riding on the escalator, we try to count the number of people riding with us, which is the inventory metric for this process, but it is hard to see everyone. Besides, there seem to be too many people to count. No worries; we can use Little's Law to determine the average inventory of people on the escalator:

$$\begin{aligned}\text{Inventory} &= R \times T\\ &= 2.5\text{ people per sec} \times 88\text{ sec}\\ &= 220\text{ people}\end{aligned}$$

To emphasize a point again, if you are told (or can observe) any two of the key process metrics, you can use Little's Law to derive the third. To give another (odd) example, suppose we define the U.S. House of Representatives as a process, as shown in Figure 2.6.

Politicians enter the House and eventually they leave the House as retired representatives. We know there is an inventory of 435 members in the House; that is, $I = 435$ people. Looking at past data, we see that, on average, there are 52 new members of the House in an election year and 0 new members of the House in nonelection years. (Every seat in the House is up for election every two years.) So, on average, there are $\frac{52}{2} = 26$ new members of the House per year. This is the flow rate; that is, $R = 26$ people per year. So how much time does the average representative remain in the House? Use Little's Law:

$$\begin{aligned}I &= R \times T\\ 435\text{ people} &= 26\text{ people per year} \times \text{T}\\ T &= \frac{435}{26}\\ &= 16.73\text{ years}\end{aligned}$$

If you are a politico, you might respond to our answer with "But John Dingell served in Congress much longer than 16.73 years. In fact, he served more than 55 years!" And you are correct! Little's Law does not tell us the time a particular flow unit spends in the process. Rather, it

Figure 2.6

A process flow diagram for the U.S. House of Representatives

Check Your Understanding 2.3

Foodcollection/Getty Images

Question: **During a typical Friday, the West End Donut Shop serves 2400 customers during the 10 hours it is open. A customer spends, on average, 5 minutes in the shop. On average, how many customers are in the shop simultaneously?**

Answer: Flow rate is

$$\frac{2400 \text{ customers}}{10 \text{ hr}} = 240 \frac{\text{customers}}{\text{hr}} = 4 \frac{\text{customers}}{\text{min}}. \text{ Flow time } = 5 \text{ min}$$

$$I = R \times T = 4 \frac{\text{customers}}{\text{min}} \times 5 \text{ min} = 20 \text{ customers}$$

Question: **During the course of an 8-hour day, there are, on average, five students in an undergraduate advising office, and each student spends, on average, 10 minutes with an advisor. At what rate do students go to the advising office (in students per hour)?**

Answer: Average inventory, I, equals 5 and average flow time, T, equals 10 min $= \frac{1}{6}$ hr.

From Little's Law, $R = \frac{I}{T}$. Thus, $R = 5$ students $\frac{1}{6}$ hr $= 30$ students per hr.

tells us the average time a flow unit spends in the process. Some, like John Dingell, may spend more than 16.73 years in the House, whereas others spend less than 16.73 years. But if there are 435 representatives (which there are) and there are 26 new names per year (which we learn from the historical data), then when we average the tenures of all representatives, we get 16.73 years. In fact, all three of the performance metrics in Little's Law are averages and only averages. For example, the radiology unit can have two or three patients at a given moment, but it never has exactly 2.16 patients even though, on average, it does have 2.16 patients. (It is OK to be the first or second patient, but who would want to be the 0.16th patient?) Similarly, the average patient's flow time in the radiology unit is 2.08 hours, but some spend less time and others more. On a related point, your next comment might be: "With elections every two years, the tenure of a representative must be a multiple of two. Nobody has spent exactly 16.73 years in the House." Right again. Even though everyone's tenure is a multiple of two (ignoring resignations and other reasons for not completing a term), the average across the tenures of all representatives can be something other than a multiple of two, as in 16.73 years. In other words, the average of a bunch of whole numbers doesn't have to be a whole number.

Table 2.2 gives more examples of processes in which the three key process metrics can be evaluated and connected to each other via Little's Law. The Connections box describes an application of Little's Law to the sports industry.

So if Little's Law has such a large impact in operations, why was it given a "small" name. Why not call it "Big Law" or "Grand Law"? Because it was first proved in a paper published in 1961 by a professor at the Massachusetts Institute of Technology named John Little.*

TABLE 2.2 Examples of Flow Rates, Flow Times, and Inventory

	U.S. Immigration	Champagne Industry	Undergraduate Program	Tablet Manufacturer
Flow unit	Visa application	Bottle of champagne	Student	Tablet
Flow rate	6 million apps per year	250 million bottles per year	5000 students per year	20,000 tablets per day
Flow time	9 months	3.5 years	4 years	10 days
Inventory	4.5 million applications	875 million bottles	20,000 students	200,000 tablets

*J.D.C. Little, "A Proof for the Queuing Formula: $L = \lambda W$," *Operations Research* 9, no. 3 (1961), pp. 383–87.