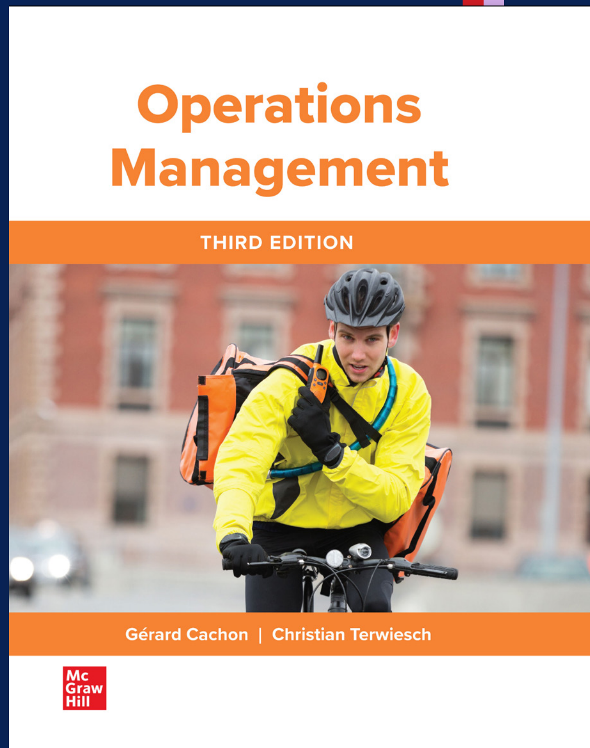
# Operations Management, 3e

Gérard Cachon | Christian Terwiesch

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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

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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 coteachers 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

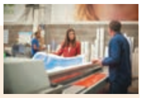
**Check Your Understanding 3.2**

**Question:** It takes a color printer 10 seconds to print a large post er. 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 .



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### 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.

*medvedsky.kz/Shutterstock*

**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**

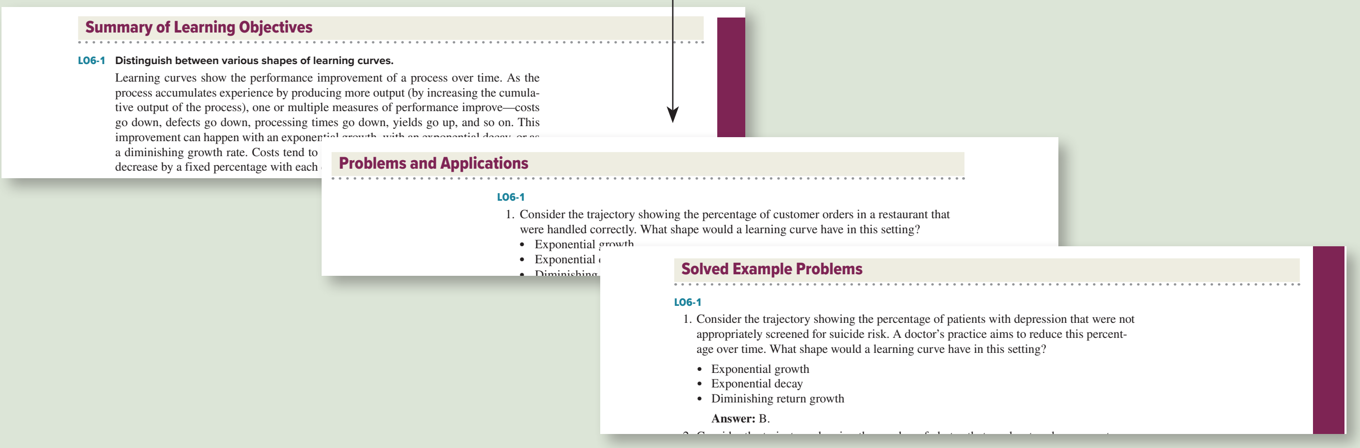
http://www.wired.com/2013/07/tesla-plant-video/
http://www.forbes.com/sites/greatspeculations/2014/09/26/fremont-factory-delays-shouldnt-affect-teslas-sales-this-quarter/

### 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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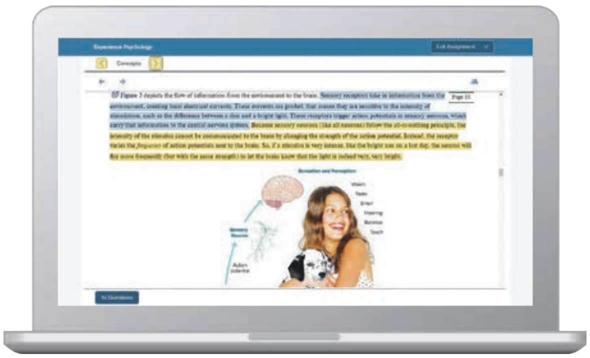

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# 3 Process Analysis

## 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



*Andersen Ross/Digital Vision/Getty Images*

## Introduction

Imagine you owned a restaurant and would be in charge of its daily operations. How would you know, on any given day, that your restaurant operates well? If you were an accountant, you probably would track the revenues and the costs of the restaurant. As long as revenues exceed costs, you might be content and leave the operations of the restaurant to the people working therein. As an operations expert, however, we want you to take a different perspective. Yes, money clearly matters and we want you to make a nice profit. But to make a profit day in and day out, to please your customers, and to secure your success in an environment where you compete with other restaurants, we argue that this requires looking inside the "black box" of the restaurant. Beyond keeping track of revenues and costs, what are some questions you would ask about the restaurant's operation? They might include the following:

- How many customers does the restaurant serve each day? And what keeps the restaurant from serving more customers?

- How busy are those working in the restaurant?
- How long does it take the restaurant to serve a given number of customers?

Knowing the answers to these questions will help you better manage the restaurant. If you can serve more customers, you can make more revenue. If your staff is busy all day, you might need to hire a new employee, but if your staff spend half of their day playing Angry Birds, chances are you might be able to reduce your expenses on labor. And if it takes you 3 hours to serve a group of 10 customers, you might be at risk of losing these customers to the restaurant next door.

## 3.1 How to Draw a Process Flow Diagram

**Process analysis**, the topic of this chapter, provides a rigorous framework for understanding the detailed operations of a business, including the answers to the questions raised in the previous section. Process analysis opens the black box of the operations and peeks inside by identifying and analyzing all the activities involved in serving one unit of demand or, put differently, in providing one unit of supply. In this chapter, you will learn how to perform a process analysis. Once you have analyzed the process, you can improve it: You can serve more customers, you can find the right number of employees to work for you, and you can get your customers what they want in less time. In short, you can make your process better.


*Andrew Resek/McGraw Hill*

Process analysis is a framework that can be used for everyone running a business. It can be used by the one who owns the restaurant, by those managing the restaurant, by those working in the restaurant, or by those consulting to the restaurant. In smaller restaurants, this is the responsibility of the owner. In bigger restaurants or restaurant chains, many job positions exist that include the term "operations" in it (such as Vice President of Operations, Chief Operating Officer, Director of Operations, Operations Expert, etc.). But understanding the operations of a business, we argue, is important to everybody. After all, wouldn't everybody in the business have an interest in making it better?

To state the obvious, this book and this chapter are not just about restaurants. At the risk of offending the (future) doctors and nurses in our readership, we propose that the framework of process analysis is just as valuable in a hospital as it is in a restaurant. Serving more patients, making sure that we have the right number of doctors and nurses available, and avoiding long patient wait times—in other words, to improve health care operations requires process analysis. So, for restaurants, hospitals, or any other business, the purpose of process analysis is to make the business better.

**LO3-1** Draw a process flow diagram.

The best way to begin any analysis of an operation is by drawing a **process flow diagram**. A process flow diagram is a graphical way to describe the process. It will help us structure the information we collect as we try to improve our understanding of the process.

We will illustrate this new material using the case of a Subway restaurant. We feel that a restaurant provides a good example, because we assume that most of you have been in restaurants, maybe even a Subway restaurant. This way, you can connect the academic content with the reality of daily life.

At the aggregate level, the restaurant consists of a number of customers, a set of employees (at Subway, oftentimes called "sandwich artists," though we will label them as employees), some work stations, and a cash register.

Just as you have a recipe when you prepare a meal, Subway has a recipe for its sandwiches. The recipe for a sandwich provides you with detailed instructions on how to make the

**Process analysis** A rigorous framework for understanding the detailed operations of a business. Among other things, the process analysis determines how many flow units can be processed per unit of time (the process capacity) and how busy the resources of the process are (utilization).

**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.

**TABLE 3.1** Recipe for a Sandwich (Including Handling of a Customer)

| Activity |
|---|
| Greet customer |
| Take order |
| Get bread |
| Cut bread |
| Add meat |
| Add cheese |
| Add onions |
| Add lettuce |
| Add tomatoes |
| Add cucumbers |
| Add pickles |
| Add green peppers |
| Add black olives |
| Add hot peppers |
| Place condiments |
| Wrap and bag |
| Offer fresh value meal |
| Offer cookies |
| Ring up bill on register |

sandwich. Table 3.1 provides you with instructions on how to prepare a sandwich. We refer to the steps shown in the table as **activities.** Some of the activities in Table 3.1 directly relate to making a sandwich (e.g., cutting the bread). But Table 3.1 also includes activities that need to happen when interacting with customers in a restaurant, from greeting the customer to ringing up the customer at the cash register.

As useful as a recipe is for the purpose of cooking, it does not offer you any information about the operations of the restaurant. Will customers have to wait? Will the restaurant serve enough customers to pay the rent and wages? The only way we can find out is to look at the process of serving the customer. Our customer is the unit of analysis—we refer to her or him as our flow unit. We also label the number of customers in the process as inventory.

If we arrive at a busy time, say during lunch hour, the first thing we notice is a line of waiting customers. When we draw a process flow diagram, we depict flow units waiting in the process without being worked on as a triangle. It is common to refer to these waiting flow units as a **buffer inventory.**

Once a customer reaches the front of the line, he or she is greeted by the first employee. That employee is in charge of taking the customer's order and starting the preparation of the sandwich. We refer to the employee as a resource. **Resources** help the flow units move from being a unit of input to becoming a unit of output.

We use directional arrows in a process flow diagram to capture the **flow unit's** journey from input to output. In our case, the flow unit has just moved from the waiting line (inventory) to the first resource. Resources are shown as rectangular boxes in the process flow diagram. So, by now, our process flow diagram consists of a triangle, an arrow, and a box (see Figure 3.1).

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

**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.

After the first employee has completed her work, the second employee takes over to now put the vegetables onto the sandwich (onions, lettuce, tomatoes, etc.) and then finishes the sandwich. She then puts it into a bag. The second employee is in charge of a different set of activities for the flow unit, which is why we create a second box for her with an arrow going from the first box to the second box. Depending on how fast employee 1 works relative to employee 2, we might see a line forming between the two stations, which is, you guessed correctly, inventory. So, we put a triangle between employees 1 and 2 to capture this in the process flow diagram.

Following employee 2, employee 3 is in charge of offering the customers a dessert and ringing up the customer. Once again, we add a box to the process flow diagram, along with two more arrows and a triangle between employees 2 and 3. Now the customer has a sandwich, and so we finish the process flow diagram. Figure 3.2 shows the complete diagram.

The process flow diagram outlines a directional flow in the process. With this in mind, we refer to the beginning of the flow as the **upstream** of the process and the end of the process as the **downstream**. We further observe that a resource upstream from another resource serves half-finished sandwiches to the resource downstream. In other words, we can think about station 2 being the customer of station 1.

The process flow diagram alone does not tell you anything about the flow rate in the process (the number of customers that go through the restaurant); however, it captures some useful information and will be the starting point for our more quantitative analysis in a moment. But before we get to the numbers, consider four alternative process flow diagrams, all summarized in Figure 3.3(a)–(d):

- Figure 3.3(a) shows three parallel processes, each with its own dedicated waiting line. This is somewhat similar to a supermarket checkout as far as the waiting line is concerned (three separate triangles). Note that a flow unit will only visit one single box in this process flow diagram. This suggests that that resource will be in charge of ALL the activities provided to the customers, going all the way from taking the order to ringing up the customer. In other words, rather than dividing up the work and each resource specializing in a subset of the activities, this process flow diagram suggests that each customer is served by only one employee.
- Figure 3.3(b) shows three parallel resources but a common waiting line. This is somewhat similar to how most airlines have you check in your luggage (ignoring priority lines and curbside check-in). Whoever is at the front of the line will be served by the next available resource.
- Finally, Figure 3.3(c) shows a three-step process similar to our first process flow diagram (Figure 3.2), except that there is no triangle at the beginning of the flow.

**Upstream** The parts of the process that are at the beginning of the process flow.

**Downstream** The parts of the process that are at the end of the process flow.

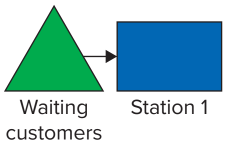



**Figure 3.1**
**Arrows for flow, triangles for inventory, and boxes for activities**

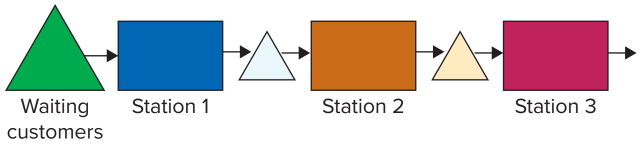
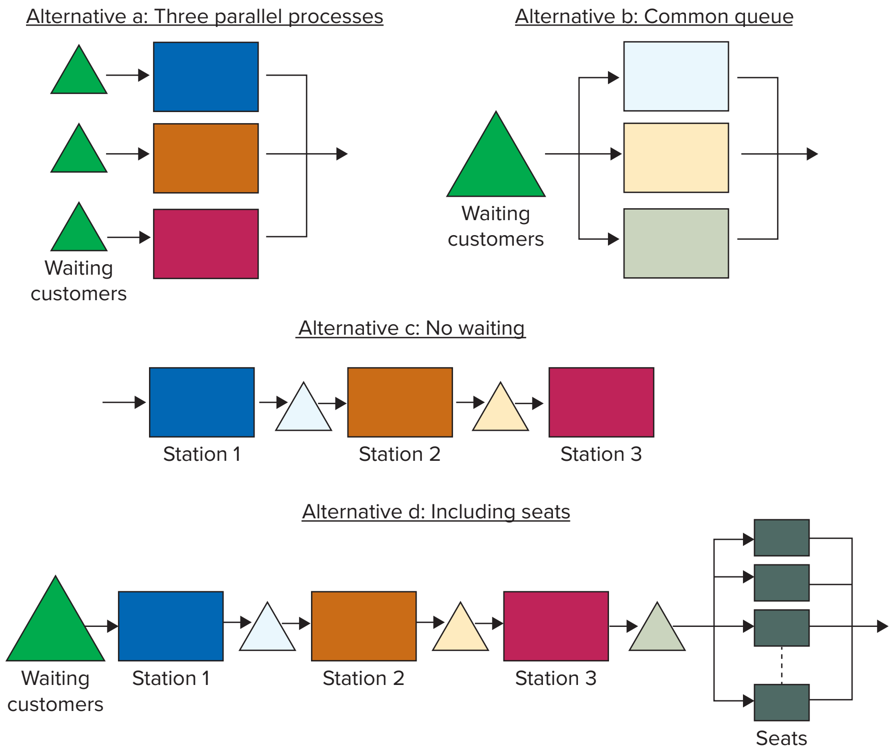



**Figure 3.2**
**Complete process flow diagram**

**Figure 3.3**
**Alternative process flow diagrams**




This means that there never is any inventory (waiting line) in this process. For example, such a situation might represent a drive-through restaurant where there is no place for waiting cars. Either a customer gets lucky and there is room at the first station or there is not (in which case the customer has to continue her journey on the road and the flow unit gets lost).

- If we also want to capture what happens to the customer after she has paid, we need to add the seats in the restaurant as an additional resource. We would extend the process flow diagram to what is shown in Figure 3.3(d). One might argue that the customers eating their sandwich in the restaurant are just another form of inventory and hence choose a triangle over a box in the process flow diagram. We chose a box here because we feel that providing eating space is part of the Subway service. One should use triangles only for those parts of the customer journey that, had the customer missed these parts, he or she would still be an equally happy customer flowing out of the process.

Before we can do a process analysis, we must first make sure we fully understand the process flow. This is why drawing a process flow diagram should always be the first thing you do in a process analysis. It is worth emphasizing that there are many process flows happening in a Subway restaurant and we could have picked a different flow unit than the customer. For example, we could analyze the flow of loaves of bread or the flow of cheese through the restaurant. We could even model the flow of employees and capture the process from recruitment to hiring to working. With different flow units, we would have obtained different process flow diagrams.

Process flow diagrams are thus very flexible and it is up to you which aspects of the operation you want to study. Consider McDonald's for a moment. You have an inventory (triangle) of waiting customers when you choose the customer as your flow unit. But you can also have an inventory of food if you choose the burger as your flow unit. So, sometimes inventory is demand (hungry customers) waiting for supply and sometimes inventory is supply (burgers kept warm) waiting for demand. Either way, inventory is a mismatch between supply and demand, and so we want to make sure we understand why it exists.

## Check Your Understanding 3.1

*David R. Frazier Photolibrary, Inc.*

**Question:** Airport security consists of the steps (1) verifying ID a nd boarding pass, (2) searching the passenger for metal objects using some form of a scanner or metal detector, and (3) running the carry-on luggage through an X-ray machine. There is a long line of passengers before the first step, but sometimes lines also build up at steps 2 and 3. Steps 2 and 3 are carried out in parallel; that is, customers go through the metal detector while their luggage is in the X-ray machine. Draw a process flow diagram of this process.

***Answer:*** See Figure 3.4.

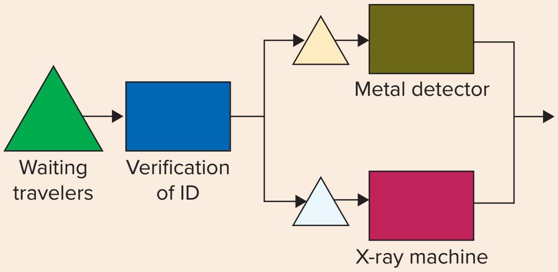



**Figure 3.4**
**Airport Security**

In the remainder of this chapter, we focus on the flow unit being the customer and analyze three alternative process flow diagrams. The first is a single employee serving the customer. Second, we will look at three employees working in parallel, as was shown in Figure 3.3(a). And third, we will look at the process flow of three (specialized) employees making sandwiches, as was shown in Figure 3.2.

## 3.2 Capacity for a One-Step Process

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

How do you make a sandwich? You follow the process recipe as was previously shown in Figure 3.3. How do you make 100 sandwiches? You move from focusing on the product (the sandwich) to focusing on the process. Part of this process focus is that you now want to figure out how you can organize your process flow—you have to choose between the various process flow diagrams discussed in the previous section. For now, assume that we follow a one-step process where one employee is in charge of completing the entire customer order.

There are many activities involved in completing one customer order, starting with "Greet the customer" and ending with "Ring on register." Table 3.2 shows these activities along with how long each activity takes per customer. Across all activities, it takes our employee 120 seconds per customer. We refer to this time as the **processing time**. The processing time of a resource is how long that particular resource takes to complete one flow unit. Table 3.3 shows examples of processing times from a range of operational settings.

For now, we will be very careful with the units, which in this case are [seconds/customer]. We encourage you to be equally concise—somewhat similar to what you most likely did in physics during high school. In physics, meters are different from meters per second. In the same way, in operations management, seconds are different from seconds per customer.

In the following calculations, we will assume that the processing times are exactly as shown in Table 3.2. This is a strong assumption. Not everybody wants hot peppers on his or her sandwich and so, sometimes, some of the activities might not be applicable. One way of interpreting the data in Table 3.2 is that it captures the average across many customers. For example, imagine it takes 10 seconds per customer to place the hot peppers on the sandwich, but only 2 out of 10 customers request hot peppers. This way, you get 2 seconds per customer, on

**Processing time** The time it takes a resource to complete one flow unit.

**TABLE 3.2** Activity Times of a Sandwich, Leading to a 120-Second-per-Customer Processing Time

| Activity | Activity Time [sec/customer] |
|---|---|
| Greet customer | 4 |
| Take order | 5 |
| Get bread | 4 |
| Cut bread | 3 |
| Add meat | 12 |
| Add cheese | 9 |
| Add onions | 3 |
| Add lettuce | 3 |
| Add tomatoes | 4 |
| Add cucumbers | 5 |
| Add pickles | 4 |
| Add green peppers | 4 |
| Add black olives | 3 |
| Add hot peppers | 2 |
| Place condiments | 5 |
| Wrap and bag | 13 |
| Offer fresh value meal | 3 |
| Offer cookies | 14 |
| Ring up bill on register | 20 |
| **Total** | **120** |

**TABLE 3.3** Typical Processing Times

| Activity | Processing Time |
|---|---|
| Cardiac surgery (double-bypass procedure) | 4 hours/patient |
| Installation of a rearview mirror in automotive assembly | 50 seconds/vehicle |
| Underwriting a simple small business loan | 40 minutes/loan |
| Simple transaction call in a bank's call center | 5 minutes/transaction |
| Primary care encounter | 15 minutes/patient |

average. You can also imagine that employees are sometimes faster and sometimes slower—they are human beings, not robots. Again, thinking in terms of averages will help. We will spend a great amount of time later in the book relaxing this assumption and capturing models of flow with variability. But, for now, this assumption will make our lives a little easier.

Next, we define the **capacity** of our single resource (the employee) as:

**Capacity** The maximum number of flow units that can flow through that resource per unit of time.

$$\text{Capacity} = \frac{1}{\text{Processing time}}$$
$$= \frac{1}{120}\ \text{customer/sec}$$
$$= 0.008333\ \text{customer/sec}$$

## Check Your Understanding 3.2

**Question:** **It takes a color printer 10 seconds to print a large post er. 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*

It is arguably somewhat difficult to imagine what 0.008333 of a customer looks like—but keep in mind that one second is also a very short moment of time. We can change units:

$$\text{Capacity} = 0.008333\,\frac{\text{customer}}{\text{sec}} \times 60\,\frac{\text{sec}}{\text{min}}$$
$$= 0.5\,\frac{\text{customer}}{\text{min}} \times 60\,\frac{\text{min}}{\text{hr}} = 30\,\frac{\text{customers}}{\text{hr}}$$

So we get a capacity of 0.008333 customer/second, or 0.5 customer/minute, or 30 customers/hour—all three mean exactly the same thing. The capacity of a resource determines the maximum number of flow units that can flow through that resource per unit of time.

Because our one lone employee is the only resource in the process, we say that the capacity of the process—that is, the **process capacity**—is also 30 customers/hour. The process capacity determines the maximum flow rate a process can provide per unit of time. It thus determines the maximum supply of the process.

**Process capacity** The maximum flow rate a process can provide per unit of time. This determines the maximum supply of the process. The process capacity is the smallest capacity of all resources in the process.

## 3.3 How to Compute Flow Rate, Utilization, and Cycle Time

Now, assume we have a **demand rate** of

$$\text{Demand} = 40\,\frac{\text{units}}{\text{hr}}$$

The demand rate is the number of flow units that customers want per unit of time. So 40 customers want a sandwich each hour, but we only have capacity to make 30. We next define the flow rate as:

$$\text{Flow rate} = \text{Minimum}\,\{\text{Demand, Process capacity}\}$$
$$= \text{Minimum}\left\{40\,\frac{\text{customers}}{\text{hr}},\ 30\,\frac{\text{customers}}{\text{hr}}\right\} = 30\,\frac{\text{customers}}{\text{hr}}$$

In this case, the factor limiting the flow rate is the process capacity. For that reason, we call such a situation in which demand exceeds supply and the flow rate is equal to process capacity as **capacity-constrained**. If the process capacity exceeds demand, the flow rate will be equal to the demand rate and so we refer to the process as **demand-constrained**. Note that, instead of flow rate, you often will hear the term **throughput**. From our perspective, the terms *flow rate* and *throughput* are identical.

**Demand rate** The number of flow units that customers want per unit of time.

**Capacity-constrained** The case in which demand exceeds supply and the flow rate is equal to process capacity.

**Demand-constrained** The case in which process capacity exceeds demand and thus the flow rate is equal to the demand rate.

**Throughput** A synonym for flow rate, the number of flow units flowing through the process per unit of time.

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

**Utilization** The ratio between the flow rate (how fast the process is currently operating) and the process capacity (capturing how fast the process could be operating if there was sufficient demand). Note that utilization can be defined at the level of an individual resource or at the level of the entire process.

**Cycle time** The time between completing two consecutive flow units.

Next, we define the **utilization** of a process as the ratio between the flow rate (how fast the process is currently operating) and the process capacity (capturing how fast the process could be operating if there was sufficient demand). So,

$$\text{Utilization} = \frac{\text{Flow rate}}{\text{Capacity}} = \frac{30}{30} = 1$$

We can define the utilization at the level of an individual resource or at the level of the entire process. In this case, it does not make a difference because the only resource in this process is our one employee.

Finally, we define the **cycle time** in a process as

$$\text{Cycle time} = \frac{1}{\text{Flow rate}} = 0.0333\ \frac{\text{hr}}{\text{customer}} = 120\ \frac{\text{sec}}{\text{customer}}$$

The cycle time measures the time between ringing up two consecutive customers. Imagine this store using a nice, old cash register that makes a loud "Riiinnnggg" every time the cash register is opened. So, cycle time measures the time between two such sounds—music to our ears because we only make money when the register rings.

Now, assume demand would be 20 units/hour. In this case, the flow rate (the minimum between demand and capacity) would be 20 units/hour and the process is now demand-constrained. Also, the utilization of the process goes down to

$$\text{Utilization} = \frac{\text{Flow rate}}{\text{Capacity}} = \frac{20}{30} = 0.6667$$

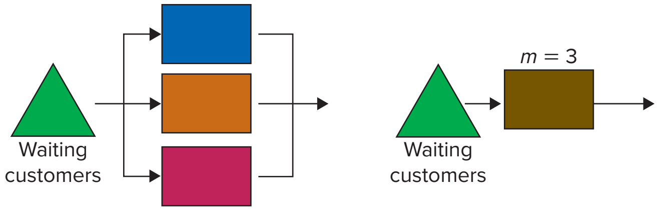
In contrast, the cycle time goes up to

$$\text{Cycle time} = \frac{1}{\text{Flow rate}} = 0.05\ \frac{\text{hr}}{\text{customer}} = 180\ \frac{\text{sec}}{\text{customer}}$$

That nice sound of the cash register that indicates we just got money from another customer now does not appear every 120 seconds, but every 180 seconds. So the cycle time has increased, indicating that the flow moves more slowly.

Now, imagine demand goes up to 100 customers per hour. If we continue to rely on our one-employee process with a process capacity of 30 customers per hour, we would be 70 customers per hour short. So, instead of working with one employee, assume we would now work with three. Moreover, for now, assume that these three employees operate three parallel work stations such as that depicted in Figure 3.5. Note that the figure shows two process flow diagrams. To the left, we show three parallel resources fed from a common inventory of waiting customers. To the right, we show one resource that is staffed with three employees (let $m$ denote the number of multiple, parallel workers or machines in a resource). These process flow diagrams are equivalent; the right one is simply an abbreviation of the left one. All our calculations will be the same for these two process flow diagrams.

**Figure 3.5**
**Three parallel resources**



Now that we have three employees, it is intuitive that we have (three times) more capacity than with one employee. More formally, define the capacity of a resource with $m$ (for multiple) employees staffing that resource as

$$\text{Capacity} = \frac{m}{\text{Processing time}} = \frac{3}{120 \text{ sec/customer}}$$
$$= 0.025 \text{ customer per sec}$$
$$= 90 \text{ customers per hr}$$

With more demand and more capacity, our flow rate would increase to

$$\text{Flow rate} = \text{Minimum } \{\text{Demand, Process capacity}\}$$
$$= \text{Minimum } \{100,\ 90\}$$
$$= 90 \text{ customers/hr}$$

We can also compute our utilization as

$$\text{Utilization} = \frac{\text{Flow rate}}{\text{Capacity}} = \frac{90}{90} = 1$$

Our cycle time thus goes down to

$$\text{Cycle time} = \frac{1}{\text{Flow rate}} = 0.0111 \frac{\text{hr}}{\text{customer}} = 40 \frac{\text{sec}}{\text{customer}}$$

Many people, even those experienced in operations, confuse the terms *cycle time* and *lead time*. We define the **cycle time** as 1/Flow rate. Consequently, cycle time is expressed in units of time per unit.

## Check Your Understanding 3.3

*Blend Images/123rf*

**Question:** A primary care doctor has the capacity to see 16 patie nts per day. The demand rate is, however, only 12 patients per day . (a) What is the flow rate? (b) What is the utilization of the doctor? (c) What is the cycle time, assuming a 10-hour work day?

***Answer:*** We compute the flow rate as the minimum of demand and process capacity:

$$\text{Flow rate} = \text{Minimum } \{\text{Demand, Process capacity}\}$$
$$= \text{Minimum } \{12 ,\ 16\}$$
$$= 12 \frac{\text{patients}}{\text{day}}$$

The utilization is the ratio between flow rate and capacity:

$$\text{Utilization} = \frac{\text{Flow rate}}{\text{Capacity}} = \frac{12}{16} = 75\%$$

The cycle time is 1/Flow rate . Over the course of the 10-hour work day, we serve 12 patients. So the cycle time is

$$\text{Cycle time} = \frac{1}{\text{Flow rate}} = \frac{1}{12} \text{ day/patient}$$

This can be expressed as:

$$\text{Cycle time} = \frac{1}{12} \text{ day/patient} \times 10 \frac{\text{hr}}{\text{day}} = \frac{10}{12} \text{ hr/patient}$$

**Lead time** The time between when an order is placed and when it is filled. Process lead time is frequently used as an alternative term for flow time.

**Lead time**, in contrast, is the time between a customer placing his or her order and that order being filled. Lead time is thus what we previously defined as flow time, the time a flow unit (a customer order) takes to get through the process. Lead time (and flow time) are expressed in units of time.

Because cycle time is driven by flow rate and lead time is the same as flow time, you may notice that cycle time and lead time are related by Little's Law. Because $I = R \times T$, and Cycle time = 1/$R$ (thus $R$ = 1/Cycle time), we get $I \times$ Cycle time = Flow time.

Think about the following example. You come to a walk-in clinic and there are 10 patients (including you) in the clinic to see the doctor. After some observation, you notice that the doctor works on a 15-minute cycle (i.e., calls in and sends out one patient every 15 minutes). How long will you be in the clinic? The answer is simply Flow time = Inventory × Cycle time = 10 patients × 15 minutes/patient = 150 minutes.

Be aware of these differences in terminology and don't be afraid to ask. Operations vocabulary is used very differently across industries and what might be called lead time in one industry is cycle time in the other. Just clarifying the measurement units (customers versus customers per hour; minutes versus minutes per unit) typically is enough to avoid misunderstandings. Thus, always be careful with the units that you use.

## 3.4 How to Analyze a Multistep Process and Locate the Bottleneck

Instead of having our three employees each serve a customer from beginning to end (i.e., carry out all the activities from greeting the customer to ringing out the customer at the cash register), we can also imagine the alternative process flow pattern that we discussed at the beginning of this chapter: three employees serving the customer, with the first employee being in charge of all activities up to (and including) putting the cheese on the sandwich, the second employee doing all activities from putting the onions onto the sandwich to bagging the sandwich, and the third employee offering cookies and the value meal as well as ringing up the customer. Assume, for the sake of argument, that the demand rate would remain constant at 100 customers per hour.

What will be the flow rate of this process? Three employees, with the same demand—one might argue that the flow rate will remain unchanged. However, things are slightly more complicated than this now that we have moved from one resource staffed by three employees to three resources staffed with one employee each. Rather than having one processing time of 120 seconds/customer, we now have three processing times. More specifically, the processing times are

$$\text{Processing time}(1) = 37 \, \frac{\text{sec}}{\text{customer}}$$
$$\text{Processing time}(2) = 46 \, \frac{\text{sec}}{\text{customer}}$$
$$\text{Processing time}(3) = 37 \, \frac{\text{sec}}{\text{customer}}$$

Just as before, we can compute the capacity for each of the three resources as

$$\text{Capacity} = \frac{1}{\text{Processing time}}$$

Given that we now have one employee again for each of the three resources, we get:

$$\text{Capacity}(1) = \frac{1}{\text{Processing time}(1)} = \frac{1}{37} = 0.027 \text{ customer per sec}$$
$$= 97.3 \text{ customers per hr}$$

$$\text{Capacity}(2) = \frac{1}{\text{Processing time}(2)} = \frac{1}{46} = 0.022 \text{ customer per sec}$$
$$= 78.3 \text{ customers per hr}$$

$$\text{Capacity}(3) = \frac{1}{\text{Processing time}(3)} = \frac{1}{37} = 0.027 \text{ customer per sec}$$
$$= 97.3 \text{ customers per hr}$$

Note that in a process with multiple resources (a process flow with multiple boxes that are not in parallel), each resource has its own capacity. To get from the resource's capacity to the overall capacity of the process—that is, to compute the process capacity—we define

$$\text{Process capacity} = \text{Min}\{\text{Capacity}(i)\} = 78.3 \text{ customers per hour}$$

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

So we find the process capacity by looking for the smallest capacity in the process. After all, a chain is only as strong as its weakest link. We define this weakest link, the resource with the lowest capacity, as the **bottleneck** of the process. It is not possible to get more customers through the process than what we have capacity for at the bottleneck.

**Bottleneck** Resource with the lowest capacity in a process.

Understanding the location of the bottleneck is critical for improving a process. Take the example of airport security. Typically, airport security consists of the steps (1) verifying ID and boarding pass, (2) searching the passenger for metal objects using some form of a scanner or metal detector, and (3) running the carry-on luggage through an X-ray machine. Most of us associate airport security with long waiting times and, all too often, a long queue greets us when we arrive at the airport—a line of passengers who wait before the first step.

So is the first step (verifying ID) the bottleneck? It certainly looks like it. But recall our definition of the bottleneck. It does not matter if a resource comes first or last; what matters is the capacity of the resource. In most airports we have visited, it is step 3 (X-raying the luggage) that slows down the process, even though the inventory (waiting passengers) are further upstream. The airport security example also helps to illustrate another point. Oftentimes, steps 2 and 3 are carried out in parallel. Does this increase the capacity of the process? The answer is a clear NO. The capacity of the security checkpoint is determined by the bottleneck and that is the smallest capacity of the three resources. Working in parallel might reduce the flow time, but it does not increase capacity.

Figure 3.6 compares the processing times visually. It is clear from the comparison that employee 2 is the bottleneck—she has the most work to do. In general, however, we caution you to jump from the processing times to identifying the bottleneck. We could have a process in which two employees would be staffing the second resource. In this case, the capacity of the second resource would be 2/46 customers/second, which is more than the capacity of either resource 1 or 3, even though resource 2 has the longest processing time.

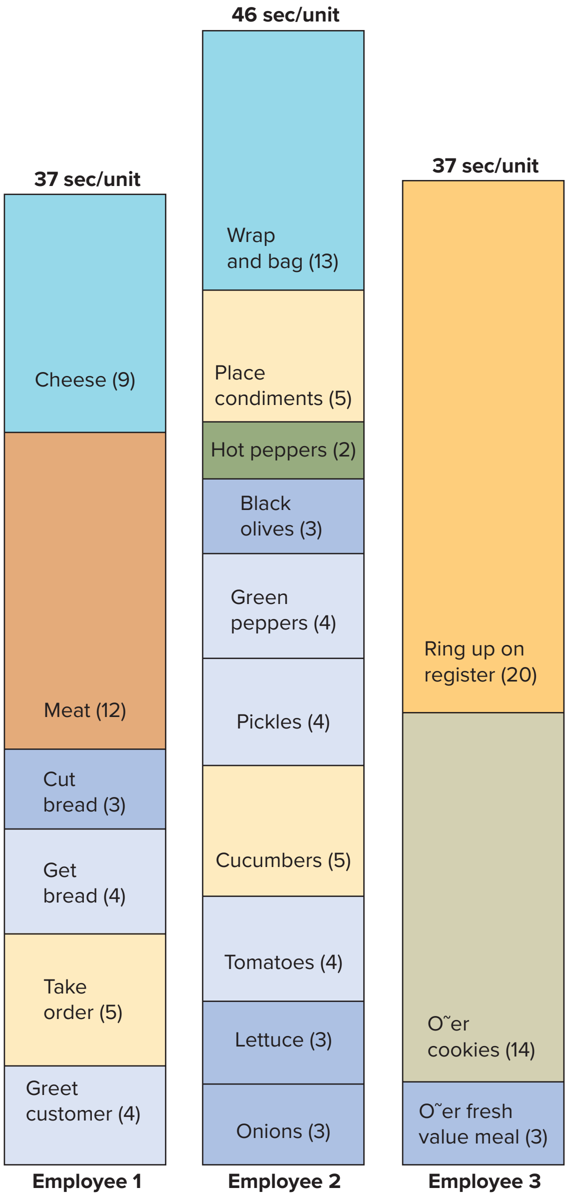
But what is flow rate? As before, when finding the flow rate, we need to look at the minimum of demand and capacity and so

$$\text{Flow rate} = \text{Minimum}\ \{\text{Demand, Process capacity}\}$$
$$= \text{Minimum}\left\{100, 78.3\right\} = 78.3\ \frac{\text{customers}}{\text{hr}}$$

In this case, we are constrained by the (bottleneck) capacity, not by demand. So it is intuitive that the bottleneck will be working "all out," which is confirmed by the following computations of utilization:

$$\text{Utilization}(1) = \frac{\text{Flow rate}}{\text{Capacity}(1)} = \frac{78.3}{97.3} = 0.804$$
$$\text{Utilization}(2) = \frac{\text{Flow rate}}{\text{Capacity}(2)} = \frac{78.3}{78.3} = 1$$
$$\text{Utilization}(3) = \frac{\text{Flow rate}}{\text{Capacity}(3)} = \frac{78.3}{97.3} = 0.804$$

**Figure 3.6**
Comparison of processing times




Note that the nonbottleneck resources have slack capacity—that is, they have utilization levels that are strictly less than 100 percent—while the bottleneck has a utilization of 100 percent. In general, a resource might have a utilization of less than 100 percent for one of two reasons:

- A nonbottleneck resource has, by definition, some extra capacity relative to the bottleneck.
- In the case of a demand-constrained process, even the bottleneck would not be working at 100 percent.

If a process is constrained by demand, we might think of demand being the bottleneck. In that case, one might argue that no single resource in the process should be called the bottleneck. However, we find it easier to always refer to the resource with the lowest capacity as the bottleneck, even in a process that is demand-constrained. So every process has a bottleneck, even if the capacity constraint created by the bottleneck might not be binding.

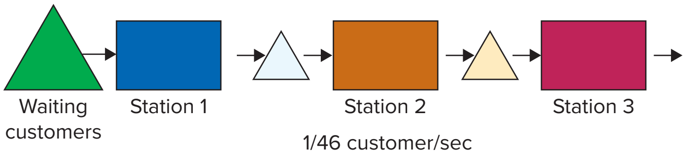



**Figure 3.7**
Summary of key calculations

| | Station 1 | Station 2 | Station 3 |
|---|---|---|---|
| | | 1/46 customer/sec | |
| **Processing Time** | 37 sec/customer | 46 sec/customer | 37 sec/customer |
| **Capacity (per second)** | $\frac{1}{37}$ customer/sec | $\frac{1}{46}$ customer/sec | $\frac{1}{37}$ customer/sec |
| **Capacity (per hour)** | 97.3 customers/h | 78.3 customers/h | 97.3 customers/h |
| **Process Capacity** | Minimum{97.3 customers/h, 78.3 customers/h, 97.3 customers/h} = 78.3 customers/h | | |
| **Bottleneck?** | No | Yes | No |
| **Flow Rate** | Minimum{78.3 customers/h, Demand} = 78.3 customers/h | | |
| **Utilization** | 78.3/97.3 = 80.4% | 78.3/97.3 = 100% | 78.3/97.3 = 80.4% |
| **Cycle Time** | $\frac{1}{1/46 \text{ customer/sec}} = 46$ sec/customer | | |

The calculations for the cycle time of the process also remain unchanged. So we get:

$$\text{Cycle time} = \frac{1}{\text{Flow rate}} = 0.012778\,\frac{\text{hr}}{\text{customer}} = 46\,\frac{\text{sec}}{\text{customer}}$$

Congratulations, this completes your first process analysis. Figure 3.7 summarizes these calculations.

## Check Your Understanding 3.4

*Ryan McVay/Photodisc/Getty Images*

**Question: Consider again the example of the three-step airport security. The first step, verifying ID and boarding pass, takes 30 seconds per passenger. The second step, searching the passenger for metal objects using a metal detector, takes 10 seconds per passenger. The third step, running the carry-on luggage through an X-ray machine, takes 60 seconds per passenger. Assume that there are many customers waiting in the process.**

**(a)** Which resource is the bottleneck? **(b)** What is the capacity of the process? **(c)** What is the flow rate? **(d)** What is the utilization of the metal detector? **(e)** What is the cycle time?

***Answer:*** Note, first of all, that none of the calculations is affected by the fact that the metal detector works in parallel with the X-ray machine for the luggage.

We first find the capacity levels as:

Capacity(ID) = $\frac{1}{30}$ passenger/second; Capacity(Metal detector) = $\frac{1}{10}$ passenger/second; Capacity(X-ray) = $\frac{1}{60}$ passenger/second. The lowest capacity is thus at the X-ray machine, which makes the X-ray machine the bottleneck and $\frac{1}{60}$ passenger/second the process capacity.

The flow rate is the minimum of demand and capacity; because many customers are waiting, the process is capacity-constrained and the flow rate is given by the process capacity—that is, $\frac{1}{60}$ passenger/second or 1 passenger per minute .

The utilization of the metal detector is

$$\text{Utilization} = \frac{\text{Flow rate}}{\text{Capacity}} = \frac{1/60}{1/10} = \frac{10}{60} = 0.1666$$

The cycle time of the process is $\frac{1}{\text{Flow rate}} = 60\,\frac{\text{sec}}{\text{customer}}$.

Note that the process flow with three workers only handling a part of the customer order is slower than the previously analyzed process of three parallel employees. We see this in the lower process capacity (78.3 customers/hour now versus previously 90 customers/hour). But why is this the case? Wouldn't we expect this process, in which each worker specializes on only a few activities, to have a *higher* capacity?

The key advantage of the parallel stations in which each employee would carry out all activities was one of utilization. Assuming sufficient demand, we had all three employees utilized 100 percent. In contrast, we saw that in the specialized process flow, only one out of three employees (employee 2, the bottleneck) was fully utilized. The other employees had capacity that was left unutilized. However, we had made the assumption that the time to carry out a particular activity (say, "greet the customer") would be the same in both the case of one employee doing all the work and the case in which workers specialize.

## 3.5 The Time to Produce a Certain Quantity


Comstock/Corbis

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

Imagine our Subway restaurant received a sudden surge in demand. A school bus would stop and 20 hungry students would rush into the restaurant, each demanding a sandwich. How long would it take to complete that demand? There are two cases that our bus of hungry students might face: They arrive at a restaurant that currently is empty or they arrive at a restaurant that is currently serving other customers (with potentially an inventory of waiting customers). For this section, assume that the restaurant is empty when the 20 students arrive.

First, let's consider a Subway restaurant that is staffed by one single employee. As discussed before, the processing time in the single-employee case would be 120 seconds/customer and we would have a capacity of 0.5 customer per minute.

Given the sudden surge in demand, the restaurant is going to be supply constrained and the flow rate is dictated by the process capacity:

$$\text{Flow rate} = \text{Min}\{\text{Demand, Capacity}\} = \frac{1}{120}\ \text{customer/sec} = 0.5\ \frac{\text{customer}}{\text{min}}$$

We can also calculate the process's cycle time for the single-employee case:

$$\text{Cycle time} = \frac{1}{\text{Flow rate}} = 120\ \frac{\text{sec}}{\text{customer}}$$

We then define the time to produce 20 sandwiches as simply

$$\begin{aligned}\text{Time to make 20 units} &= \text{Cycle time} \times 20\ \text{customers}\\ &= 120\ \frac{\text{sec}}{\text{customer}} \times 20\ \text{customers}\\ &= 2400\ \text{sec}\end{aligned}$$

Or, more generally, we write the **time to make *Q* units** as:

$$\text{Time to make } Q \text{ units} = \text{Cycle time} \times Q$$

Next, consider the case in which we have three employees available to make sandwiches and we want to use the three-step process we had analyzed previously (see Figure 3.7). Recall that we determined that station 2 was the bottleneck, with a capacity of $\frac{1}{46}$ customer/second, or 78.3 customers/hour, as the process capacity and 46 seconds/customer as the cycle time.

Again, we will attempt to move as many sandwiches through the system as possible. Therefore, we are capacity-constrained and the flow rate of the process is determined by the capacity of the bottleneck. We will operate on the 46 second/customer cycle time derived earlier. A naïve analysis suggests that

$$\begin{aligned}\text{Time to make 20 units} &= \text{Cycle time} \times 20 \text{ customers}\\ &= 46 \frac{\text{sec}}{\text{customer}} \times 20 \text{ customers}\\ &= 920 \text{ sec}\end{aligned}$$

However, this analysis is not 100 percent accurate. The reason for this is that these calculations implicitly assume that each of the workers would be able to start working immediately. In a process flow with one step, nothing holds the associated employee back from starting work. However, in the case of three employees, the third employee will remain unutilized until the sandwich finally arrives at her station. We therefore need to adjust our calculations for the time it takes the first unit to flow through the empty process.

The current system is called a **worker-paced** line because each worker is free to work at his or her own pace: If the first worker finishes before the next worker is ready to accept the sandwich (the customer), then the first worker puts the completed work in the inventory between them. This is why we included the triangles between process steps in the process flow diagram.

The first customer order will be served once all three employees have done their work, which will take 37 seconds + 46 seconds + 37 seconds. The calculations would change if steps in the process are carried out in parallel; for example, if all three steps could be carried out in parallel, the time it would take to serve the first customer would be driven by the longest processing time. So, working in parallel helps with getting the first customer through the process, but, as we discussed before, it does not alter the capacity and flow calculations.

An alternative to the worker-paced process is a **machine-paced** process, as depicted in Figure 3.8. In a machine-paced process, all steps are connected through a conveyor belt and all of the steps must work at the same rate even if some of them have more capacity than others. Except for sushi bars, we have not seen restaurants use a machine-paced line. However, they are common in assembly operations, such as the production of electronic devices or automotive vehicles.

Imagine, for example, an automotive plant with 300 assembly stations. In such settings, the process flow diagram corresponds to a set of 300 boxes in a row, with no triangles in between (though, as we will discuss in later chapters, in practice, automotive assembly lines do have some buffer inventory between a select few assembly stations). But, for now, what matters is that every resource has to work in perfect synchronization. The flow unit stays with each resource for exactly the duration of one cycle time (46 seconds in our process), irrespective of whether the processing time at that resource is 20 seconds per unit or 46 seconds per unit.

In these settings, we determine the **time through the empty system**:

$$\text{Time through an empty machine-paced process} = \text{\# of stations} \times \text{cycle time}$$

Now return to our worker-paced process. Ignoring any parallel work, we saw that the time through the empty process was given by:

$$\text{Time through empty worker-paced process} = \text{Sum of all processing times}$$

**Worker-paced** A process line in which each resource is free to work at its own pace: if the first resource finishes before the next one is ready to accept the flow unit, then the first resource puts the completed flow unit in the inventory between the two resources.

**Machine-paced** A process in which all steps are connected through a conveyor belt and all of the steps must work at the same rate even if some of them have more capacity than others.

**Time through the empty system** The time it takes the first flow unit to flow through an empty process; that is, a process that has no inventory.

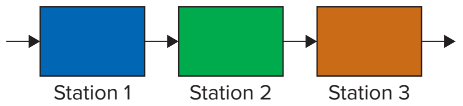



**Figure 3.8**
**Process flow diagram for a machine-paced line with three stations**

## Check Your Understanding 3.5

**Question:** **Recall the example of the three-step airport security from Check Your Understanding 3.1 (refer to Figure 3.4). The first step, verifying ID and boarding pass, takes 30 seconds per passenger. The second step, searching the passenger for metal objects using a metal detector, takes 10 seconds per passenger. The third step, running the carry-on luggage through an X-ray machine, takes 60 seconds per passenger.**

The process is empty at 7 a.m. in the morning when a group of 30 passengers arrives. How long will it take to serve all 30 passengers?

***Answer:*** The process is empty, so we first have to compute the time until the first customer is served. The first customer will take 30 seconds at the verification of her ID and then 60 seconds at the X-ray machine. Note that the time at the metal detector does not matter because it happens in parallel with the X-ray machine. Thus, it takes 90 seconds = 1.5 minutes until the first customer is served.

From then onward, we are serving a customer every minute. Because we have 29 customers to serve, this will take 29 minutes, for a total time of 1.5 + 29 = 30.5 minutes.

We can also use the previously introduced formula:

$$\begin{array}{c}\text{Time to finish } X \text{ units}\\ \text{starting with an empty system}\end{array} = \begin{array}{c}\text{Time through}\\ \text{an empty process}\end{array} + [(X-1) \times \text{Cycle time}]$$

$$\begin{array}{c}\text{Time to finish 30 units}\\ \text{starting with an empty system}\end{array} = 1.5 \text{ mins} + [29 \times 1 \text{ min}] = 30.5 \text{ mins}$$

In our case, this was given by 37 seconds + 46 seconds + 37 seconds = 120 seconds.

After waiting for 120 seconds, we have completed our first order; that is, we have fed the first of the 20 hungry customers. Now we have 19 more to go. How long will it take us? Customer 2 will be served after 120 + 46 = 166 seconds. Customer 3 after 120 + 46 + 46, and so on. From now on, we are completing a new customer order every 46 seconds. So we need 19 customers × 46 seconds/customers more time to finish the job.

In general, we can compute the **time that is required to produce a given quantity *X* starting with an empty system** as

$$\begin{array}{c}\text{Time to finish } X \text{ units}\\ \text{starting with an empty system}\end{array} = \begin{array}{c}\text{Time through}\\ \text{an empty process}\end{array} + [(X-1) \times \text{Cycle time}]$$

**Time required to produce a given quantity *X* starting with an empty system** The time it takes a process with no inventory to produce a given quantity.

## Conclusion

In this chapter, we introduced the framework of process analysis. Instead of looking at the process as a black box, merely tracking inventory, flow rate, and flow time, we want to understand how the process works. We saw that the process flow diagram is a useful tool to visually describe the flow. The process flow diagram is like a map of the process, using triangles for inventory locations, arrows for the movement of flow units, and boxes for resources. We also saw how the same work (making one sandwich) can be organized in very different ways. Even when the activities were the same, we could organize the process flow in different ways.

But the process flow diagram only tells parts of the story. Just like a street map will not provide you with any information about how many cars are actually traveling on the road or where to expect a traffic jam, a process flow diagram will not tell you how many units flow through the process.

To understand flow rate, you first have to look at the capacity of the process. You find the capacity of the process by looking for the resource with the smallest capacity, the resource that we labeled the bottleneck. The bottleneck will determine the process capacity. Flow rate, then, is found by looking at the minimum between demand and capacity. The flow rate determines how many flow units are flowing through the process per unit of time, while the capacity measures how much could be flowing through the process if there were no demand constraints. The ratio between flow rate and capacity captures the utilization of the process; we can also define utilization at the level of individual resources by taking the ratio between flow rate and the capacity at that resource. Resources might not be fully utilized, either because they are nonbottleneck resources or because the process is currently constrained by demand.

Finally, with flow rate you can compute the cycle time of a process. The cycle time of the process captures the "rhythm" of the operation. If your cycle time is 46 seconds/customer, that means every 46 seconds your cash register rings and you are bringing in money. Cycle time will also be an important starting point for several calculations in the next chapter on process improvement.

Exhibit 3.1 shows the calculations from the process flow diagram.

**EXHIBIT 3.1**

### Summary Calculations—HOW TO Exhibit

| | |
|---|---|
| Processing time | Time to carry out all activities for a flow unit at one resource |
| Capacity of a resource | Number of workers at resource/processing time |
| Process capacity | Minimum of the capacity of all resources |
| Bottleneck | Resource with the smallest capacity |
| Flow rate | Minimum{Demand, Process capacity} |
| Utilization of a resource | Flow rate/Capacity of the resource |
| Utilization of a process | Flow rate/Process capacity |
| Cycle time | 1/Flow rate |
| Time to produce $X$ units (with a "full" system) | $X \times$ Cycle time |
| Time to produce $X$ units starting with an empty process | Time through empty system + $\left[(X-1) \times \begin{matrix}\text{Cycle}\\ \text{time}\end{matrix}\right]$ |

## Summary of Learning Objectives

**LO3-1 Draw a process flow diagram.**

A process flow diagram is a graphical way to describe the process. When drawing a process flow diagram, map the flow of a flow unit from input to output. Use boxes to depict the resources, arrows to depict flows, and triangles to depict inventory location. The process flow diagram alone provides no quantitative information—it is like a map of the process.

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

The capacity of a process is the maximum number of flow units that can flow through that resource per unit of time. If there is only one step in the process, the capacity of the process is equal to the capacity of the resource that carries out this one step. To find this capacity, simply divide the number of machines or workers by the processing time.

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

The flow rate of a process is given by the minimum of the capacity of the process and the demand for the process. For the process as a whole, we can then compute the utilization as the ratio between the flow rate (how fast the process is currently operating) and the process capacity (capturing how fast the process could be operating if there was sufficient demand). We can also define utilization at the level of an individual resource. To find the cycle time, we take the reciprocal of the flow rate. Instead of saying that a process makes four units per hour, we can say it makes a unit every ¼ of an hour. So the cycle time measures how much time goes by between completing two consecutive units.

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

A chain is only as strong as its weakest link. One of the resources in the process has the lowest capacity. We refer to that one resource as the bottleneck. By definition, the capacity of the bottleneck determines the capacity of the entire process.

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

When computing the time it takes to produce a certain order quantity, we have to first ask ourselves if we face a situation in which the process starts empty or a situation in which the process already includes some inventory (customers). If the process is already running, we find the time it takes to produce a certain quantity by simply multiplying that quantity by the cycle time of the process. If the process starts empty, we have to add the time it takes the process to produce the first unit.

## Key Terms

### 3.1 How to Draw a Process Flow Diagram

**Process analysis** A rigorous framework for understanding the detailed operations of a business. Among other things, the process analysis determines how many flow units can be processed per unit of time (the process capacity) and how busy the resources of the process are (utilization).

**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.

**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.

**Upstream** The parts of the process that are at the beginning of the process flow.

**Downstream** The parts of the process that are at the end of the process flow.

### 3.2 Capacity for a One-Step Process

**Processing times** The time it takes a resource to complete one flow unit.

**Capacity** The maximum number of flow units that can flow through that resource per unit of time.

**Process capacity** The maximum flow rate a process can provide per unit of time. This determines the maximum supply of the process. The process capacity is the smallest capacity of all resources in the process.

### 3.3 How to Compute Flow Rate, Utilization, and Cycle Time

**Demand rate** The number of flow units that customers want per unit of time.

**Capacity-constrained** The case in which demand exceeds supply and the flow rate is equal to process capacity.

**Demand-constrained** The case in which process capacity exceeds demand and thus the flow rate is equal to the demand rate.

**Throughput** A synonym for flow rate, the number of flow units flowing through the process per unit of time.

**Utilization** The ratio between the flow rate (how fast the process is currently operating) and the process capacity (capturing how fast the process could be operating if there was sufficient demand). Note that utilization can be defined at the level of an individual resource or at the level of the entire process.

**Cycle time** The time between completing two consecutive flow units.

**Lead time** The time between when an order is placed and when it is filled. Process lead time is frequently used as an alternative term for flow time.

### 3.4 How to Analyze a Multistep Process and to Locate the Bottleneck

**Bottleneck** Resource with the lowest capacity in a process.

### 3.5 The Time to Produce a Certain Quantity

**Worker-paced** A process line in which each resource is free to work at its own pace: if the first resource finishes before the next one is ready to accept the flow unit, then the first resource puts the completed flow unit in the inventory between the two resources.

**Machine-paced** A process in which all steps are connected through a conveyor belt and all of the steps must work at the same rate even if some of them have more capacity than others.

**Time through the empty system** The time it takes the first flow unit to flow through an empty process; that is, a process that has no inventory.

**Time required to produce a given quantity *X* starting with an empty system** The time it takes a process with no inventory to produce a given quantity.

## Conceptual Questions

**LO3-1**

1. Which of the following questions would be asked in a process analysis of a college admissions office?
   a. When was the college founded?
   b. How long does it take the office to process an application?
   c. How much is the yearly tuition at the college?
   d. How long does it take the average student to complete a degree program at the college?
2. Which of the following items would be considered resources in a restaurant?
   a. Recipes
   b. Food
   c. Brand image
   d. Chefs
3. You are sitting in a restaurant and the waiter brings you the food you ordered a while ago. If you think about you being the flow unit in the process of the restaurant, which step of this process will be downstream relative to your current position in the process?
   a. Waiting to order
   b. Being seated at a table
   c. Paying the bill
   d. Reviewing the menu

**LO3-2**

4. What is the relationship between the processing time at a resource and its capacity?
   a. They are the same.
   b. They are reciprocals of each other.
   c. They are multiples of each other.
   d. They are not related.
5. You observe a long line at the airport security. The process currently is:
   a. capacity-constrained.
   b. demand-constrained.

c. unconstrained.
d. linearly constrained.

LO3-3

6. You observe a bank and notice that a customer leaves the bank about every 5 minutes. These 5 minutes between customers are:
   a. the capacity of the process.
   b. the processing time of the last resource.
   c. the cycle time.
   d. the lead time.
7. What is the maximum utilization a resource can achieve?
   a. A value equal to the demand
   b. A value equal to the capacity
   c. There is no maximum utilization.
   d. 1.00

LO3-4

8. Is the capacity of the bottleneck larger than, equal to, or smaller than the capacity of the process?
   a. Larger than
   b. Equal to
   c. Smaller than
   d. The answer depends on the specific process under consideration.

LO3-5

9. Smartphones are made on a 40-step assembly process. All 40 steps are connected through a conveyor belt and all of the 40 steps must work at the same rate even if some of them have more capacity than others. Is this process a machine-paced process or a worker-paced process?
   a. Machine-paced
   b. Worker-paced
10. You observe a vehicle registration department at your local township. Assume that all employees are ready to work at 9 a.m. You arrive at 9 a.m. sharp and are the first customer. Is your time through the empty process longer or shorter than the flow time averaged across all customers that arrive over the course of the day?
   a. Longer than the average flow time
   b. Shorter than the average flow time

## Solved Example Problems

LO3-1

1. The School of Dentistry at Penn provides general dental care to residents of Philadelphia on a walk-in basis. Upon arrival, customers first provide health-relevant information such as personal health records and insurance provider to a receptionist who enters the information into the computer system for the dentist to see. A dental assistant then takes an X-ray of the patient. A dentist then performs the checkup and discusses any issues with the patient. Depending on the day, patients might have to wait at any of these resources. This concludes the process. Draw a process flow diagram of this process.

   **Answer:** There are three resources in the process, corresponding to three boxes: the receptionist, the dental assistant, and the dentist.

   Because patients might have to wait in the process, we draw a triangle in front of every box in Figure 3.9.

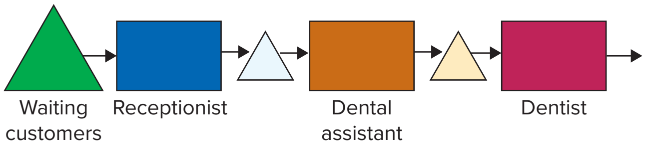



**Figure 3.9**

**LO3-2**

2. It takes a dentist 20 minutes to see one patient. What is the capacity of the dentist expressed in patients per hour?

   **Answer:** The dentist has a capacity of $\frac{1}{20}$ patient per minute, which is three patients per hour.

3. A plumbing company has eight crews fielding repair calls. It takes a crew 2 hours to complete one repair call (including travel time and breaks). What is the capacity of the plumbing company over the course of a 10-hour workday?

   **Answer:** Each crew has a capacity of $\frac{1}{2}$ call per hour. The eight crews together have a capacity of $8 \times \frac{1}{2} = 4$ calls per hour. Over a 10-hour workday, this equates to 40 calls per workday.

**LO3-3**

4. A food-truck can produce 20 meals per hour. The demand rate is, however, only 15 meals per hour. (a) What is the flow rate? (b) What is the utilization of the food-truck? (c) What is the cycle time?

   **Answer:** (a) Flow rate = Minute{Demand, Capacity} = Minute{15, 20} = 15 meals per hour

   (b) $\text{Utilization} = \frac{\text{Flow rate}}{\text{Capacity}} = \frac{15}{20} = 0.75$

   (c) $\text{Cycle time} = \frac{1}{\text{Flow rate}} = \frac{1}{15}\ \text{hr/meal} = 4\ \frac{\text{min}}{\text{meal}}$

**LO3-4**

5. Mr. K's is a very popular hair salon. It offers high-quality hairstyling and physical relaxation services at a reasonable price, so it always has unlimited demand. The service process includes five activities that are conducted in the sequence described below (the time required for each activity is shown in parentheses): activity 1—welcome a guest and offer homemade herb tea (10 minutes); activity 2—wash and condition hair (10 minutes); activity 3—neck, shoulder, and back stress release massage (10 minutes); activity 4—design the hairstyle and do the hair (25 minutes); activity 5—ring up the guest's bill (5 minutes).

   Each activity has one employee dedicated to it. For the following questions, assume unlimited demand. Also assume that the employee at activity 1 only admits new guests at the rate of the bottleneck.

   **(a)** Which resource is the bottleneck? (b) What is the capacity of the process? (c) What is the flow rate? (d) What is the utilization of the employee at activity 3? (e) What is the cycle time?

   **Answer**: (a) The capacity of each employee is given by $\frac{1}{\text{Processing time}}$. The lowest capacity is at activity 4 with $\frac{1}{25}$ guest/minute.

   (b) The capacity is $\frac{1}{25}$ guest/min $= \frac{60}{25}$ guests/hr $= 2.4\ \frac{\text{guests}}{\text{hr}}$.

   (c) There is unlimited demand; thus, the flow rate is equal to the capacity at 2.4 guests per hour.

(d) The capacity at employee 3 is $\frac{1}{10}$ guest/minute, which is 6 guests/hour.

$$\text{Utilization} = \frac{\text{Flow rate}}{\text{Capacity}} = \frac{2.4}{6} = 0.4$$

(e) $$\text{Cycle time} = \frac{1}{\text{Flow rate}} = 2.4\,\frac{\text{hrs}}{\text{guest}} = 25\,\frac{\text{min}}{\text{guest}}$$

LO3-5

6. Consider the process described in question 5. How long would it take to serve five guests, starting with an empty system?

**Answer:** We first have to think about how long it will take to serve one guest. This is a worker-paced process, so the first guest will be served after 10 + 10 + 10 + 25 + 5 = 60 minutes.

From then, we will have to serve four more guests:

Time to serve five guests starting with empty system = 60 minutes + [4 × 25 min/guest] = (60 + 100) minutes = 160 minutes.

## Problems and Applications

LO3-2, 3-3

1. It takes a barber 15 minutes to serve one customer.
   a. What is the capacity of the barber expressed in customers per hour?
   b. Assuming the demand for the barber is two customers per hour, what is the flow rate?
   c. Assuming the demand for the barber is two customers per hour, what is the utilization?
   d. Assuming the demand for the barber is two customers per hour, what is the cycle time?
2. A community health system's nurse team consists of 12 nurses working in the local community. It takes a nurse 1.5 hours to complete one patient visit (including travel time and breaks).
   a. What is the capacity of the nurse team over the course of a 9-hour workday?
   b. Assuming the demand for the nurses is 60 patients per day, what is the utilization of the nurse team?
   c. Assuming the demand for the nurses is 60 patients per day, what is the cycle time?

LO3-1, 3-2, 3-4, 3-5

3. Consider a process consisting of three resources. Assume there exists unlimited demand for the product.
   a. Resource 1 has a processing time of 6 minutes per unit.
   b. Resource 2 has a processing time of 3 minutes per unit.
   c. Resource 3 has a processing time of 5 minutes per unit.

   All three resources are staffed by one worker.
   a. Draw a process flow diagram of this process.
   b. What is the capacity of resource 2?
   c. What is the bottleneck in the process?
   d. What is the utilization of resource 2?
   e. How long does it take the process to produce 200 units starting with an empty system, assuming this is a worker-paced process?
4. A small, privately owned Asian company is producing a private-label soft drink called Yoggo. A bottling line puts the soft drinks into plastic bottles and then packages the bottles into boxes holding 10 bottles each. The bottling line is comprised of the following four steps: (1) the **bottling machine** takes 1 second to fill a bottle, (2) the **lid machine** takes 3 seconds to cover the bottle with a lid, (3) a **labeling machine** takes 3 seconds per bottle, and (4) the **packaging machine** takes 4 seconds to place a bottle

into a box. When a box has been filled with 10 bottles, a worker tending the packaging machine removes the filled box and replaces it with an empty box. Assume that the time for the worker to remove a filled box and replace it with an empty box is negligible and hence does not affect the capacity of the line. Problem data are summarized in the following table.

| Process Step | Number of Machines | Seconds per Bottle |
|---|---|---|
| Bottling | 1 | 1 |
| Apply a lid | 1 | 3 |
| Labeling | 1 | 3 |
| Packaging | 1 | 4 |

a. Draw a process flow diagram of this process.
b. What is the capacity (bottles/hour) at the resource "Apply a lid"?
c. What is the bottleneck in the process?
d. Assuming unlimited demand, what would be the flow rate?
e. Assuming unlimited demand, what would be the utilization at resource "Apply a lid"?
f. Assume the process started empty and that this is a machine-paced process. How long would it take to produce 500 bottles?

5. Glenn Dental Clinic provides general dental care to residents of Philadelphia on a walk-in basis. The clinic has started receiving complaints from patients that the waiting time is too long and has asked you to investigate whether this problem can be solved.

Upon arrival, customers first receive a series of paperwork from the receptionist and fill out relevant information such as personal health records and insurance provider. The form is then handed back to the receptionist who enters the information into the computer system for the dentist to see. A dental assistant then takes an X-ray from the patient. A dentist then performs the checkup and discusses any issues with the patient.

Based on conversations with staff members at the clinic, you have obtained the following information on the process:

a. It takes about 5 minutes for a customer to fill out the paperwork.
b. Entry of information on the paperwork into the system and verification with past records takes another 5 minutes for a receptionist. There are two receptionists.
c. It takes 15 minutes, on average, for the dental assistant to take an X-ray. There are three dental assistants on shift at any moment.
d. There are 10 dentists working at the clinic. Each checkup takes 30 minutes, on average.

The following table summarizes the process data collected above.

| Resource | Process | Staffing (Number of Workers) | Activity Time (Minutes per Patient) |
|---|---|---|---|
| Self-serve | Paperwork | – | 5 |
| Receptionists | Data entry | 2 | 5 |
| Dental assistant | X-ray | 3 | 15 |
| Dentist | Checkup | 10 | 30 |

Assume that there exists unlimited demand, unless otherwise stated.

a. Draw a process flow diagram of this process.
b. What is the capacity (patients/hour) at the resource "Dentist"?
c. What is the bottleneck in the process?
d. Assuming unlimited demand, what would be the flow rate?
e. Assuming unlimited demand, what would be the utilization at resource "Receptionists"?
f. Assume the process started empty. How long would it take to serve 20 patients?

**LO3-2, 3-4, 3-5**

6. Consider the following production process for manufacturing biscuits. The first step of the process is mixing, where all of the ingredients are combined in the correct proportion to form dough. In the next step of the process, the dough is formed into sheets and cut into pieces in preparation for baking. The cut dough is then baked into biscuits and subsequently must be cooled. The final step of the process is packaging the biscuits for the consumer.

   The following table summarizes the production process along with the processing times at each step of the process. The process is highly automated, so assume that this is a machine-paced process with one machine available at each step.

| Process Step | Activity Time (Minutes per Batch) |
|---|---|
| Mixing | 15 |
| Forming | 10 |
| Baking | 12 |
| Cooling | 18 |
| Packing | 10 |

   a. What is the capacity of the baking process step (in batches per hour)?
   b. What is the bottleneck of the manufacturing process?
   c. Assuming unlimited demand, what is the process flow rate (in batches per hour)?
   d. Assuming unlimited demand, what is the utilization of the mixing process step?
   e. If the manufacturing process is currently full of work-in-process inventory, how long would it take to complete 50 batches of biscuits?

**LO3-4, 3-5**

7. A small mortgage lender has one receptionist, four loan officers, and two office managers. When applicants apply for a new loan in person, they first fill out paperwork with the receptionist. Then the applicants meet with one of the loan officers to discuss their needs. The loan officer spends additional time processing the application after the applicants leave the office. Finally, the application must be reviewed by an office manager before it can be approved. The following table lists the processing times at each stage. The office is open for 8 hours per day, 5 days per week.

| Resource | Staffing (Number of Employees) | Activity Time (Hours per Loan) |
|---|---|---|
| Receptionist | 1 | 1 |
| Loan officers | 4 | 7 |
| Office managers | 2 | 4 |

   a. What is the bottleneck of the process?
   b. Assuming unlimited demand, what is the process flow rate (in loans per week)?
   c. If the customer demand is 18 loans per week, what is the utilization of the office managers resource?
   d. Assuming that the office currently has no backlog of loans that it is processing, how long will it take to complete 10 loans?

**LO3-5**

8. Consider a four-step serial process with processing times given in the following list. There is one machine at each step of the process, and this is a machine-paced process.
   a. Step 1: 25 minutes per unit
   b. Step 2: 15 minutes per unit

c. Step 3: 30 minutes per unit
d. Step 4: 20 minutes per unit

Assuming that the process starts out empty, how long will it take (in hours) to complete a batch of 105 units?

9. Consider a four-step serial process with the number of workers at each step and processing times given in the following table.

| Process Step | Number of Workers | Time per Customer (in Minutes) |
|---|---|---|
| 1 | 1 | 5 |
| 2 | 5 | 15 |
| 3 | 3 | 10 |
| 4 | 1 | 3 |

Assuming that the process starts out empty and is worker-paced, how long will it take (in minutes) to serve 20 customers?

**LO3-4**

10. An automated car wash serves customers with the following serial process: pre-treat, wash, rinse, wax, hand dry. Each of these steps is performed by a dedicated machine except for the hand-dry step, which is performed manually on each car by one of three workers. The steps of the process have the following processing times:
    a. Pre-treat: 1 minute per car
    b. Wash: 5 minutes per car
    c. Rinse: 2 minutes per car
    d. Wax: 3 minutes per car
    e. Hand dry: 8 minutes per car
    f. If the car wash has a demand of 15 cars per hour, what is the flow rate of the process?
    g. If the car wash has a demand of 15 cars per hour, what is the utilization of the machine that performs the wax process?
11. The local driver's license center processes applications for driver's license renewals through the following three steps. First, the customer registers with the receptionist, who updates the customer's information in the database. This first step takes 2 minutes per customer. Then, the customer visits one of two cashiers to pay the associated fees for the license renewal. This takes 8 minutes per customer because several forms must be printed from the computer and signed by the customer. Finally, the customer visits one of three license processing stations where the customer's picture is taken and the license is printed. This final step takes 15 minutes per customer.
    a. Assuming unlimited demand, what is the flow rate of the process in customers per hour?
    b. Assuming unlimited demand, what would the new flow rate be if the center added one server to the bottleneck resource?

## 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

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## References

Activities and processing time data are taken from Subway training materials.