## Planning Long-Term Capacity

**1.** The Dahlia Medical Center has 33 labor rooms, 16 combination labor and delivery rooms, and 4 delivery rooms. All of these facilities operate around the clock. Time spent in labor rooms varies from hours to days. The average uncomplicated delivery requires about one hour in the delivery room. The average time in a combination labor-delivery room is about 24 hours.

During an exceptionally busy three-day period, 100 healthy babies were born at Dahlia Medical Center. 72 babies were born in separate labor and delivery rooms and 28 were born in combined labor and delivery rooms. Which of the facilities (labor rooms, combination labor and delivery rooms, or delivery rooms) had the greatest utilization rate?

**2.** A process currently services an average of 61 customers per day. Observations in recent weeks show that its utilization is about 90 percent, allowing for just a 10 percent capacity cushion. If demand is expected to be 80 percent of the current level in five years and management wants to have a capacity cushion of just 4 percent, what capacity requirement should be planned?

**3.** An airline company must plan its fleet capacity and its long-term schedule of aircraft usage. For one flight segment, the average number of customers per day is 70, which represents a 65 percent utilization rate of the equipment assigned to the flight segment. If demand is expected to increase to 84 customers for this flight segment in three years, what capacity requirement should be planned? Assume that management deems that a capacity cushion of 25 percent is appropriate.

**4.** Food Goblin Supermarkets use both cashiers and baggers to serve customers at check out. During the first 6 hours of each workday (Monday–Friday), 4 cashiers and 2 baggers serve approximately 20 customers per hour. A cashier and a bagger who require approximately 5 minutes at checkout and 5 minutes at bagging serve each customer.

**a.** Calculate the utilization of both cashiers and baggers.

**b.** Assume that both baggers and cashiers are cross-trained to perform both activities so that they can serve customers independently. Customers are now both checked and their groceries bagged by one individual. Further, assume that it takes 12 minutes for one individual to both cash out and bag each customer's groceries. Calculate the utilization of this new group of 6 cross-trained employees.

**5.** Returning to Problem 4, under both assumption of cashiers and baggers working together (part a.) and, cross-trained, working independently (part b.) how many employees should Food Goblin Supermarket schedule if it requires a 10 percent capacity cushion?

## A Systematic Approach to Long-Term Capacity Decisions

**6.** Purple Swift manufactures birdhouses in lots of 10. Each birdhouse takes 45 minutes to paint. After 10 birdhouses are painted, the company switches paint color which requires a one hour changeover. The company works 8 hours per shift, one shift per day, 220 days per year. Currently the company has one paint booth. What is Purple Swift's paint capacity cushion if it builds 2,000 birdhouses per year?

**7.** Macon Controls produces three different types of control units used to protect industrial equipment from overheating. Each of these units must be processed by a machine that Macon considers to be their process bottleneck. The plant operates on two 8-hour shifts, 5 days per week, 52 weeks per year. Table 4.2 provides the time standards at the bottleneck, lot sizes, and demand forecasts for the three units. Due to demand uncertainties, the operations manager obtained three demand forecasts (pessimistic, expected, and optimistic). The manager believes that a 20 percent capacity cushion is best.

**TABLE 4.2** CAPACITY INFORMATION FOR MACON CONTROLS

| | TIME STANDARD | | | DEMAND FORECAST | | |
|---|---|---|---|---|---|---|
| **Component** | **Processing (hr/unit)** | **Setup (hr/lot)** | **Lot Size (units/lot)** | **Pessimistic** | **Expected** | **Optimistic** |
| A | 0.05 | 1.0 | 60 | 16,000 | 16,000 | 26,000 |
| B | 0.30 | 4.1 | 80 | 11,000 | 12,000 | 18,000 |
| C | 0.05 | 8.3 | 100 | 16,000 | 23,000 | 35,000 |

**a.** How many machines are required to meet minimum (pessimistic) demand, expected demand, and maximum (optimistic) demand?

**b.** How many machines are required if the operations manager decides to double lot sizes?

**c.** If the operations manager has three machines and believes that the plant can reduce setup time by 25 percent through process improvement initiatives, does that plant have adequate capacity to meet all demand scenarios without increasing lot sizes?

**8.** Up, Up, and Away is a producer of kites and wind socks. Relevant data on a bottleneck operation in the shop for the upcoming fiscal year are given in the following table:

| Item | Kites | Wind Socks |
|---|---|---|
| Demand forecast | 30,000 units/year | 12,000 units/year |
| Lot size | 20 units | 70 units |
| Standard processing time | 0.3 hour/unit | 1.0 hour/unit |
| Standard setup time | 3.0 hours/lot | 4.0 hours/lot |

The shop works two shifts per day, 8 hours per shift, 200 days per year. Currently, the company operates four machines, and desires a 25 percent capacity cushion. How many machines should be purchased to meet the upcoming year's demand without resorting to any short-term capacity solutions?

**9.** Tuff-Rider, Inc., manufactures touring bikes and mountain bikes in a variety of frame sizes, colors, and component combinations. Identical bicycles are produced in lots of 100. The projected demand, lot size, and time standards are shown in the following table:

| Item | Touring | Mountain |
|---|---|---|
| Demand forecast | 5,000 units/year | 10,000 units/year |
| Lot size | 100 units | 100 units |
| Standard processing time | .25 hour/unit | .50 hour/unit |
| Standard setup time | 2 hours/lot | 3 hours/lot |

The shop currently works 8 hours a day, 5 days a week, 50 weeks a year. It operates five workstations, each producing one bicycle in the time shown in the table. The shop maintains a 15 percent capacity cushion. How many workstations will be required next year to meet expected demand without using overtime and without decreasing the firm's current capacity cushion?

**10.** Knott's Industries manufactures standard and super premium backyard swing sets. Currently it has four identical swing-set-making machines, which are operated 250 days per year and 8 hours each day. A capacity cushion of 20 percent is desired. The following information is also known:

| | Standard Model | Super Premium Model |
|---|---|---|
| Annual Demand | 20,000 | 10,000 |
| Standard Processing Time | 7 min | 20 min |
| Average Lot Size | 50 | 30 |
| Standard Setup Time per Lot | 30 min | 45 min |

**a.** Does Knott's have sufficient capacity to meet annual demand?

**b.** If Knott's was able to reduce the setup time for the Super Premium Model from 45 minutes to 30 minutes, would there be enough current capacity to produce 20,000 units of each type of swing set?

**11.** Arabelle is considering expanding the floor area of her high-fashion import clothing store, The French Prints of Arabelle, by increasing her leased space in the upscale Cherry Creek Mall from 2,000 square feet to 3,000 square feet. The Cherry Creek Mall boasts one of the country's highest ratios of sales value per square foot. Rents (including utilities, security, and similar costs) are $110 per square foot per year. Salary increases related to French Prints' expansion are shown in the following table, along with projections of sales per square foot. The purchase cost of goods sold averages 70 percent of the sales price. Sales are seasonal, with an important peak during the year-end holiday season.

| Year | Quarter | Sales (per sq ft) | Incremental Salaries |
|---|---|---|---|
| 1 | 1 | $90 | $12,000 |
| | 2 | 60 | 8,000 |
| | 3 | 110 | 12,000 |
| | 4 | 240 | 24,000 |
| 2 | 1 | 99 | 12,000 |
| | 2 | 66 | 8,000 |
| | 3 | 121 | 12,000 |
| | 4 | 264 | 24,000 |

**a.** If Arabelle expands French Prints at the end of year 0, what will her quarterly pretax cash flows be through year 2?

**b.** Project the quarterly pretax cash flows assuming that the sales pattern (10 percent annually compounded increase) continues through year 3.

**12.** The Astro World amusement park has the opportunity to expand its size now (the end of year 0) by purchasing adjacent property for $250,000 and adding attractions at a cost of $550,000. This expansion is expected to increase attendance by 30 percent over projected attendance without expansion. The price of admission is $30, with a $5 increase planned for the beginning of year 3. Additional operating costs are expected to be $100,000 per year. Estimated attendance for the next five years, *without expansion*, is as follows:

| Year | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Attendance | 30,000 | 34,000 | 36,250 | 38,500 | 41,000 |

**a.** What are the pretax combined cash flows for years 0 through 5 that are attributable to the park's expansion?

**b.** Ignoring tax, depreciation, and the time value of money, determine how long it will take to recover (pay back) the investment.

**13.** Kim Epson operates a full-service car wash, which operates from 8 A.M. to 8 P.M., 7 days a week. The car wash has two stations: an automatic washing and drying station and a manual interior cleaning station. The automatic washing and drying station can handle 30 cars per hour. The interior cleaning station can handle 200 cars per day. Based on a recent year-end review of operations, Kim estimates that future demand for the interior cleaning station for the 7 days of the week, expressed in average number of cars per day, would be as follows:

| Day | Mon. | Tues. | Wed. | Thurs. | Fri. | Sat. | Sun. |
|---|---|---|---|---|---|---|---|
| Cars | 160 | 180 | 150 | 140 | 280 | 300 | 250 |

By installing additional equipment (at a cost of $50,000), Kim can increase the capacity of the interior cleaning station to 300 cars per day. Each car wash generates a pretax contribution of $4.00. Should Kim install the additional equipment if she expects a pretax payback period of three years or less?

**14.** Roche Brothers is considering a capacity expansion of its supermarket. The landowner will build the addition to suit in return for $200,000 upon completion and a 5-year lease. The increase in rent for the addition is $10,000 per month. The annual sales projected through year 5 follow. The current effective capacity is equivalent to 500,000 customers per year. Assume a 2 percent pretax profit on sales.

| Year | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Customers | 560,000 | 600,000 | 685,000 | 700,000 | 715,000 |
| Average Sales per Customer | $50.00 | $53.00 | $56.00 | $60.00 | $64.00 |

**a.** If Roche expands its capacity to serve 700,000 customers per year now (end of year 0), what are the projected annual incremental pretax cash flows attributable to this expansion?

**b.** If Roche expands its capacity to serve 700,000 customers per year at the end of year 2, the landowner will build the same addition for $240,000 and a 3-year lease at $12,000 per month. What are the projected annual incremental pretax cash flows attributable to this expansion alternative?

**15.** MKM International is seeking to purchase a new CNC machine in order to reduce costs. Two alternative machines are in consideration. Machine 1 costs $500,000 but yields a 15 percent savings over the current machine used. Machine 2 costs $900,000 but yields a 25 percent savings over the current machine used. In order to meet demand, the following forecasted cost information for the current machine is also provided.

**a.** Based on the NPV of the cash flows for these five years, which machine should MKM International Purchase? Assume a discount rate of 12 percent.

**b.** If MKM International lowered its required discount rate to 8 percent, what machine would it purchase?

| Year | Projected Cost |
|---|---|
| 1 | 1,000,000 |
| 2 | 1,350,000 |
| 3 | 1,400,000 |
| 4 | 1,450,000 |
| 5 | 2,550,000 |

**16.** Several years ago, River City built a water purification plant to remove toxins and filter the city's drinking water. Because of population growth, the demand for water next year will be more than the plant's capacity of 120 million gallons per year. Therefore, the city must expand the facility. The estimated demand over the next 20 years is given in Table 4.3.

The city planning commission is considering three alternatives.

- *Alternative 1:* Expand enough at the end of year 0 to last 20 years, which means an 80 million gallon increase (200 – 120).
- *Alternative 2:* Expand at the end of year 0 and at the end of year 10.
- *Alternative 3:* Expand at the end of years 0, 5, 10, and 15.

Each alternative would provide the needed 200 million gallons per year at the end of 20 years, when the value of the plant would be the same regardless of the alternative chosen. Significant economies of scale can be achieved in construction costs: A 20 million gallon expansion would cost $18 million; a 40 million gallon expansion, $30 million; and an 80 million gallon expansion, only $50 million. The level of future interest rates is uncertain, leading to uncertainty about the hurdle rate. The city believes that it could be as low as 12 percent and as high as 16 percent (see MyOMLab Supplement F, "Financial Analysis").

**a.** Compute the cash flows for each alternative, compared to a base case of doing nothing. (*Note*: As a municipal utility, the operation pays no taxes.)

**b.** Which alternative minimizes the present value of construction costs over the next 20 years if the discount rate is 12 percent? 16 percent?

**c.** Because the decision involves public policy and compromise, what political considerations does the planning commission face?

**TABLE 4.3 | WATER DEMAND**

| Year | Demand | Year | Demand | Year | Demand |
|---|---|---|---|---|---|
| 0 | 120 | 7 | 148 | 14 | 176 |
| 1 | 124 | 8 | 152 | 15 | 180 |
| 2 | 128 | 9 | 156 | 16 | 184 |
| 3 | 132 | 10 | 160 | 17 | 188 |
| 4 | 136 | 11 | 164 | 18 | 192 |
| 5 | 140 | 12 | 168 | 19 | 196 |
| 6 | 144 | 13 | 172 | 20 | 200 |

**17.** Mars Incorporated is interested in going to market with a new fuel savings device that attaches to electrically powered industrial vehicles. The device, code named "Python," promises to save up to 15 percent of the electrical power required to operate the average electric forklift. Mars expects that modest demand expected during the introductory year will be followed by a steady increase in demand in subsequent years. The extent of this increase in demand will be based on customer's expectations regarding the future cost of electricity and which is shown in Table 4.4. Mars expects to sell the device for $500 each, and does not expect to be able to raise its price over the foreseeable future.

**TABLE 4.4 | DEMAND FOR PYTHON POWER SAVING DEVICE**

| | EXPECTED DEMAND OF THE DEVICE IN UNITS/YEAR | |
|---|---|---|
| **Year** | **Small Increases in the Cost of Electrical Power** | **Large Increases in the Cost of Electrical Power** |
| 1 | 1,000 | 10,000 |
| 2 | 5,000 | 8,000 |
| 3 | 1,000 | 15,000 |
| 4 | 15,000 | 20,000 |
| 5 | 18,000 | 30,000 |

Mars is faced with two alternatives:

- *Alternative 1:* Make the device themselves, which requires an initial outlay of $250,000 in plant and equipment and a variable cost of $75 per unit.
- *Alternative 2:* Outsource the production, which requires no initial investment, but incurs a per unit cost of $300.

**a.** Assuming small increases in the cost of electrical power, compute the cash flows for each alternative. Over the next five years, which alternative maximizes the NPV of this project if the discount rate is 10 percent?

**b.** Assuming large increases in the cost of electrical power, compute the cash flows for each alternative. Over the next five years, which alternative maximizes the NPV of this project if the discount rate is 10 percent?

**18.** Mackelprang, Inc., is in the initial stages of building the premier planned community in the greater Phoenix, Arizona, metropolitan area. The main selling point will be the community's lush golf courses. Homes with golf course views will generate premiums far larger than homes with no golf course views, but building golf courses is expensive and takes up valuable space that non-view homes could be built upon. Mackelprang, Inc., has limited land capacity. In order to maximize its profits, it is faced with a decision as to how many golf courses it should build, which, in turn, will impact how many homes with and without golf course views it will be able to construct. Mackelprang, Inc., realizes that this decision is directly related to the premium buyers will be willing to spend to buy homes with golf course views. Mackelprang, Inc., is required to build at least one golf course but has enough space to build up to three golf courses. The following table indicates the costs and potential revenues for each course:

| | Indian River | The Cactus | Wildwood |
|---|---|---|---|
| Cost | $2.6M | $1.25M | $2.5M |
| Highest Possible Revenue | $4M | $2M | $2M |
| Probability of High Revenue | 0.3 | 0.2 | 0.3 |
| Likely Revenue | $2.5M | $1.5M | $4M |
| Probability of Likely Revenue | 0.4 | 0.5 | 0.5 |
| Lowest Possible Revenue | $1M | $1M | $1M |
| Probability of Low Revenue | 0.3 | 0.3 | 0.2 |

**a.** Which golf course or courses should Mackelprang, Inc., build?

**b.** What is the expected payoff for this project?

**19.** Two new alternatives have come up for expanding Grandmother's Chicken Restaurant (see Solved Problem 2). They involve more automation in the kitchen and feature a special cooking process that retains the original-recipe taste of the chicken. Although the process is more capital-intensive, it would drive down labor costs, so the pretax profit for *all* sales (not just the sales from the capacity added) would go up from 20 to 22 percent. This gain would increase the pretax profit by 2 percent of each sales dollar through $800,000 (80,000 meals × $10) and by 22 percent of each sales dollar between $800,000 and the new capacity limit. Otherwise, the new alternatives are much the same as those in Example 4.2 and Solved Problem 2.

- *Alternative 1:* Expand both the kitchen and the dining area now (at the end of year 0), raising the capacity to 130,000 meals per year. The cost of construction, including the new automation, would be $336,000 (rather than the earlier $200,000).
- *Alternative 2:* Expand only the kitchen now, raising its capacity to 105,000 meals per year. At the end of year 3, expand both the kitchen and the dining area to the 130,000 meals-per-year volume. Construction and equipment costs would be $424,000, with $220,000 at the end of year 0 and the remainder at the end of year 3. As with alternative 1, the contribution margin would go up to 22 percent.

With both new alternatives, the salvage value would be negligible. Compare the cash flows of all alternatives. Should Grandmother's Chicken Restaurant expand with the new or the old technology? Should it expand now or later?

## Tools for Capacity Planning

**20.** Dawson Electronics is a manufacturer of high-tech control modules for lawn sprinkler systems. Denise, the CEO, is trying to decide if the company should develop one of the two potential new products, the Water Saver 1000 or the Greener Grass 5000. With each product, Dawson can capture a bigger market share if it chooses to expand capacity by buying additional machines. Given different demand scenarios, their probabilities of occurrence, and capacity expansion versus no change in capacity, the potential sales of each product are summarized in Table 4.5.

**TABLE 4.5 DEMAND AND SALES INFORMATION FOR DAWSON ELECTRONICS**

| | Water Saver 1000 Dollar Sales ($1,000) | Greener Grass 5000 Dollar Sales ($1,000) | Probability of Occurrence |
|---|---|---|---|
| **With Capacity Expansion** | | | |
| Low Demand | 1,000 | 2,500 | 0.25 |
| Medium Demand | 2,000 | 3,000 | 0.50 |
| High Demand | 3,000 | 5,000 | 0.25 |
| **Without Capacity Expansion** | | | |
| Low Demand | 700 | 1,000 | 0.25 |
| Medium Demand | 1,000 | 2,000 | 0.50 |
| High Demand | 2,000 | 3,000 | 0.25 |

**a.** What is the expected payoff for Water Saver 1000 and the Greener Grass 5000, with and without capacity expansion?

**b.** Which product should Denise choose to produce, and with which capacity expansion option?

**21.** A manager is trying to decide whether to buy one machine or two. If only one machine is purchased and demand proves to be excessive, the second machine can be purchased later. Some sales would be lost, however, because the lead time for delivery of this type of machine is 6 months. In addition, the cost per machine will be lower if both machines are purchased at the same time. The probability of low demand is estimated to be 0.30 and that of high demand to be 0.70. The after-tax NPV of the benefits from purchasing two machines together is $90,000 if demand is low and $170,000 if demand is high.

If one machine is purchased and demand is low, the NPV is $120,000. If demand is high, the manager has three options: (1) doing nothing, which has an NPV of $120,000; (2) subcontracting, with an NPV of $140,000; and (3) buying the second machine, with an NPV of $130,000.

**a.** Draw a decision tree for this problem.

**b.** What is the best decision and what is its expected payoff?

**22.** Acme Steel Fabricators experienced booming business for the past five years. The company fabricates a wide range of steel products, such as railings, ladders, and light structural steel framing. The current manual method of materials handling is causing excessive inventories and congestion. Acme is considering the purchase of an overhead rail-mounted hoist system or a forklift truck to increase capacity and improve manufacturing efficiency.

The annual pretax payoff from the system depends on future demand. If demand stays at the current level, the probability of which is 0.50, annual savings from the overhead hoist will be $10,000. If demand rises, the hoist will save $25,000 annually because of operating efficiencies in addition to new sales. Finally, if demand falls, the hoist will result in an estimated annual loss of $65,000. The probability is estimated to be 0.30 for higher demand and 0.20 for lower demand.

If the forklift is purchased, annual payoffs will be $5,000 if demand is unchanged, $10,000 if demand rises, and −$25,000 if demand falls.

**a.** Draw a decision tree for this problem and compute the expected value of the payoff for each alternative.

**b.** Which is the best alternative, based on the expected values?

**23.** Referring to Problem 7, the operations manager at Macon Controls believes that pessimistic demand has a probability of 20 percent, expected demand has a probability of 50 percent, and optimistic demand has a probability of 30 percent. Currently, new machines must be purchased at a cost of $500,000 a piece, the price charged for each control unit is $110, and the variable cost of production is $50 per unit. (Hint: since the price and variable cost for each control unit are the same, the profit maximizing product mix will be the same as the mix that maximizes the total number of units produced.)

**a.** Draw a decision tree for this problem.

**b.** How many machines should the company purchase, and what is the expected payoff?

**24.** Darren Mack owns the Gas n' Go convenience store and gas station. After hearing a marketing lecture, he realizes that it might be possible to draw more customers to his high-margin convenience store by selling his gasoline at a lower price. However, the Gas n' Go is unable to qualify for volume discounts on its gasoline purchases, and therefore cannot sell gasoline for profit if the price is lowered. Each new pump will cost $95,000 to install, but will increase customer traffic in the store by 1,000 customers per year. Also, because the Gas n' Go would be selling its gasoline at no profit, Darren plans on increasing the profit margin on convenience store items incrementally over the next five years. Assume a discount rate of 8 percent. The projected convenience store sales per customer and the projected profit margin for the next five years are as follows:

| Year | Projected Convenience Store Sales Per Customer | Projected Profit Margin |
|---|---|---|
| 1 | $5.00 | 20% |
| 2 | $6.50 | 25% |
| 3 | $8.00 | 30% |
| 4 | $10.00 | 35% |
| 5 | $11.00 | 40% |

**a.** What is the NPV of the next five years of cash flows if Darren had four new pumps installed?

**b.** If Darren required a payback period of four years, should he go ahead with the installation of the new pumps?

**25.** The vice president of operations at Dintell Corporation, a major supplier of passenger-side automotive air bags, is considering a $50 million expansion at the firm's Fort Worth, Texas, production complex. The most recent economic projections indicate a 0.60 probability that the overall market will be $400 million per year over the next five years and a 0.40 probability that the market will be only $200 million per year during the same period. The marketing department estimates that Dintell has a 0.50 probability of capturing 40 percent of the market and an equal probability of obtaining only 30 percent of the market. The cost of goods sold is estimated to be 70 percent of sales. For planning purposes, the company currently uses a 12 percent discount rate, a 40 percent tax rate, and the MACRS depreciation schedule. The criteria for investment decisions at Dintell are (1) the net expected present value must be greater than zero; (2) there must be at least a 70 percent chance that the net present value will be positive; and (3) there must be no more than a 10 percent chance that the firm will lose more than 20 percent of the initial value.

**a.** Based on the stated criteria, determine whether Dintell should fund the project.

**b.** What effect will a probability of 0.70 of capturing 40 percent of the market have on the decision?

**c.** What effect will an increase in the discount rate to 15 percent have on the decision? A decrease to 10 percent?

**d.** What effect will the need for another $10 million in the third year have on the decision?

## VIDEO CASE Gate Turnaround at Southwest Airlines

Rollin King and Herb Kelleher started Southwest Airlines in 1971 with this idea: If they could take airline passengers where they want to go, on time, at the lowest possible price, and have a good time while doing it, people would love to fly their airline. The result? No other airline in the industry's history has enjoyed the customer loyalty and extended profitability for which Southwest is now famous. The company now flies more than 3,400 times each day to over 64 destinations across the United States.

There's more to the story, however, than making promises and hoping to fulfill them. A large part of Southwest Airlines' success lies in its ability to plan long-term capacity to better match demand and also improving the utilization of its fleet by turning around an aircraft at the gate faster than its competitors. Capacity at Southwest is measured in seat-miles, and even a single minute reduction in aircraft turnaround time system wide means additional seat-miles being added to the available capacity of Southwest Airlines.

As soon as an aircraft calls "in range" at one of Southwest's airport locations, called a station, the local operations manager notifies the ground operations team so that they can start mobilizing all the parties involved in servicing the aircraft in preparation for its next departure. The grounds operations team consists of a baggage transfer driver who has responsibility for getting connecting flight bags to their proper planes, a local baggage driver who moves bags to baggage claim for passenger pick-up, a lavatory truck driver who handles restroom receptacle drainage, a lead gate agent to handle baggage carts and track incoming and outgoing bag counts, and a bin agent to manage baggage and cargo inside the plane. The ground operations team knows it must turn the plane around in 25 minutes or less. The clock starts when the pilot sets the wheel brakes.


Pearson

Baggage transfer starts less than 40 seconds after engine shutdown at Southwest Airlines.

Inbound and outbound flights are coordinated by the supervisors between Southwest's 64 airport stations through the company's Operations Terminal Information System (OTIS). Each local supervisor is able to keep track of their flights and manage any delays or problems that may have crept into the system by keeping in touch with headquarters in Dallas for system-wide issues that may impact a local station, along with using the OTIS information coming from stations sending flights their way.

Just what, exactly, does it take to turn around an aircraft? In-bound flight 3155 from Phoenix to Dallas' Love Field is a good example. In Phoenix, the operations coordinators and ground operations team push back the plane as scheduled at 9:50 A.M. The flight is scheduled to arrive at 3:35 P.M. in Dallas. The Phoenix team enters into OTIS the information the ground operations team will need in Dallas, such as wheelchairs, gate-checked baggage, cargo bin locator data, and other data needed to close out the flight on their end. This action lets the Dallas station know what to expect when the plane lands.

In Dallas, the local ground operations coordinators have been monitoring all 110 inbound flights and now see Phoenix flight 3155 in the system, scheduled for an on-time arrival. When the pilot calls "in range" as it nears Dallas, the ground crew prepares for action.

As the plane is guided to its "stop mark" at the gate, the lead agent waits for the captain's signal that the engines have been turned off and brakes set. Within just 10 seconds, the provisioning truck pulls up to open the back door for restocking supplies such as drinks and snacks. The waiting fuel truck extends its hose to the underwing connection and in less than 2 minutes picks up refueling instructions and starts to load fuel. As soon as the aircraft is in position, the operations team steers the jetway into position and locks it against the aircraft. The door is opened, the in-flight crew is greeted, and passengers start to deplane.

Outside, less than 40 seconds after engine shutdown, baggage is rolling off the plane and gets placed onto the first cart. Any transfer bags get sent to their next destination, and gate-checked bags are delivered to the top of the jetway stairs for passenger pick-up.

While passengers make their way out of the plane, the in-flight crew helps clean up and prepare the cabin for the next flight. If all goes well, the last passenger will leave the plane after only 8 minutes. By this time, passengers waiting to board have already lined up in their designated positions for boarding. The gate agent confirms that the plane is ready for passenger boarding and calls for the first group to turn in their boarding passes and file down the jetway.

At the completion of boarding, the operations agent checks the fuel invoice, cargo bin loading schedule with actual bag counts in their bins from the baggage agents, and a lavatory service record confirming that cleaning has taken place. Final paperwork is given to the captain. The door to the aircraft is closed, and the jetway is retracted. Thirty seconds later, the plane is pushed back and the operations agent gives a traditional salute to the captain to send the flight on its way. Total elapsed time: less than 25 minutes.

Managing Southwest's capacity has been somewhat simplified by strategic decisions made early on in the company's life. First, the company's fleet of aircraft is all Boeing 737's. This single decision impacts all areas of operations—from crew training to aircraft maintenance. The single-plane configuration also provides Southwest with crew scheduling flexibility. Since pilots and flight crews can be deployed across the entire fleet, there are no constraints with regard to training and certification pegged to specific aircraft types.

The way Southwest has streamlined its operations for tight turnarounds means it must maintain a high capacity cushion to accommodate variability in its daily operations. Anything from weather delays to unexpected maintenance issues at the gate can slow down the flow of operations to a crawl. To handle these unplanned but anticipated challenges, Southwest builds into its schedules enough cushion to manage these delays yet not so much that employees and planes are idle. Additionally, the company encourages discussion to keep on top of what's working and where improvements can be made. If a problem is noted at a downstream station, say bags were not properly loaded, this information quickly travels back up to the originating station for correction so that it does not happen again.

Even with the tightly managed operations Southwest Airlines enjoys, company executives know that continued improvement is necessary if the company is to remain profitable into the future. Company executives know when they have achieved their goals when internal and external metrics are reached. For example, the Department of Transportation (DOT) tracks on-time departures, customer complaints, and mishandled baggage for all airlines. The company sets targets for achievement on these dimensions and lets employees know on a monthly basis how the company is doing against those metrics and the rest of the industry. Regular communication with all employees is delivered via meetings, posters, and newsletters. Rewards such as prizes and profit sharing are given for successful achievement.

As for the future, Bob Jordan, Southwest's executive vice president for strategy and planning, puts it this way: "We make money when our planes are in the air, not on the ground. If we can save one minute off every turn system-wide, that's like putting five additional planes in the air. If a single plane generates annual revenue of $25 million, there's $125 million in profit potential from those time savings."

### QUESTIONS

1. How can capacity and utilization be measured at an airline such as Southwest Airlines?
2. Which factors can adversely impact turnaround times at Southwest Airlines?
3. How does Southwest Airlines know they are achieving their goals?
4. What are the important long-term issues relevant for managing capacity, revenue, and customer satisfaction for Southwest Airlines?

## CASE Fitness Plus, Part A

*Fitness Plus, Part B, explores alternatives to expanding a new downtown facility and is included in the Instructor's Resource Manual. If you are interested in this topic, ask your instructor for a preview.*

Fitness Plus is a full-service health and sports club in Greensboro, North Carolina. The club provides a range of facilities and services to support three primary activities: fitness, recreation, and relaxation. Fitness activities generally take place in four areas of the club: the (1) aerobics room, which can accommodate 35 people per class; a (2) room equipped with free weights; a (3) workout room with 24 pieces of Nautilus equipment; and a (4) large workout room containing 29 pieces of cardiovascular equipment. This equipment includes nine stairsteppers, six treadmills, six life-cycle bikes, three Airdyne bikes, two cross-aerobics machines, two rowing machines, and one climber. Recreational facilities comprise eight racquetball courts, six tennis courts, and a large outdoor pool. Fitness Plus also sponsors softball, volleyball, and swim teams in city recreation leagues. Relaxation is accomplished through yoga classes held twice a week in the aerobics room, whirlpool tubs located in each locker room, and a trained massage therapist.

Situated in a large suburban office park, Fitness Plus opened its doors in 1995. During the first two years, membership was small and use of the facilities was light. By 1997, membership had grown as fitness began to play a large role in more and more people's lives. Along with this growth came increased use of club facilities. Records indicate that in 2000, an average of 15 members per hour checked into the club during a typical day. Of course, the actual number of members per hour varied by both day and time. On some days during a slow period, only six to eight members would check in per hour. At a peak time, such as Mondays from 4:00 P.M. to 7:00 P.M., the number would be as high as 40 per hour.

The club was open from 6:30 A.M. to 11:00 P.M. Monday through Thursday. On Friday and Saturday, the club closed at 8:00 P.M., and on Sunday the hours were 12:00 P.M. to 8:00 P.M.

As the popularity of health and fitness continued to grow, so did Fitness Plus. By May 2005, the average number of members arriving per hour during a typical day had increased to 25. The lowest period had a rate of 10 members per hour; during peak periods, 80 members per hour checked in to use the facilities. This growth brought complaints from members about overcrowding and unavailability of equipment. Most of these complaints centered on the Nautilus, cardiovascular, and aerobics fitness areas. The owners began to wonder whether the club was indeed too small for its membership. Past research indicated that individuals work out an average of 60 minutes per visit. Data collected from member surveys showed the following facilities usage pattern: 30 percent of the members do aerobics, 40 percent use the cardiovascular equipment, 25 percent use the Nautilus machines, 20 percent use the free weights, 15 percent use the racquetball courts, and 10 percent use the tennis courts. The owners wondered whether they could use this information to estimate how well existing capacity was being utilized.

If capacity levels were being stretched, now was the time to decide what to do. It was already May, and any expansion of the existing facility would take at least four months. The owners knew that January was always a peak membership enrollment month and that any new capacity needed to be ready by then. However, other factors had to be considered. The area was growing both in terms of population and geographically. The downtown area just received a major facelift, and many new offices and businesses were moving back to it, causing a resurgence in activity.

With this growth came increased competition. A new YMCA was offering a full range of services at a low cost. Two new health and fitness facilities had opened within the past year in locations 10 to 15 minutes from Fitness Plus. The first, called the Oasis, catered to the young adult crowd and restricted the access of children under 16 years old. The other facility, Gold's Gym, provided excellent weight and cardiovascular training only.

As the owners thought about the situation, they had many questions: Were the capacities of the existing facilities constrained, and if so, where? If capacity expansion was necessary, should the existing facility be expanded? Because of the limited amount of land at the current site, expansion of some services might require reducing the capacity of others. Finally, owing to increased competition and growth downtown, was now the time to open a facility to serve that market? A new facility would take 6 months to renovate, and the financial resources were not available to do both.

## QUESTIONS

1. What method would you use to measure the capacity of Fitness Plus? Has Fitness Plus reached its capacity?
2. Which capacity strategy would be appropriate for Fitness Plus? Justify your answer.
3. How would you link the capacity decision being made by Fitness Plus to other types of operating decisions?

SUPPLEMENT

# B

# WAITING LINE MODELS

Anyone who has ever waited at a stoplight, at McDonald's, or at the registrar's office has experienced the dynamics of waiting lines. Perhaps one of the best examples of effective management of waiting lines is that of Walt Disney World. One day the park may have only 25,000 customers, but on another day the numbers may top 90,000. Careful analysis of process flows, technology for people-mover (materials handling) equipment, capacity, and layout keeps the waiting times for attractions to acceptable levels.

A **waiting line** is one or more "customers" waiting for service. The customers can be people or inanimate objects, such as machines requiring maintenance, sales orders waiting for shipping, or inventory items waiting to be used. A waiting line forms because of a temporary imbalance between the demand for service and the capacity of the system to provide the service. In most real-life waiting-line problems, the demand rate varies; that is, customers arrive at unpredictable intervals. Most often, the rate of producing the service also varies, depending on customer needs. Suppose that bank customers arrive at an average rate of 15 per hour throughout the day and that the bank can process an average of 20 customers per hour. Why would a waiting line ever develop? The answers are that the customer arrival rate varies throughout the day and the time required to process a customer can vary. During the noon hour, 30 customers may arrive at the bank. Some of them may have complicated transactions requiring above-average process times. The waiting line may grow to 15 customers for a period of time before it eventually disappears. Even though the bank manager provided for more than enough capacity on average, waiting lines can still develop.

**waiting line**

One or more "customers" waiting for service.

In a similar fashion, waiting lines can develop even if the time to process a customer is constant. For example, a subway train is computer controlled to arrive at stations along its route. Each train is programmed to arrive at a station, say, every 15 minutes. Even with the constant service time, waiting lines develop while riders wait for the next train or cannot get on a train because of the size of the crowd at a busy time of the day. Consequently, variability in the rate of demand determines the sizes of the waiting

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

1. Identify the structure of waiting lines in real situations.
2. Use the single-server, multiple-server, and finite-source models to analyze operations and estimate the operating characteristics of a process.
3. Describe the situations where simulation should be used for waiting-line analysis and the nature of the information that can be obtained.
4. Explain how waiting-line models can be used to make managerial decisions.

lines in this case. In general, if no variability in the demand or service rate occurs and enough capacity is provided, no waiting lines form.

Waiting-line theory applies to service as well as manufacturing firms, relating customer arrival and service-system processing characteristics to service-system output characteristics. In our discussion, we use the term *service* broadly—the act of doing work for a customer. The service system might be hair cutting at a hair salon, satisfying customer complaints, or processing a production order of parts on a certain machine. Other examples of customers and services include lines of theatergoers waiting to purchase tickets, trucks waiting to be unloaded at a warehouse, machines waiting to be repaired by a maintenance crew, and patients waiting to be examined by a physician. Regardless of the situation, waiting-line problems have several common elements.

The analysis of waiting lines is of concern to managers because it affects process design, capacity planning, process performance, and ultimately, supply chain performance. In this supplement we discuss why waiting lines form, the uses of waiting-line models in operations management, and the structure of waiting-line models. We also discuss the decisions managers address with these models. Waiting lines can also be analyzed using computer simulation. Software such as SimQuick or Excel spreadsheets can be used to analyze the problems in this supplement.

# Structure of Waiting-Line Problems

Analyzing waiting-line problems begins with a description of the situation's basic elements. Each specific situation will have different characteristics, but four elements are common to all situations:

**customer population**

An input that generates potential customers.

**service facility**

A person (or crew), a machine (or group of machines), or both necessary to perform the service for the customer.

**priority rule**

A rule that selects the next customer to be served by the service facility.

**service system**

The number of lines and the arrangement of the facilities.

1. An input, or **customer population**, that generates potential customers
2. A waiting line of customers
3. The **service facility**, consisting of a person (or crew), a machine (or group of machines), or both necessary to perform the service for the customer
4. A **priority rule**, which selects the next customer to be served by the service facility

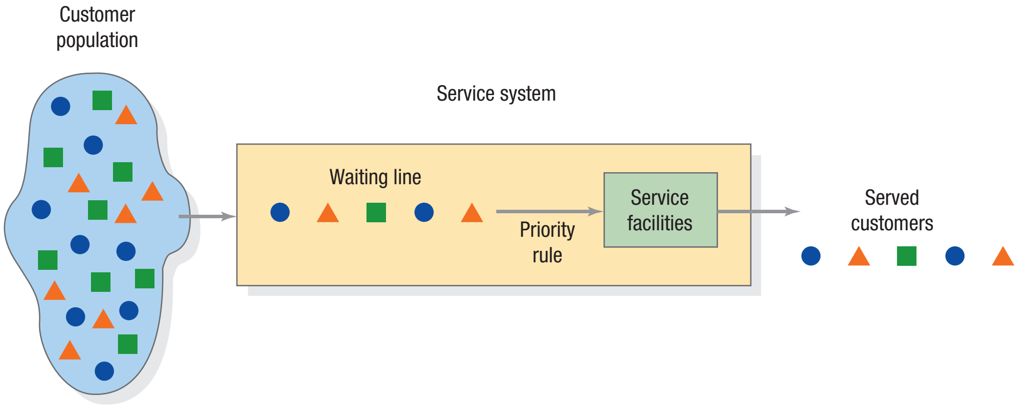
Figure B.1 shows these basic elements. The triangles, circles, and squares are intended to show a diversity of customers with different needs. The **service system** describes the number of lines and the arrangement of the facilities. After the service has been performed, the served customers leave the system.

## Customer Population

A customer population is the source of input to the service system. If the potential number of new customers for the service system is appreciably affected by the number of customers already in the system, the input source is said to be *finite*. For example, suppose that a maintenance crew is assigned responsibility for the repair of 10 machines. The customer population for the maintenance crew is 10 machines in working order. The population generates customers for the maintenance crew as a function of the failure rates for the machines. As more machines fail and enter the service system, either waiting for service or for being repaired, the customer population becomes smaller or the rate at which it can generate another customer falls. Consequently, the customer population is said to be finite.

Alternatively, an *infinite* customer population is one in which the number of customers in the system does not affect the rate at which the population generates new customers. For example,

**FIGURE B.1 ▶** Basic Elements of Waiting-Line Models



consider a mail-order operation for which the customer population consists of shoppers who have received a catalog of products sold by the company. Because the customer population is so large and only a small fraction of the shoppers place orders at any one time, the number of new orders it generates is not appreciably affected by the number of orders waiting for service or being processed by the service system. In this case, the customer population is said to be infinite.

Customers in waiting lines may be *patient* or *impatient*, which has nothing to do with the colorful language a customer may use while waiting in line for a long time on a hot day. In the context of waiting-line problems, a patient customer is one who enters the system and remains there until being served; an impatient customer is one who either decides not to enter the system (balks) or leaves the system before being served (reneges). For the methods used in this supplement, we make the simplifying assumption that all customers are patient.


Islemount Images/Alamy

Sometimes customers are not organized neatly into lines. Here ships wait to use the port facilities in Victoria Harbor,West Kowloon, Hong Kong.

## The Service System

The service system may be described by the number of lines and the arrangement of facilities.

**Number of Lines** Waiting lines may be designed to be a *single line* or *multiple lines*. Figure B.2 shows an example of each arrangement. Generally, single lines are utilized at airline counters, inside banks, and at some fast-food restaurants whereas multiple lines are utilized in grocery stores, at drive-in bank operations, and in discount stores. When multiple servers are available and each one can handle general transactions, the single-line arrangement keeps servers uniformly busy and gives customers a sense of fairness. Customers believe that they are being served on the basis of when they arrived and not on how well they guessed their waiting time when selecting a particular line. The multiple-line design is best when some of the servers provide a limited set of services. In this arrangement, customers select the services they need and wait in the line where that service is provided, such as at a grocery store that provides special lines for customers paying with cash or having fewer than 10 items.

Sometimes customers are not organized neatly into "lines." Machines that need repair on the production floor of a factory may be left in place, and the maintenance crew comes to them. Nonetheless, we can think of such machines as forming a single line or multiple lines, depending on the number of repair crews and their specialties. Likewise, passengers who telephone for a taxi also form a line even though they may wait at different locations.

**Arrangement of Service Facilities** Service facilities consist of the personnel and equipment necessary to perform the service for the customer. Service facility arrangement is described by the number of channels and phases. A **channel** is one or more facilities required to perform a given service. A **phase** is a single step in providing the service. Some services require a single phase, while others require a sequence of phases. Consequently, a service facility uses some combination of channels and phases. Managers should choose an arrangement based on customer volume and the nature of services provided. Figure B.3 shows examples of the five basic types of service facility arrangements.

**channel**
One or more facilities required to perform a given service.

**phase**
A single step in providing a service.

In the *single-channel, single-phase* system, all services demanded by a customer can be performed by a single-server facility. Customers form a single line and go through the service facility one at a time. Examples are a drive-through car wash and a machine that must process several batches of parts.

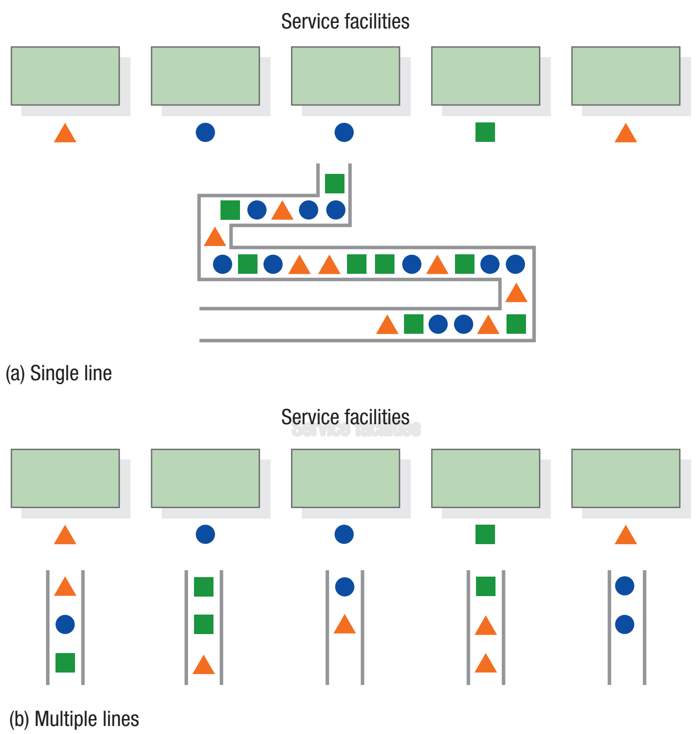



**FIGURE B.2**
Waiting-Line Arrangements

The *single-channel, multiple-phase* arrangement is used when the services are best performed in sequence by more than one facility, yet customer volume or other constraints limit the design to one channel. Customers form a single line and proceed sequentially from one service facility to the next. An example of this arrangement is a McDonald's drive-through, where the first facility takes the order, the second takes the money, and the third provides the food.

The *multiple-channel, single-phase* arrangement is used when demand is large enough to warrant providing the same service at more than one facility or when the services offered by the facilities are different. Customers form one or more lines, depending on the design. In the single-line design, the first available server serves customers, just as it is usually done in the lobby of a bank. If each channel has its own waiting line, customers wait until the server for their line can serve them, as at a bank's drive-through facilities.

The *multiple-channel, multiple-phase* arrangement occurs when customers can be served by one of the first-phase facilities but then require service from a second-phase facility, and so on. In some cases, customers cannot switch channels after service has begun; in others they can. An example of this arrangement is a laundromat. Washing machines are the first-phase facilities, and dryers are the second-phase facilities. Some of the washing machines and dryers may be designed for extra-large loads, thereby providing the customer a choice of channels.

The most complex waiting-line problem involves customers who have unique sequences of required services; consequently, service cannot be described neatly in phases. A *mixed* arrangement is used in such a case. In the mixed arrangement, waiting lines can develop in front of each facility, as in a medical center, where a patient goes to an exam room for a nurse to take his or her blood pressure and weight, goes back to the waiting room until the doctor can see him or her, and after consultation proceeds to the laboratory to give a blood sample, radiology to have an X-ray taken, or the pharmacy for prescribed drugs, depending on specific needs.

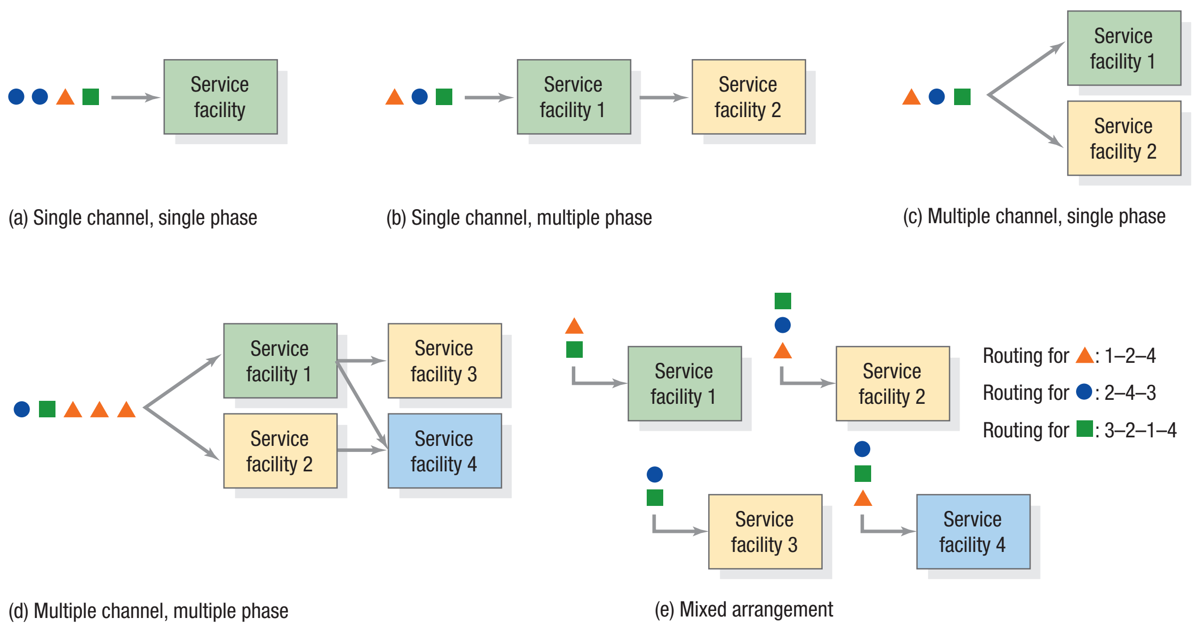



**FIGURE B.3**
Examples of Service Facility Arrangements

## Priority Rule

The priority rule determines which customer to serve next. Most service systems that you encounter use the first-come, first-served (FCFS) rule. The customer at the head of the waiting line has the highest priority, and the customer who arrived last has the lowest priority. Other priority disciplines might take the customer with the earliest promised due date (EDD) or the customer with the shortest expected processing time (SPT).[1]

A **preemptive discipline** is a rule that allows a customer of higher priority to interrupt the service of another customer. For example, in a hospital emergency room, patients with the most life-threatening injuries receive treatment first, regardless of their order of arrival. Modeling of systems having complex priority disciplines is usually done using computer simulation.

**preemptive discipline**

A rule that allows a customer of higher priority to interrupt the service of another customer.

## Probability Distributions

The sources of variation in waiting-line problems come from the random arrivals of customers and the variations in service times. Each of these sources can be described with a probability distribution.

## Arrival Distribution

Customers arrive at service facilities randomly. The variability of customer arrivals often can be described by a Poisson distribution, which specifies the probability that $n$ customers will arrive in $T$ time periods:

$$P_n = \frac{(\lambda T)^n}{n!} e^{-\lambda T} \text{ for } n = 0,1,2,\ldots$$

where

$P_n$ = probability of $n$ arrivals in $T$ time periods
$\lambda$ = average number of customer arrivals per period
$e$ = 2.7183

The mean of the Poisson distribution is $\lambda T$, and the variance also is $\lambda T$. The Poisson distribution is a discrete distribution; that is, the probabilities are for a specific number of arrivals per unit of time.

### EXAMPLE B.1 Calculating the Probability of Customer Arrivals

Management is redesigning the customer service process in a large department store. Accommodating four customers is important. Customers arrive at the desk at the rate of two customers per hour. What is the probability that four customers will arrive during any hour?

**SOLUTION**

In this case $\lambda = 2$ customers per hour, $T = 1$ hour, and $n = 4$ customers. The probability that four customers will arrive in any hour is

$$P_4 = \frac{[2(1)]^4}{4!} e^{-2(1)} = \frac{16}{24} e^{-2} = \mathbf{0.090}$$

**DECISION POINT**

The manager of the customer service desk can use this information to determine the space requirements for the desk and waiting area. There is a relatively small probability that four customers will arrive in any hour. Consequently, seating capacity for two or three customers should be more than adequate unless the time to service each customer is lengthy. Further analysis on service times is warranted.

Another way to specify the arrival distribution is to do it in terms of customer **interarrival times**—that is, the time between customer arrivals. If the customer population generates customers according to a Poisson distribution, the *exponential distribution* describes the probability that the next customer will arrive, or that service to a customer will conclude, in the next $T$ time periods.

**interarrival times**

The time between customer arrivals.

[1] We focus on FCFS in this supplement. See Chapter 10, "Planning and Scheduling Operations," for additional discussion of FCFS and EDD.

## Service Time Distribution

The exponential distribution describes the probability that the service time of the customer at a particular facility will be no more than $T$ time periods. The probability can be calculated by using the formula

$$P(t \leq T) = 1 - e^{-\mu T}$$

where

$\mu$ = average number of customers completing service per period
$t$ = service time of the customer
$T$ = target service time

The mean of the service time distribution is $1/\mu$, and the variance is $(1/\mu)^2$. As $T$ increases, the probability that the customer's service time will be less than $T$ approaches 1.0.

For simplicity, let us look at a single-channel, single-phase arrangement.

### EXAMPLE B.2 Calculating the Service Time Probability

The management of the large department store in Example B.1 must determine whether more training is needed for the customer service clerk. The clerk at the customer service desk can serve an average of three customers per hour. What is the probability that a customer will require 10 minutes or less of service?

**SOLUTION**

We must have all the data in the same time units. Because $\mu = 3$ customers per hour, we convert minutes of time to hours, or $T = 10 \text{ minutes} = 10/60 \text{ hour} = 0.167 \text{ hour}$. Then

$$P(t \leq T) = 1 - e^{-\mu T}$$

$$P(t \leq 0.167 \text{ hour}) = 1 - e^{-3(0.167)} = 1 - 0.61 = \mathbf{0.39}$$

**DECISION POINT**

The probability that the customer will require only 10 minutes or less is not high, which leaves the possibility that customers may experience lengthy delays. Management should consider additional training for the clerk so as to reduce the time it takes to process a customer request.

Some characteristics of the exponential distribution do not always conform to an actual situation. The exponential distribution model is based on the assumption that each service time is independent of those that preceded it. In real life, however, productivity may improve as human servers learn about the work. Another assumption underlying the model is that very small, as well as very large, service times are possible. However, real-life situations often require a fixed-length start-up time, some cutoff on total service time, or nearly constant service time.

# Using Waiting-Line Models to Analyze Operations

Operations managers can use waiting-line models to balance the gains that might be made by increasing the efficiency of the service system against the costs of doing so. In addition, managers should consider the costs of *not* making improvements to the system: Long waiting lines or long waiting times may cause customers to balk or renege. Managers should therefore be concerned about the following operating characteristics of the system.

1. *Line Length.* The number of customers in the waiting line reflects one of two conditions. Short lines could mean either good customer service or too much capacity. Similarly, long lines could indicate either low server efficiency or the need to increase capacity.
2. *Number of Customers in System.* The number of customers in line and being served also relates to service efficiency and capacity. A large number of customers in the system causes congestion and may result in customer dissatisfaction, unless more capacity is added.
3. *Waiting Time in Line.* Long lines do not always mean long waiting times. If the service rate is fast, a long line can be served efficiently. However, when waiting time seems long, customers perceive

the quality of service to be poor. Managers may try to change the arrival rate of customers or design the system to make long wait times seem shorter than they really are. For example, at Walt Disney World, customers in line for an attraction are entertained by videos and also are informed about expected waiting times, which seems to help them endure the wait.

4. *Total Time in System.* The total elapsed time from entry into the system until exit from the system may indicate problems with customers, server efficiency, or capacity. If some customers are spending too much time in the service system, it may be necessary to change the priority discipline, increase productivity, or adjust capacity in some way.
5. *Service Facility Utilization.* The collective utilization of service facilities reflects the percentage of time that they are busy. Management's goal is to maintain high utilization and profitability without adversely affecting the other operating characteristics.

The best method for analyzing a waiting-line problem is to relate the five operating characteristics and their alternatives to dollars. However, placing a dollar figure on certain characteristics (such as the waiting time of a shopper in a grocery store) is difficult. In such cases, an analyst must weigh the cost of implementing the alternative under consideration against a subjective assessment of the cost of *not* making the change.

We now present three models and some examples showing how waiting-line models can help operations managers make decisions. We analyze problems requiring the single-server, multiple-server, and finite-source models, all of which are single phase. References to more advanced models are cited at the end of this supplement.

## Single-Server Model

The simplest waiting-line model involves a single server and a single line of customers, commonly referred to as a single-channel, single-phase system. To further specify the single-server model, we make the following assumptions:

1. The customer population is infinite and all customers are patient.
2. The customers arrive according to a Poisson distribution, with a mean arrival rate of $\lambda$.
3. The service distribution is exponential, with a mean service rate of $\mu$.
4. The mean service rate exceeds the mean arrival rate.
5. Customers are served on a first-come, first-served basis.
6. The length of the waiting line is unlimited.

Melyn Longhurst/Alamy

Visitors to Disney MGM Studios, Disney World, Orlando, Florida patiently wait in line for the Aerosmith Rock N Roller Coaster ride, which is an example of a single-channel, single-phase system.

With these assumptions, we can apply various formulas to describe the operating characteristics of the system:

$$\rho = \text{Average utilization of the system} = \frac{\lambda}{\mu}$$

$$P_n = \text{Probability that } n \text{ customers are in the system} = (1-\rho)\rho^n$$

$$P_0 = \text{Probability that zero customers are in the system} = 1-\rho$$

$$L = \text{Average number of customers in the service system} = \frac{\lambda}{\mu-\lambda}$$

$$L_q = \text{Average number of customers in the waiting line} = \rho L$$

$$W = \text{Average time spent in the system, including service} = \frac{1}{\mu-\lambda}$$

$$W_q = \text{Average waiting time in line} = \rho W$$

## EXAMPLE B.3 Calculating the Operating Characteristics of a Single-Channel, Single-Phase System with the Single-Server Model

MyOMLab

Active Model B.1 in MyOMLab provides additional insight on the single-server model and its uses for this problem.

The manager of a grocery store in the retirement community of Sunnyville is interested in providing good service to the senior citizens who shop in her store. Currently, the store has a separate checkout counter for senior citizens. On average, 30 senior citizens per hour arrive at the counter, according to a Poisson distribution, and are served at an average rate of 35 customers per hour, with exponential service times. Find the following operating characteristics:

**a.** Probability of zero customers in the system

**b.** Average utilization of the checkout clerk

**c.** Average number of customers in the system

**d.** Average number of customers in line

**e.** Average time spent in the system

**f.** Average waiting time in line

### SOLUTION

The checkout counter can be modeled as a single-channel, single-phase system. Figure B.4 shows the results from the *Waiting-Lines* Solver from OM Explorer. Manual calculations of the equations for the *single-server model* are demonstrated in the Solved Problem at the end of the supplement.

**FIGURE B.4 ▶** *Waiting-Lines* Solver for Single-Channel, Single-Phase System

| | | |
|---|---|---|
| Servers | | (Number of servers $s$ assumed to be 1 in single-serve model) |
| Arrival Rate (λ) | 30 | |
| Service Rate (μ) | 35 | |

| | |
|---|---|
| Probability of zero customers in the system ($P_0$) | 0.1429 |
| Probability of exactly 0 customers in the system | 0.1429 |
| Average utilization of the server ($\rho$) | 0.8571 |
| Average number of customers in the system ($L$) | 6.0000 |
| Average number of customers in line ($L_q$) | 5.1429 |
| Average waiting/service time in the system ($W$) | 0.2000 |
| Average waiting time in line ($W_q$) | 0.1714 |

Both the average waiting time in the system ($W$) and the average time spent waiting in line ($W_q$) are expressed in hours. To convert the results to minutes, simply multiply by 60 minutes/hour. For example, $W = 0.20(60) =$ **12.00** minutes, and $W_q = 0.1714(60) =$ **10.28** minutes.

## EXAMPLE B.4 Analyzing Service Rates with the Single-Server Model

MyOMLab

Tutor B.1 in MyOMLab provides a new example to practice the single-server model.

The manager of the Sunnyville grocery in Example B.3 wants answers to the following questions:

**a.** What service rate would be required so that customers averaged only 8 minutes in the system?

**b.** For that service rate, what is the probability of having more than four customers in the system?

**c.** What service rate would be required to have only a 10 percent chance of exceeding four customers in the system?

### SOLUTION

The *Waiting-Lines* Solver from OM Explorer could be used iteratively to answer the questions. Here we show how to solve the problem manually.

**a.** We use the equation for the average time in the system and solve for $\mu$.

$$W = \frac{1}{\mu - \lambda}$$

$$8 \text{ minutes} = 0.133 \text{ hour} = \frac{1}{\mu - 30}$$

$$0.133\mu - 0.133(30) = 1$$

$$\mu = \mathbf{37.52} \text{ customers/hour}$$

**b.** The probability of more than four customers in the system equals 1 minus the probability of four or fewer customers in the system.

$$P = 1 - \sum_{n=0}^{4} P_n$$
$$= 1 - \sum_{n=0}^{4} (1 - \rho)\rho^n$$

and

$$\rho = \frac{30}{37.52} = 0.80$$

Then,

$$P = 1 - 0.2(1 + 0.8 + 0.8^2 + 0.8^3 + 0.8^4)$$
$$= 1 - 0.672 = \mathbf{0.328}$$

Therefore, there is a nearly 33 percent chance that more than four customers will be in the system.

**c.** We use the same logic as in part (b), except that $\mu$ is now a decision variable. The easiest way to proceed is to find the correct average utilization first, and then solve for the service rate.

$$\begin{aligned} P &= 1 - (1 - \rho)(1 + \rho + \rho^2 + \rho^3 + \rho^4) \\ &= 1 - (1 + \rho + \rho^2 + \rho^3 + \rho^4) + \rho(1 + \rho + \rho^2 + \rho^3 + \rho^4) \\ &= 1 - 1 - \rho - \rho^2 - \rho^3 - \rho^4 + \rho + \rho^2 + \rho^3 + \rho^4 + \rho^5 \\ &= \rho^5 \end{aligned}$$

or

$$\rho = P^{1/5}$$

If $P = 0.10$,

$$\rho = (0.10)^{1/5} = 0.63$$

Therefore, for a utilization rate of 63 percent, the probability of more than four customers in the system is 10 percent. For $\lambda = 30$, the mean service rate must be

$$\frac{30}{\mu} = 0.63$$
$$\mu = \mathbf{47.62} \text{ customers/hour}$$

**DECISION POINT**

The service rate would only have to increase modestly to achieve the 8-minute target. However, the probability of having more than four customers in the system is too high. The manager must now find a way to increase the service rate from 35 per hour to approximately 48 per hour. She can increase the service rate in several different ways, ranging from employing a high school student to help bag the groceries to installing self-checkout stations.

## Multiple-Server Model

With the multiple-server model, customers form a single line and choose one of $s$ servers when one is available. The service system has only one phase; consequently, we are focusing our discussion on multiple-channel, single phase systems. We make the following assumptions in addition to those for the single-server model: There are $s$ identical servers, and the service distribution for each server is exponential, with a mean service time of $1/\mu$. It should always be the case that $s\mu$ exceeds $\lambda$.

**EXAMPLE B.5** **Estimating Idle Time and Hourly Operating Costs with the Multiple-Server Model**

The management of the American Parcel Service terminal in Verona, Wisconsin, is concerned about the amount of time the company's trucks are idle (not delivering on the road), which the company defines as waiting to be unloaded and being unloaded at the terminal. The terminal operates with four unloading bays. Each bay requires a crew of two employees, and each crew costs $30 per hour. The estimated cost of an idle truck is $50 per hour. Trucks arrive at an average rate of three per hour, according to a Poisson distribution. On average, a crew can unload a semitrailer rig in one hour, with exponential service times. What is the total hourly cost of operating the system?

MyOMLab

Tutor B.2 in MyOMLab provides a new example to practice the multiple-server model.

MyOMLab

Active Model B.2 in MyOMLab provides additional insight on the multiple-server model and its uses for this problem.

**SOLUTION**

The *multiple-server model* for $s = 4$, $\mu = 1$, and $\lambda = 3$ is appropriate. To find the total cost of labor and idle trucks, we must calculate the average number of trucks in the system at all times.

Figure B.5 shows the results for the American Parcel Service problem using the *Waiting-Lines* Solver from OM Explorer. The results show that the four-bay design will be utilized 75 percent of the time and that the average number of trucks either being serviced or waiting in line is 4.53 trucks. That is, on average at any point in time, we have 4.53 idle trucks. We can now calculate the hourly costs of labor and idle trucks:

| | |
|---|---|
| Labor cost: | $\$30(s) = \$30(4) = \$120.00$ |
| Idle truck cost: | $\$50(L) = \$50(4.53) = \$226.50$ |
| | Total hourly cost $=$ **\$346.50** |

**FIGURE B.5 ▶**
*Waiting-Lines* Solver for Multiple-Server Model

| | |
|---|---|
| Servers | 4 |
| Arrival Rate ($\lambda$) | 3 |
| Service Rate ($\mu$) | 1 |

| | |
|---|---|
| Probability of zero customers in the system ($P_0$) | 0.0377 |
| Probability of exactly 0 customers in the system | 0.0377 |
| Average utilization of the servers ($\rho$) | 0.7500 |
| Average number of customers in the system ($L$) | 4.5283 |
| Average number of customers in line ($L_q$) | 1.5283 |
| Average waiting/service time in the system ($W$) | 1.5094 |
| Average waiting time in line ($W_q$) | 0.5094 |

**DECISION POINT**

Management must now assess whether \$346.50 per day for this operation is acceptable. Attempting to reduce costs by eliminating crews will only increase the waiting time of the trucks, which is more expensive per hour than the crews. However, the service rate can be increased through better work methods; for example, $L$ can be reduced and daily operating costs will be less.

## Little's Law

**Little's law**

A fundamental law that relates the number of customers in a waiting-line system to the arrival rate and waiting time of customers.

One of the most practical and fundamental laws in waiting-line theory is **Little's law**, which relates the number of customers in a waiting-line system to the arrival rate and the waiting time of customers. Using the same notation we used for the single-server model, Little's law can be expressed as $L = \lambda W$ or $L_q = \lambda W_q$. However, this relationship holds for a wide variety of arrival processes, service-time distributions, and numbers of servers. The practical advantage of Little's law is that you only need to know two of the parameters to estimate the third. For example, consider the manager of a motor vehicle licensing facility who receives many complaints about the time people must spend either having their licenses renewed or getting new license plates. It would be difficult to obtain data on the times individual customers spend at the facility. However, the manager can have an assistant monitor the number of people who arrive at the facility each hour and compute the average ($\lambda$). The manager also could periodically count the number of people in the sitting area and at the stations being served and compute the average ($L$). Using Little's law, the manager can then estimate $W$, the average time each customer spent in the facility. For example, if 40 customers arrive per hour and the average number of customers being served or waiting is 30, the average time each customer spends in the facility can be computed as

$$\text{Average time in the facility} = W = \frac{L \text{ customers}}{\lambda \text{ customers/hour}} = \frac{30}{40} = 0.75 \text{ hour, or } \mathbf{45} \text{ minutes}$$

If the time a customer spends at the facility is unreasonable, the manager can focus on either adding capacity or improving the work methods to reduce the time spent serving the customers.

Likewise, Little's law can be used for manufacturing processes. Suppose that a production manager knows the average time a unit of product spends at a manufacturing process ($W$) and the average number of units per hour that arrive at the process ($\lambda$). The production manager can then estimate the average work-in-process ($L$) using Little's law. *Work-in-process* (WIP) consists of items, such as components or assemblies, needed to produce a final product in manufacturing. For example, if the average time a gear case used for an outboard marine motor spends at a machine center is 3 hours,


CuboImagessrl/Alamy

Cars line up at the Triborough Bridge toll, New York City. This is an example of a multiple-channel, single-phase system where some channels are devoted to special services.

and an average of five gear cases arrive at the machine center per hour, the average number of gear cases waiting and being processed (or work-in-process) at the machine center can be calculated as

$$\text{Work-in-process} = L = \lambda W = (5 \text{ gear cases/hour})(3 \text{ hours}) = \mathbf{15} \text{ gear cases}$$

Knowing the relationship between the arrival rate, the lead time, and the work-in-process, the manager has a basis for measuring the effects of process improvements on the work-in-process at the facility. For example, adding some capacity to a bottleneck in the process can reduce the average lead time of the product at the process, thereby reducing the work-in-process inventory.

Even though Little's law is applicable in many situations in both service and manufacturing environments, it is not applicable in situations where the customer population is finite, which we address next.

## Finite-Source Model

We now consider a situation in which all but one of the assumptions of the single-server model are appropriate. In this case, the customer population is finite, having only $N$ potential customers. If $N$ is greater than 30 customers, the single-server model with the assumption of an infinite customer population is adequate. Otherwise, the finite-source model is the one to use.

### EXAMPLE B.6 Analyzing Maintenance Costs with the Finite-Source Model

The Worthington Gear Company installed a bank of 10 robots about three years ago. The robots greatly increased the firm's labor productivity, but recently attention has focused on maintenance. The firm does no preventive maintenance on the robots because of the variability in the breakdown distribution. Each machine has an exponential breakdown (or interarrival) distribution with an average time between failures of 200 hours. Each machine hour lost to downtime costs $30, which means that the firm has to react quickly to machine failure. The firm employs one maintenance person, who needs 10 hours on average to fix a robot. Actual maintenance times are exponentially distributed. The wage rate is $10 per hour for the maintenance person, who can be put to work productively elsewhere when not fixing robots. Determine the daily cost of labor and robot downtime.

MyOMLab

Tutor B.3 in MyOMLab provides a new example to practice the finite-source model.

**SOLUTION**

The *finite-source model* is appropriate for this analysis because the customer population consists of only 10 machines and the other assumptions are satisfied. Here, $\lambda = 1/200$, or 0.005 break-down per hour, and $\mu = 1/10 = 0.10$ robot per hour. To calculate the cost of labor and robot downtime, we need to estimate the average utilization of the maintenance person and $L$, the average number of robots in the maintenance system at any time. Either OM Explorer or POM for Windows can be used to help with the calculations. Figure B.6 shows the results for the Worthington Gear Problem using the *Waiting-Lines* Solver

MyOMLab

Active Model B.3 in MyOMLab provides additional insight on the finite-source model and its uses for this problem.

from OM Explorer. The results show that the maintenance person is utilized only **46.2** percent of the time, and the average number of robots waiting in line or being repaired is **0.76** robot. However, a failed robot will spend an average of **16.43** hours in the repair system, of which 6.43 hours of that time is spent waiting for service. While an individual robot may spend more than two days with the maintenance person, the maintenance person has a lot of idle time with a utilization rate of only **42.6** percent. That is why there is only an average of 0.76 robot being maintained at any point of time.

**FIGURE B.6** ▶ *Waiting-Lines* Solver for Finite-Source Model

| | |
|---|---|
| Customers | 10 |
| Arrival Rate ($\lambda$) | 0.005 |
| Service Rate ($\mu$) | 0.1 |

| | |
|---|---|
| Probability of zero customers in the system ($P_0$) | 0.5380 |
| Probability of [fewer than] [0] customers in the system | #N/A |
| Average utilization of the server ($\rho$) | 0.4620 |
| Average number of customers in the system ($L$) | 0.7593 |
| Average number of customers in line ($L_q$) | 0.2972 |
| Average waiting/service time in the system ($W$) | 16.4330 |
| Average waiting time in line ($W_q$) | 6.4330 |

The daily cost of labor and robot downtime is

$$\begin{aligned}
&\text{Labor cost:} && (\$10/\text{hour})(8\text{ hours/day})(0.462\text{ utilization}) &&= \$\ 36.96\\
&\text{Idle robot cost:} && (0.76\text{ robot})(\$30/\text{robot hour})(8\text{ hours/day}) &&= \underline{182.40}\\
& && \text{Total daily cost} &&= \mathbf{\$219.36}
\end{aligned}$$

**DECISION POINT**

The labor cost for robot repair is only 20 percent of the idle cost of the robots. Management might consider having a second repair person on call in the event two or more robots are waiting for repair at the same time.

# Waiting Lines and Simulation

For each of the problems we analyzed with the waiting-line models, the arrivals had a Poisson distribution (or exponential interarrival times), the service times had an exponential distribution, the service facilities had a simple arrangement, the waiting line was unlimited, and the priority discipline was first-come, first-served. Waiting-line theory has been used to develop other models in which these criteria are not met, but these models are complex. For example, POM for Windows includes a finite system-size model in which limits can be placed on the size of the system (waiting line and server capacity). It also has several models that relax assumptions on the service time distribution. Nonetheless, many times the nature of the customer population, the constraints on the line, the priority rule, the service-time distribution, and the arrangement of the facilities are such that waiting-line theory is no longer useful. In these cases, simulation often is used. MyOMLab Supplement E, "Simulation," discusses simulation programming languages and powerful PC-based packages. Here we illustrate process simulation with the SimQuick software (also provided in MyOMLab).

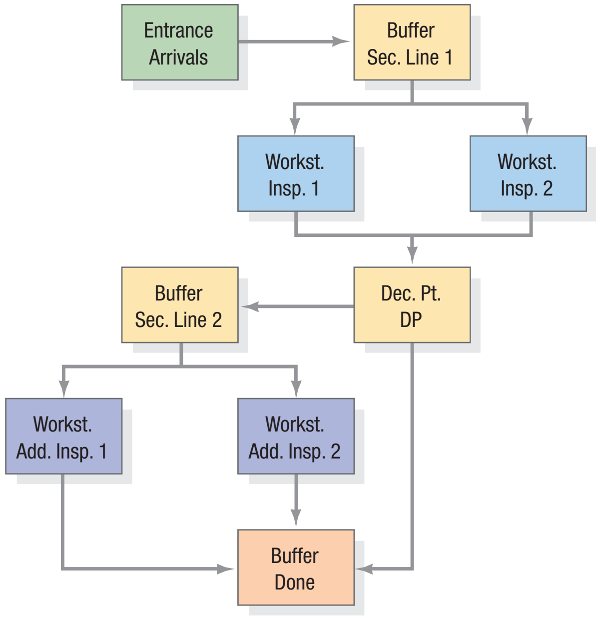
Vicki Beaver/Alamy

Passengers go through a TSA, security checkpoint screening at Boston International Airport, Boston Massachusetts. The airport security process is a multi-channel, multi phase system.

## SimQuick

SimQuick is an easy-to-use package that is simply an Excel spreadsheet with some macros. Models can be created for a variety of simple processes, such as waiting lines, inventory control, and projects. Here, we consider the passenger security process at one terminal of a medium-sized airport between the hours of 8 A.M. and 10 A.M. The process works as follows. Passengers arriving at the security area immediately enter a single line. After waiting in line, each passenger goes through one of two inspection stations, which involves walking through a metal detector and running any carry-on baggage through a scanner. After completing this inspection, 10 percent of the passengers are randomly selected for an additional inspection, which involves a pat-down and a more thorough search of the person's carry-on baggage. Two stations handle this additional inspection, and selected passengers go through only one of them. Management is interested in examining the effect of increasing the percentage of passengers who undergo the second inspection. In particular, they want to compare the waiting times for the second inspection when 10 percent, then 15 percent, and then 20 percent of the passengers are randomly selected for this inspection. Management also wants to know how opening a third station for the second inspection would affect these waiting times.

A first step in simulating this process with SimQuick is to draw a flowchart of the process using SimQuick's building blocks. SimQuick has five building blocks that can be combined in a wide variety of ways. Four of these types are used to model this process. An *entrance* is used to model the arrival of passengers at the security process. A *buffer* is used to model each of the two waiting lines, one before each type of inspection, as well as the passengers that have finished the process. Each of the four inspection stations is modeled with a *workstation*. Finally, the random selection of passengers for the second inspection is modeled with a *decision point*. Figure B.7 shows the flowchart.




▲ **FIGURE B.7**
Flowchart of Passenger Security Process

Information describing each building block is entered into SimQuick tables. In this model, three key types of information are entered: (1) when people arrive at the entrance, (2) how long inspections take at the four stations, and (3) what percentage of passengers are randomly selected for the additional inspection. All of this information must be entered into SimQuick in the form of statistical distributions. The first two types of information are determined by observing the real process from 8 A.M. and 10 A.M. The third type of information is a policy decision (10 percent, 15 percent, or 20 percent).

The original model is run 30 times, simulating the arrival of passengers during the hours from 8 A.M. to 10 A.M. Statistics are collected by SimQuick and summarized. Figure B.8 provides some key results for the model of the present process as output by SimQuick (many other statistics are collected, but not displayed here).

| Element Types | Element Names | Statistics | Overall Means |
|---|---|---|---|
| Entrance(s) | Door | Objects entering process | 237.23 |
| Buffer(s) | Line 1 | Mean inventory | 5.97 |
| | | Mean cycle time | 3.12 |
| | Line 2 | Mean inventory | 0.10 |
| | | Mean cycle time | 0.53 |
| | Done | Final inventory | 224.57 |

▲ **FIGURE B.8**
Simulation Results of Passenger Security Process

The numbers shown are averages across the 30 simulations. The number 237.23 is the average number of passengers that enter line 1 during the simulated two hours. The two mean inventory statistics tell us, on average, 5.97 simulated passengers were standing in line 1 and 0.10 standing in line 2. The two statistics on *cycle time*, interpreted here as the time a passenger spends in one or more SimQuick building blocks, tell us that the simulated passengers in line 1 waited an average of 3.12 minutes, while those in line 2 waited 0.53 minutes. The final inventory statistic tells us that, on average, 224.57 simulated passengers passed through the security process in the simulated two hours. The next step is to change the percentage of simulated passengers selected for the second inspection to 15 percent, and then to 20 percent, and rerun the model. Of course, these process changes will increase the average waiting time for the second inspection, but by how much? The final step is to rerun these simulations with one more workstation and see its effect on the waiting time for the second inspection. All the details for this model (as well as many others) appear in the book *SimQuick: Process Simulation with Excel*, which is included, along with the SimQuick software, in MyOMLab.

MyOMLab

# Decision Areas for Management

After analyzing a waiting-line problem, management can improve the service system by making changes in one or more of the following areas.

1. *Arrival Rates.* Management often can affect the rate of customer arrivals, $\lambda$, through advertising, special promotions, or differential pricing. For example, hotels in the Caribbean will reduce their room rates during the hot, rainy season to attract more customers and increase their utilization.

2. *Number of Service Facilities.* By increasing the number of service facilities, such as tool cribs, toll booths, or bank tellers, or by dedicating some facilities in a phase to a unique set of services, management can increase system capacity.

3. *Number of Phases.* Managers can decide to allocate service tasks to sequential phases if they determine that two sequential service facilities may be more efficient than one. For instance, in assembly lines a decision concerns the number of phases or workers needed along the assembly line. Determining the number of workers needed on the line also involves assigning a certain set of work elements to each one. Changing the facility arrangement can increase the service rate, $\mu$, of each facility and the capacity of the system.
4. *Number of Servers per Facility.* Managers can influence the service rate by assigning more than one person to a service facility.
5. *Server Efficiency.* By adjusting the capital-to-labor ratio, devising improved work methods, or instituting incentive programs, management can increase the efficiency of servers assigned to a service facility. Such changes are reflected in $\mu$.
6. *Priority Rule.* Managers set the priority rule to be used, decide whether to have a different priority rule for each service facility, and decide whether to allow preemption (and, if so, under what conditions). Such decisions affect the waiting times of the customers and the utilization of the servers.
7. *Line Arrangement.* Managers can influence customer waiting times and server utilization by deciding whether to have a single line or a line for each facility in a given phase of service.

Obviously, these factors are interrelated. An adjustment in the customer arrival rate might have to be accompanied by an increase in the service rate, $\lambda$, in some way. Decisions about the number of facilities, the number of phases, and waiting-line arrangements also are related.

## LEARNING GOALS IN REVIEW

| Learning Goal | Guidelines for Review | MyOMLab Resources |
|---|---|---|
| 1 Identify the structure of waiting lines in real situations. | The section "Structure of Waiting-Line Problems," pp. 180–184, defines the four elements of every waiting-line problem. Figures B.1, B.2, and B.3 depict these elements and various service facility arrangements. | |
| 2 Use the single-server, multiple-server, and finite-source models to analyze operations and estimate the operating characteristics of a process. | See the section "Using Waiting-Line Models to Analyze Operations," pp. 184–190, for a description and demonstration of these three models. Examples B.3, B.4, and the Solved Problem at the end of the supplement apply the single-server model. Example B.5 shows the multiple-server model and Example B.6 applies the finite-source model. In addition, Examples B.3 through B.6 show how to obtain estimates for the important operating characteristics of processes using waiting-line models. | **Active Model Exercises:** B.1: Single-Server Waiting-Line Model; B.2: Multi-Server Model with Costs; B.3: Finite Source Model with Costs<br>**OM Explorer Solvers:** Single-Server Waiting-Line Model; Multi-Server Model; Finite Source Model<br>**OM Explorer Tutors:** B.1: Single-Server Waiting-Line Model; B.2: Multi-Server Model; B.3: Finite Source Model<br>**POM for Windows**: B.1: Single-Server Waiting-Line Model; B.2: Multi-Server Model with Costs; B.3: Finite Source Model with Costs; B.4: Finite System-Size Model |
| 3 Describe the situations where simulation should be used for waiting-line analysis and the nature of the information that can be obtained. | The section "Waiting Lines and Simulation," pp. 190–191, explains when simulation must be used and discusses an example that demonstrates the nature of the managerial information that can be obtained from that analysis. | **Online Text:** SimQuick: Process Simulation with Excel, 2e |
| 4 Explain how waiting-line models can be used to make managerial decisions. | The section "Decision Areas for Management," pp. 191–192, describes seven decision areas that can be analyzed with waiting-line models. | |

# Key Equations

## Structure of Waiting-Line Problems

**1.** Customer arrival Poisson distribution:

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

**2.** Service time exponential distribution:

$$P(t \leq T) = 1 - e^{-\mu T}$$

## Using Waiting-Line Models to Analyze Operations

**3.** Average utilization of the system:

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

**4.** Probability that $n$ customers are in the system:

$$P_n = (1 - \rho)\rho^n$$

**5.** Probability that zero customers are in the system:

$$P_0 = 1 - \rho$$

**6.** Average number of customers in the service system:

$$L = \frac{\lambda}{\mu - \lambda}$$

**7.** Average number of customers in the waiting line:

$$L_q = \rho L$$

**8.** Average time spent in the system, including service:

$$W = \frac{1}{\mu - \lambda}$$

**9.** Average waiting time in line:

$$W_q = \rho W$$

**10.** Little's Law

$$L = \lambda W$$

# Key Terms

channel 181
customer population 180
interarrival times 183
Little's law 188
phase 181
preemptive discipline 183
priority rule 180
service facility 180
service system 180
waiting line 179

# Solved Problem

MyOMLab Video

A photographer takes passport pictures at an average rate of 20 pictures per hour. The photographer must wait until the customer smiles, so the time to take a picture is exponentially distributed. Customers arrive at a Poisson-distributed average rate of 19 customers per hour.

**a.** What is the utilization of the photographer?

**b.** How much time will the average customer spend with the photographer?

**SOLUTION**

**a.** The assumptions in the problem statement are consistent with a single-server model. Utilization is

$$\rho = \frac{\lambda}{\mu} = \frac{19}{20} = \mathbf{0.95}$$

**b.** The average customer time spent with the photographer is

$$W = \frac{1}{\mu - \lambda} = \frac{1}{20 - 19} = \mathbf{1}\text{ hour}$$

# Problems

The OM Explorer and POM for Windows software is available to all students using the 11th edition of this textbook. Go to **http://www.pearsonglobaleditions.com/krajewski** to download these computer packages. If you purchased MyOMLab, you also have access to Active Models software and significant help in doing the following problems. Check with your instructor on how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software entirely replaces the manual calculations.

## Structure of Waiting-Line Problems

**1.** Wingard Credit Union is redesigning the entryway into its bank of ATM machines. Management is trying to conceptually understand the interarrival of individuals, which has been described to them as following a Poisson distribution. If on an average, two customers arrive per minute randomly during busy times, calculate the probability that during a specific minute, no customers arrive. Calculate the probability that between one and four customers arrive.

**2.** Wingard Credit Union (from Problem 1) is also interested in understanding how long customers spend in front of the ATMs. Customer service times follow an Exponential distribution, with an average customer taking 1.5 minutes to complete a transaction. Calculate the probability that a customer will take less than half a minute. Additionally, calculate the probability that a customer will take more than 3 minutes.

## Using Waiting-Line Models to Analyze Operations

**3.** The Solomon, Smith, and Samson law firm produces many legal documents that must be word processed for clients and the firm. Requests average eight pages of documents per hour, and they arrive according to a Poisson distribution. The secretary can word process 10 pages per hour on average according to an exponential distribution.

**a.** What is the average utilization rate of the secretary?

**b.** What is the probability that more than four pages are waiting or being word processed?

**c.** What is the average number of pages waiting to be word processed?

**4.** Benny's Arcade has six video game machines. The average time between machine failures is 50 hours. Jimmy, the maintenance engineer, can repair a machine in 15 hours on average. The machines have an exponential failure distribution, and Jimmy has an exponential service-time distribution.

**a.** What is Jimmy's utilization?

**b.** What is the average number of machines out of service, that is, waiting to be repaired or being repaired?

**c.** What is the average time a machine is out of service?

**5.** Moore, Aiken, and Payne is a critical care dental clinic serving the emergency needs of the general public on a first-come, first-served basis. The clinic has five dental chairs, three of which are currently staffed by a dentist. Patients in distress arrive at the rate of five per hour, according to a Poisson distribution, and do not balk or renege. The average time required for an emergency treatment is 30 minutes, according to an exponential distribution. Use POM for Windows or OM Explorer to answer the following questions:

**a.** If the clinic manager would like to ensure that patients do not spend more than 15 minutes on average waiting to see the dentist, are three dentists on staff adequate? If not, how many more dentists are required?

**b.** From the current state of three dentists on staff, what is the change in each of the following operating characteristics when a fourth dentist is placed on staff:

- Average utilization
- Average number of customers in line
- Average number of customers in the system

**c.** From the current state of three dentists on staff, what is the change in each of the following operating characteristics when a fifth dentist is placed on staff:

- Average utilization
- Average number of customers in line
- Average number of customers in the system

**6.** Fantastic Styling Salon is run by three stylists, Jenny Perez, Jill Sloan, and Jerry Tiller, each capable of serving four customers per hour, on average. Use POM for Windows or OM Explorer to answer the following questions:

*During busy periods of the day, when nine customers on average arrive per hour, all three stylists are on staff.*

**a.** If all customers wait in a common line for the next available stylist, how long would a customer wait in line, on average, before being served?

**b.** Suppose that each customer wants to be served by a specific stylist, 1/3 want Perez, 1/3 want Sloan, 1/3 want Tiller. How long would a customer wait in line, on average, before being served?

*During less busy periods of the day, when six customers on average arrive per hour, only Perez and Sloan are on staff.*

**c.** If all customers wait in a common line for the next available stylist, how long would a customer wait in line, on average, before being served?

**d.** Suppose that each customer wants to be served by a specific stylist, 60 percent want Perez and 40 percent want Sloan. How long would a customer wait in line, on average, before being served by Perez? By Sloan? Overall?

**7.** You are the manager of a local bank where three tellers provide services to customers. On average, each teller takes 3 minutes to serve a customer. Customers arrive, on average, at a rate of 50 per hour. Having recently received complaints from some customers that they waited a long time before being served, your boss asks you to evaluate the service system. Specifically, you must provide answers to the following questions:

**a.** What is the average utilization of the three-teller service system?

**b.** What is the probability that no customers are being served by a teller or are waiting in line?

**c.** What is the average number of customers waiting in line?

**d.** On average, how long does a customer wait in line before being served?

**e.** On average, how many customers would be at a teller's station and in line?

**8.** Pasquist Water Company (PWC) operates a 24-hour facility designed to efficiently fill water-hauling tanker trucks. Trucks arrive randomly to the facility and wait in line to access a wellhead pump. Since trucks vary in size and the filling operation is manually performed by the truck driver, the time to fill a truck is also random.

**a.** If the manager of PWC uses the multiple-server model to calculate the operating characteristics of the facility's waiting line, list three assumptions she must make regarding the behavior of waiting trucks and the truck arrival process.

**b.** Suppose an average of 336 trucks arrive each day, there are four wellhead pumps, and each pump can serve an average of four trucks per hour.

- What is the probability that exactly 10 trucks will arrive between 1:00 P.M. and 2:00 P.M. on any given day?
- How likely is it that once a truck is in position at a wellhead, the filling time will be less than 15 minutes?

**c.** Contrast and comment on the performance differences between:

- One waiting line feeding all four stations.
- One waiting line feeding two wellhead pumps and a second waiting line feeding two other wellhead pumps. Assume that drivers cannot see each line and must choose randomly between them. Further, assume that once a choice is made, the driver cannot back out of the line.

**9.** The supervisor at the Precision Machine Shop wants to determine the staffing policy that minimizes total operating costs. The average arrival rate at the tool crib, where tools are dispensed to the workers, is eight machinists per hour. Each machinist's pay is $20 per hour. The supervisor can staff the crib either with a junior attendant who is paid $5 per hour and can process 10 arrivals per hour or with a senior attendant who is paid $12 per hour and can process 16 arrivals per hour. Which attendant should be selected, and what would be the total estimated hourly cost?

**10.** The daughter of the owner of a local hamburger restaurant is preparing to open a new fast-food restaurant called Hasty Burgers. Based on the arrival rates at her father's outlets, she expects customers to arrive at the drive-up window according to a Poisson distribution, with a mean of 20 customers per hour. The service rate is flexible; however, the service times are expected to follow an exponential distribution. The drive-in window is a single-server operation.

**a.** What service rate is needed to keep the average number of customers in the service system (waiting line and being served) to four?

**b.** For the service rate in part (a), what is the probability that more than four customers are in line and being served?

**c.** For the service rate in part (a), what is the average waiting time in line for each customer? Does this average seem satisfactory for a fast-food business?

**11.** The manager of a branch office of Banco Mexicali observed that during peak hours an average of 20 customers arrives per hour and that there is an average of four customers in the branch office at any time. How long does the average customer spend waiting in line and being serviced?

**12.** Paula Caplin is manager of a major electronics repair facility owned by Fisher Electronics. Recently, top management expressed concern over the growth in the number of repair jobs in process at the facility. The average arrival rate is 120 jobs per day. The average job spends four days at the facility.

**a.** What is the current work-in-process level at the facility?

**b.** Suppose that top management has put a limit of one-half the current level of work-in-process. What goal must Paula establish, and how might she accomplish it?

**13.** Failsafe Textiles employs three highly skilled maintenance workers who are responsible for repairing the numerous industrial robots used in its manufacturing process. A worker can fix one robot every 8 hours on average, with an exponential distribution. An average of one robot fails every 3 hours, according to a Poisson distribution. Each down robot costs the company $100.00 per hour in lost production. A new maintenance worker costs the company $80.00 per hour in salary, benefits, and equipment. Should the manager hire any new personnel? If so, how many people? What would you recommend to the manager, based on your analysis?

**14.** The College of Business and Public Administration at Benton University has a copy machine on each floor for faculty use. Heavy use of the five copy machines causes frequent failures. Maintenance records show that a machine fails every 2.5 days (or $\lambda = 0.40$ failure/day). The college has a maintenance contract with the authorized dealer of the copy machines. Because the copy machines fail so frequently, the dealer has assigned one person to the college to repair them. The person can repair an average of 2.5 machines per day. Using the finite-source model, answer the following questions:

**a.** What is the average utilization of the maintenance person?

**b.** On average, how many copy machines are being repaired or waiting to be repaired?

**c.** What is the average time spent by a copy machine in the repair system (waiting and being repaired)?

**15.** The manager of Vintage Time Video Machine Parlor is responsible for ensuring that all six of his machines are in good condition. Machines frequently need attention but can normally be returned to service quickly. On an average, each machine requires attention five times each hour. The manager averages 4 minutes per repair.

**a.** What percentage of each hour is the manager fixing machines?

**b.** On an average, how many machines are broken down and waiting for repair?

**c.** On an average, how many minutes in an hour are machines waiting for repair or being repaired?

**16.** Two nurses at Northwood Hospital's Cardiac Care Unit are assigned to care for eight patients. Nurses are responsible for administering medication, taking vital signs, and responding to frequent calls for assistance that can come either from the patient, or the equipment monitoring the patient's current condition. On an average, each patient requires attention three times each hour. Nurses average 6 minutes per patient visit.

**a.** What is the average utilization of the nursing staff?

**b.** On an average, how many patients are waiting for a nurse?

**c.** By how much would adding a third nurse reduce the patient waiting time?

**17.** You are in charge of a quarry that supplies sand and stone aggregates to your company's construction sites. Empty trucks from construction sites arrive at the quarry's huge piles of sand and stone aggregates and wait in line to enter the station, which can load either sand or aggregate. At the station, they are filled with material, weighed, checked out, and proceed to a construction site. Currently, nine empty trucks arrive per hour, on average. Once a truck has entered a loading station, it takes 6 minutes for it to be filled, weighed, and checked out. Concerned that trucks are spending too much time waiting and being filled, you are evaluating two alternatives to reduce the average time the trucks spend in the system. The first alternative is to add side boards to the trucks (so that more material could be loaded) and to add a helper at the loading station (so that filling time could be reduced) at a total cost of $50,000. The arrival rate of trucks would change to six per hour, and the filling time would be reduced to 4 minutes. The second alternative is to add another loading station identical to the current one at a cost of $80,000. The trucks would wait in a common line and the truck at the front of the line would move to the next available station.

Which alternative would you recommend if you want to reduce the current average time the trucks spend in the system, including service?


Oil containment boom and sorbent boom block a patch of oil from reaching an island populated by brown and white pelicans and many other species of birds in Barataria Bay, Grand Isle, Louisiana.

# 5

# MANAGING PROCESS CONSTRAINTS

## British Petroleum Oil Spill in Gulf of Mexico

British Petroleum (BP) is one of the world's leading international oil, gas, and petrochemical products company that provides a diverse range of products and services across the hydrocarbon value chain. It has operations in around 80 countries, 83,900 employees, and revenues of $377 billion. It operates over 17,500 retail sites. On April 20, 2010, there was an explosion and fire on Transocean Ltd's Deepwater Horizon drilling rig that had been licensed to BP. It sank two days later in 5,000 feet of water, and released as many as 4.9 billion barrels of oil into the Gulf of Mexico before the damaged well was finally capped in mid-July 2010. The resulting oil spill closed down fisheries and threatened the delicate coastline and its fragile ecosystems. Pinnacle Strategies was one of the firms hired by BP to help in boosting the output of spill-fighting equipment like boats, ships, and rigs, as well as supplies of critical resources like containment booms, skimmers, and decontamination suits.

A boom is an inflatable floating device that can be used to trap oil downwind on a body of water. This oil can then be pumped into containers by skimming equipment. Limited production capacities of booms, however, represented a daunting challenge. Prestige Products in Walker, Michigan, could only make 500 feet of boom a day, whereas a single order of the size requested by BP would exceed the combined capacity of every boom manufacturer in the United States. Despite increasing the staff from 5 to 75 and raising production to 12,800 feet daily, the Prestige plant felt that it had reached its limit. That is where Ed Kincer from Pinnacle Strategies stepped in. He noticed that the boom was assembled in a flurry, with little to do in-between for several minutes. Cutters sliced boom by cutting one side, then walking 100 feet to cut the other side. Workers also sat idle while waiting for a welding machine. Waste occurred in the form of excessive walks, waiting for machines, and changing production rhythms. Kincer identified the constraints in the process, found ways to manage them, and more than tripled capacity. Prestige eventually ended up making more than a million feet of boom for BP.

Theory of constraints is the scientific approach that was used by Pinnacle to boost throughput for BP's other key suppliers as well. Kvichak Marine in Seattle quadrupled output of oil skimmers, while Illinois-based Elastec increased production from four skimmers a week to 26. Abasco, a Houston-based boom manufacturer, increased production by 20 percent due to rebalancing staff such that the welding operation kept going even during the breaks. At Supply Pro, a Texan manufacturer of absorbent boom, capacity increased several fold by using cellulose instead of scarce polypropylene. In six months, Pinnacle more than doubled the supply of skimmers, booms, and other critical resources by identifying bottlenecks at dozens of factories and working around them. These capacity enhancements throughout BP's supply chain ensured that lack of materials did not end up constraining the clean-up operations in the fight against the oil spill.

*Source:* Brown, A. "Theory of Constraints Tapped to Accelerate BP's Gulf of Mexico Cleanup." *Industry Week* (March 18, 2011); **http://www.newsweek.com/photo/2010/05/22/oil-spill-timeline.html**; **http://www.bp.com/** (July 25, 2014).



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

1. Explain the theory of constraints.
2. Identify and manage bottlenecks in service processes.
3. Identify and manage bottlenecks in manufacturing processes.
4. Apply the theory of constraints to product mix decisions.
5. Describe how to manage constraints in line processes and balance assembly lines.

**constraint**

Any factor that limits the performance of a system and restricts its output. In linear programming, a limitation that restricts the permissible choices for the decision variables.

**bottleneck**

A capacity constraint resource (CCR) whose available capacity limits the organization's ability to meet the product volume, product mix, or demand fluctuation required by the marketplace.

Suppose one of a firm's processes was recently reengineered, and yet results were disappointing. Costs were still high or customer satisfaction still low. What could be wrong? The answer might be constraints that remain in one or more steps in the firm's processes. A **constraint** is any factor that limits the performance of a system and restricts its output, while *capacity* is the maximum rate of output of a process or a system. When constraints exist at any step, as they did at suppliers of BP, capacity can become imbalanced—too high in some departments and too low in others. As a result, the overall performance of the system suffers.

Constraints can occur up or down the supply chain, with either the firm's suppliers or customers or within one of the firm's processes like service or product development or order fulfillment. Three kinds of constraints can generally be identified: physical (usually machine, labor, or workstation capacity or material shortages, but could be space or quality), market (demand is less than capacity), or managerial (policy, metrics, or mind-sets that create constraints that impede work flow). A **bottleneck**[1] is a special type of a constraint that relates to the capacity shortage of a process and is defined as any

[1]Under certain conditions, a bottleneck is also called a *capacity constrained resource* (CCR). The process with the least capacity is called a bottleneck if its output is less than the market demand, or called a CCR if it is the least capable resource in the system but still has higher capacity than the market demand.

resource whose available capacity limits the organization's ability to meet the service or product volume, product mix, or fluctuating requirements demanded by the marketplace. A business system or a process would have at least one constraint or a bottleneck; otherwise, its output would be limited only by market demand.

Firms must manage their constraints and make appropriate capacity choices at the individual-process level as well as at the organization level. Hence, this process involves inter-functional cooperation. Detailed decisions and choices made within each of these levels affect where resource constraints or bottlenecks show up, both within and across departmental lines. Relieving a bottleneck in one part of an organization might not have the desired effect unless a bottleneck in another part of the organization is also addressed. A bottleneck could be the sales department not getting enough sales or the loan department not processing loans fast enough. The constraint could be a lack of capital or equipment, or it could be planning and scheduling.

The experience of BP and other firms in the health care, banking, and manufacturing industries demonstrates how important managing constraints can be to an organization's future. Therefore managers throughout the organization must understand how to identify and manage bottlenecks in all types of processes, how to relate the capacity and performance measures of one process to another, and how to use that information to determine the firm's best service or product mix. This chapter explains how managers can best make these decisions.

## The Theory of Constraints

The **theory of constraints (TOC)** is a systematic management approach that focuses on actively managing those constraints that impede a firm's progress toward its goal of maximizing profits and effectively using its resources. The theory was developed nearly three decades ago by Eli Goldratt, a well-known business systems analyst. It outlines a deliberate process for identifying and overcoming constraints. The process focuses not just on the efficiency of individual processes but also on the bottlenecks that constrain the system as a whole. Pinnacle Strategies in the opening vignette followed this theory to improve BP's operations.

**theory of constraints (TOC)**
A systematic management approach that focuses on actively managing those constraints that impede a firm's progress toward its goal.

TOC methods increase the firm's profits more effectively by focusing on making materials flow rapidly through the entire system. They help firms look at the big picture—how processes can be improved to increase overall work flows, and how inventory and workforce levels can be reduced while still effectively utilizing critical resources. To do this, it is important to understand the relevant performance and capacity measures at the operational level, as well as their relationship to the more broadly understood financial measures at the firm level. These measures and relationships, so critical in successfully applying the principles of the TOC, are defined in Table 5.1.

**TABLE 5.1** HOW THE FIRM'S OPERATIONAL MEASURES RELATE TO ITS FINANCIAL MEASURES

| Operational Measures | TOC View | Relationship to Financial Measures |
|---|---|---|
| Inventory (I) | All the money invested in a system in purchasing things that it intends to sell | A decrease in I leads to an increase in net profit, ROI, and cash flow. |
| Throughput (T) | Rate at which a system generates money through sales | An increase in T leads to an increase in net profit, ROI, and cash flows. |
| Operating Expense (OE) | All the money a system spends to turn inventory into throughput | A decrease in OE leads to an increase in net profit, ROI, and cash flows. |
| Utilization (U) | The degree to which equipment, space, or workforce is currently being used; it is measured as the ratio of average output rate to maximum capacity, expressed as a percentage | An increase in U at the bottleneck leads to an increase in net profit, ROI, and cash flows. |

According to the TOC view, every capital investment in the system, including machines and work-in-process materials, represents inventory because they could all potentially be sold to make money. Producing a product or a service that does not lead to a sale will not increase a firm's throughput, but will increase its inventory and operating expenses. It is always best to manage the system so that utilization at the bottleneck resource is maximized to maximize throughput.

## Key Principles of the TOC

The chief concept behind the TOC is that the bottlenecks should be scheduled to maximize their throughput of services or products while adhering to promised completion dates. The underlying assumption is that demand is greater or equal to the capacity of the process that produces the service or product, otherwise instead of internal changes, marketing must work toward promoting increasing demand. For example, manufacturing a garden rake involves attaching a bow to the rake's head. Rake heads must be processed on the blanking press, welded to the bow, cleaned, and attached to the handle to make the rake, which is packaged and finally shipped to Sears, Home Depot, or Walmart, according to a specific delivery schedule. Suppose that the delivery commitments for all styles of rakes for the next month indicate that the welding station is loaded at 105 percent of its capacity, but that the other processes will be used at only 75 percent of their capacities. According to the TOC, the welding station is the bottleneck resource, whereas the blanking, cleaning, handle attaching, packaging, and shipping processes are non-bottleneck resources. Any idle time at the welding station must be eliminated to maximize throughput. Managers should therefore focus on the welding schedule.

Seven key principles of the TOC that revolve around the efficient use and scheduling of bottlenecks and improving flow and throughput are summarized in Table 5.2.

**TABLE 5.2 | SEVEN KEY PRINCIPLES OF THE THEORY OF CONSTRAINTS**

| |
|---|
| 1. The focus should be on balancing flow, not on balancing capacity. |
| 2. Maximizing the output and efficiency of every resource may not maximize the throughput of the entire system. |
| 3. An hour lost at a bottleneck or a constrained resource is an hour lost for the whole system. In contrast, an hour saved at a non-bottleneck resource is a mirage, because it does not make the whole system more productive. |
| 4. Inventory is needed only in front of the bottlenecks to prevent them from sitting idle and in front of assembly and shipping points to protect customer schedules. Building inventories elsewhere should be avoided. |
| 5. Work, which can be materials, information to be processed, documents, or customers, should be released into the system only as frequently as the bottlenecks need it. Bottleneck flows should be equal to the market demand. Pacing everything to the slowest resource minimizes inventory and operating expenses. |
| 6. Activating a non-bottleneck resource (using it for improved efficiency that does not increase throughput) is not the same as utilizing a bottleneck resource (that does lead to increased throughput). Activation of non-bottleneck resources cannot increase throughput, nor promote better performance on financial measures outlined in Table 5.1. |
| 7. Every capital investment must be viewed from the perspective of its global impact on overall throughput (T), inventory (I), and operating expense (OE). |

Practical application of the TOC involves the implementation of the following steps.

1. *Identify the System Bottleneck(s).* For the rake example, the bottleneck is the welding station because it is restricting the firm's ability to meet the shipping schedule and, hence, total value-added funds. Other ways of identifying the bottleneck will be looked at in more detail a little later in this chapter.
2. *Exploit the Bottleneck(s).* Create schedules that maximize the throughput of the bottleneck(s). For the rake example, schedule the welding station to maximize its utilization while meeting the shipping commitments to the extent possible. Also make sure that only good quality parts are passed on to the bottleneck.
3. *Subordinate All Other Decisions to Step 2.* Non-bottleneck resources should be scheduled to support the schedule of the bottleneck and not produce more than the bottleneck can handle. That is, the blanking press should not produce more than the welding station can handle, and the activities of the cleaning and subsequent operations should be based on the output rate of the welding station.
4. *Elevate the Bottleneck(s).* After the scheduling improvements in steps 1–3 have been exhausted, and the bottleneck is still a constraint to throughput, management should consider increasing the capacity of the bottleneck. For example, if the welding station is still a constraint after exhausting schedule improvements, consider increasing its capacity by adding another shift or another welding machine. Other mechanisms are also available for increasing bottleneck capacity, and we address them a little later.
5. *Do Not Let Inertia Set In.* Actions taken in steps 3 and 4 will improve the welder throughput and may alter the loads on other processes. Consequently, the system constraint(s) may shift. Then, the practical application of steps 1–4 must be repeated to identify and manage the new set of constraints.

Because of its potential for improving performance dramatically, many manufacturers have applied the principles of the TOC. All manufacturers implementing TOC principles can also dramatically change the mind-set of employees and managers. Instead of focusing solely on their own functions, they can see the "big picture" and where other improvements in the system might lie. A study shows that more than one third of winners and finalists of *Industry Week's* best manufacturing plants have extensively implemented TOC, while up to 80 percent make some use of it.

# Managing Bottlenecks in Service Processes

Bottlenecks can both be internal or external to the firm, and typically represent a process, a step, or a workstation with the lowest capacity. **Throughput time** is the total elapsed time from the start to the finish of a job or a customer being processed at one or more work centers. Where a bottleneck lies in a given service or manufacturing process can be identified in two ways. A workstation in a process is a bottleneck if (1) it has the highest total time per unit processed, or (2) it has the highest average utilization and total workload.

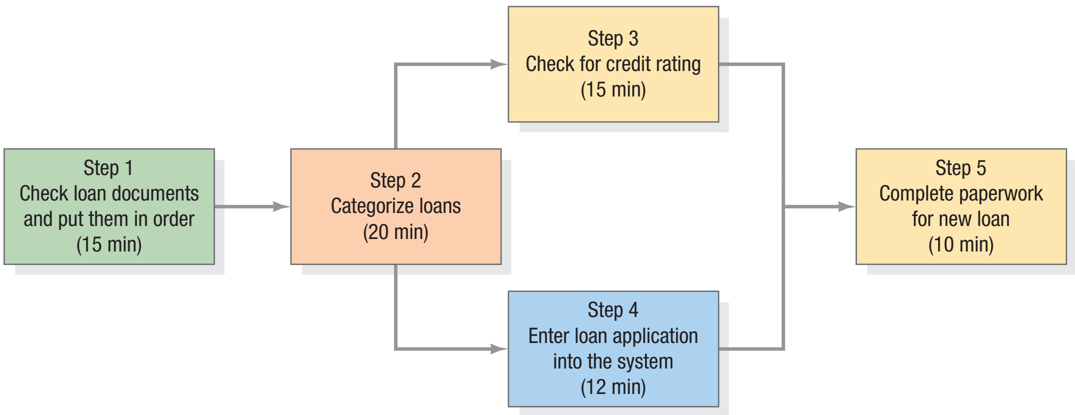
**throughput time**
Total elapsed time from the start to the finish of a job or a customer being processed at one or more work centers.

Example 5.1 illustrates how a bottleneck step or activity can be identified for a loan approval process at a bank.

## EXAMPLE 5.1 Identifying the Bottleneck in a Service Process

Managers at the First Community Bank are attempting to shorten the time it takes customers with approved loan applications to get their paperwork processed. The flowchart for this process, consisting of several different activities, each performed by a different bank employee, is shown in Figure 5.1. Approved loan applications first arrive at activity or Step 1, where they are checked for completeness and put in order. At Step 2, the loans are categorized into different classes according to the loan amount and whether they are being requested for personal or commercial reasons. While credit checking commences at Step 3, loan application data are entered in parallel into the information system for record-keeping purposes at Step 4. Finally, all paperwork for setting up the new loan is finished at Step 5. The time taken in minutes is given in parentheses.

Which single step is the bottleneck, assuming that market demand for loan applications exceeds the capacity of the process? The management is also interested in knowing the maximum number of approved loans this system can process in a 5-hour workday.




▲ FIGURE 5.1
Processing Credit Loan Applications at First Community Bank

### SOLUTION

We define the bottleneck as Step 2, which has the highest time per loan processed. The throughput time to complete an approved loan application is $15 + 20 + \max(15, 12) + 10 = \mathbf{60}$ minutes. Although we assume no waiting time in front of any step, in practice such a smooth process flow is not always the case. So the actual time taken for completing an approved loan will be longer than 60 minutes due to nonuniform arrival of applications, variations in actual processing times, and the related factors.

The capacity for loan completions is derived by translating the "minutes per customer" at the bottleneck step to "customer per hour." At First Community Bank, it is three customers per hour because the bottleneck Step 2 can process only one customer every 20 minutes (60/3).

### DECISION POINT

Step 2 is the bottleneck constraint. The bank will be able to complete a maximum of only three loan accounts per hour, or 15 new loan accounts in a 5-hour day. Management can increase the flow of loan applications by increasing the capacity of Step 2 up to the point where another step becomes the bottleneck.

Todd Bigelow/Aurora Photos/Alamy

Due to constrained resources like doctors, nurses, and equipment, patients wait for medical care in a crowded waiting room at South Central Family Health Center in Los Angeles, California.

A front-office process with high customer contact and divergence does not enjoy the simple line flows shown in Example 5.1. Its operations may serve many different customer types, and the demands on any one operation could vary considerably from one day to the next. Computing the average utilization of each operation can still identify bottlenecks. However, the variability in workload also creates *floating bottlenecks.* One week the mix of work may make operation 1 a bottleneck, and the next week it may make operation 3 the bottleneck. This type of variability increases the complexity of day-to-day scheduling. In this situation, management prefers lower utilization rates, which allow greater slack to absorb unexpected surges in demand.

TOC principles outlined here are fairly broad-based and widely applicable to many types of processes. They can be useful for evaluating individual processes as well as large systems for both manufacturers as well as service providers. Service organizations, such as Delta Airlines, United Airlines, and major hospitals across the United States, including the U.S. Air Force health care system, use the TOC to their advantage.

## Managing Bottlenecks in Manufacturing Processes

Bottlenecks can exist in all types of manufacturing processes, including the job process, batch process, line process, and continuous process. Since these processes differ in their design, strategic intent, and allocation of resources (see Chapter 2, "Process Strategy and Analysis," for additional details), identification and management of bottlenecks will also differ accordingly with process type. We first discuss in this section issues surrounding management of bottlenecks in job and batch processes, while relegating constraint management in line processes for a later section.

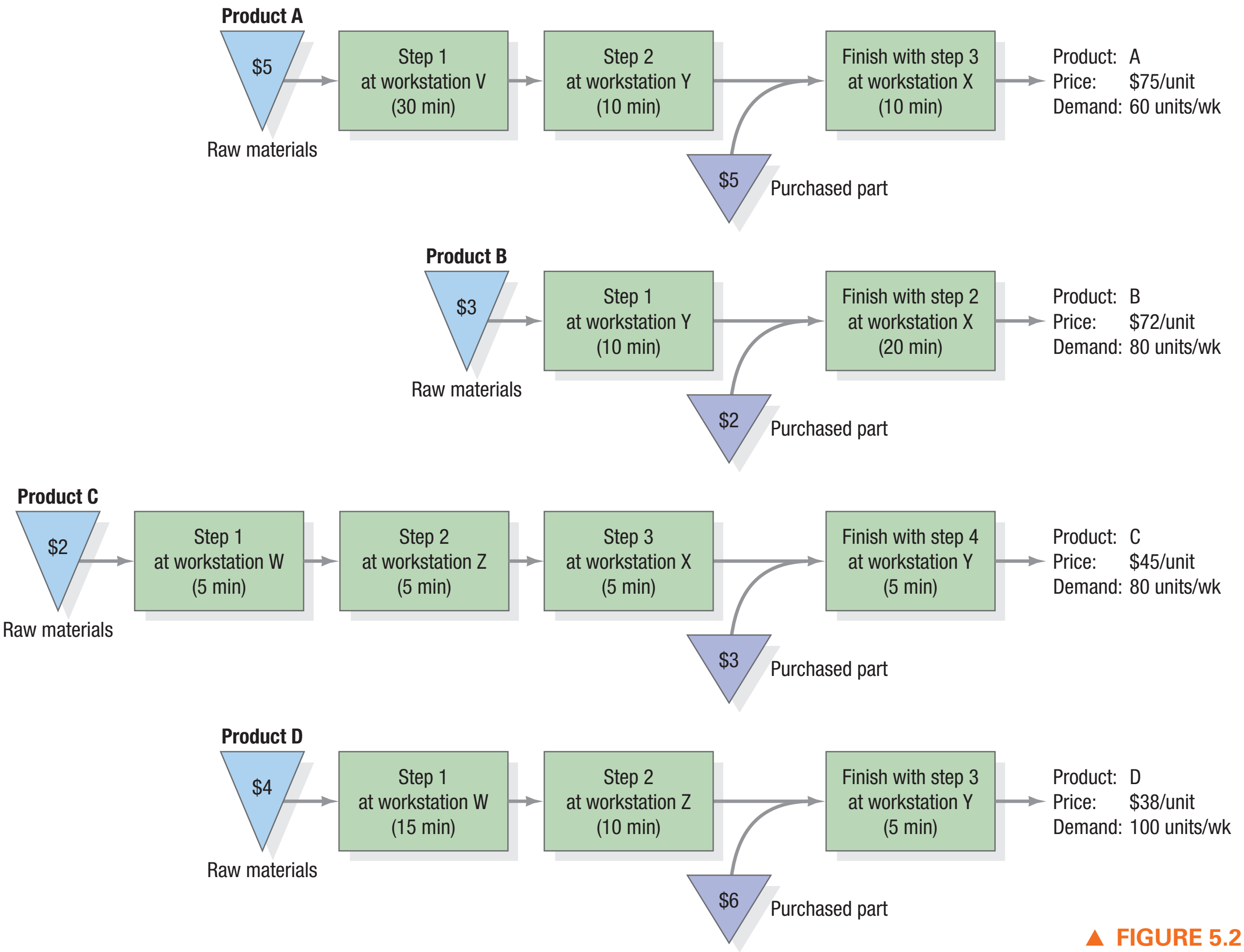
### Identifying Bottlenecks

Manufacturing processes often pose some complexities when identifying bottlenecks. If multiple services or products are involved, extra setup time at a workstation is usually needed to change over from one service or product to the next, which in turn increases the overload at the workstation being changed over. *Setup times* and their associated costs affect the size of the lots traveling through the job or batch processes. Management tries to reduce setup times because they represent unproductive time for workers or machines and thereby allow for smaller, more economic, batches. Nonetheless, whether setup times are significant or not, one way to identify a bottleneck operation is by its utilization. Example 5.2 illustrates how a bottleneck can be identified in a manufacturing setting where setups are negligible.

**EXAMPLE 5.2** **Identifying the Bottleneck in a Batch Process**

Diablo Electronics manufactures four unique products (A, B, C, and D) that are fabricated and assembled in five different workstations (V, W, X, Y, and Z) using a small batch process. Each workstation is staffed by a worker who is dedicated to work a single shift per day at an assigned workstation. Batch setup times have been reduced to such an extent that they can be considered negligible. A flowchart denotes the path each product follows through the manufacturing process as shown in Figure 5.2, where each product's price, demand per week, and processing times per unit are indicated as well. Inverted triangles represent purchased parts and raw materials consumed per unit at different workstations. Diablo can make and sell up to the limit of its demand per week, and no penalties are incurred for not being able to meet all the demand.

Which of the five workstations (V, W, X, Y, or Z) has the highest utilization, and thus serves as the bottleneck for Diablo Electronics?




▲ **FIGURE 5.2**
Flowchart for Products A, B, C, and D

## SOLUTION

Because the denominator in the utilization ratio is the same for every workstation, with one worker per machine at each step in the process, we can simply identify the bottleneck by computing aggregate workloads at each workstation.

The firm wants to satisfy as much of the product demand in a week as it can. Each week consists of 2,400 minutes of available production time. Multiplying the processing time at each station for a given product by the number of units demanded per week yields the workload represented by that product. These loads are summed across all products going through a workstation to arrive at the total load for the workstation, which is then compared with the others and the existing capacity of 2,400 minutes.

| Workstation | Load from Product A | Load from Product B | Load from Product C | Load from Product D | Total Load (min) |
|---|---|---|---|---|---|
| V | $60 \times 30 = 1800$ | 0 | 0 | 0 | 1,800 |
| W | 0 | 0 | $80 \times 5 = 400$ | $100 \times 15 = 1{,}500$ | 1,900 |
| X | $60 \times 10 = 600$ | $80 \times 20 = 1{,}600$ | $80 \times 5 = 400$ | 0 | **2,600** |
| Y | $60 \times 10 = 600$ | $80 \times 10 = 800$ | $80 \times 5 = 400$ | $100 \times 5 = 500$ | 2,300 |
| Z | 0 | 0 | $80 \times 5 = 400$ | $100 \times 10 = 1{,}000$ | 1,400 |

## DECISION POINT

Workstation X is the bottleneck for Diablo Electronics because the aggregate workload at X is larger than the aggregate workloads of workstations V, W, Y, and Z and the maximum available capacity of 2,400 minutes per week.

Identifying the bottlenecks becomes considerably harder when setup times are lengthy and the degree of divergence in the process is greater than that shown in Example 5.2. When the setup time is large, the operation with the highest total time per unit processed would typically tend to be the bottleneck. Variability in the workloads will again likely create floating bottlenecks, especially if most processes involve multiple operations, and often their capacities are not identical. In practice, these bottlenecks can also be determined by asking workers and supervisors in the plant where the bottlenecks might lie, and looking for piled up material in front of different workstations.

## Relieving Bottlenecks

The key to preserving bottleneck capacity is to carefully monitor short-term schedules and keep bottleneck resource as busy as is practical. Managers should minimize idle time at the bottlenecks caused by delays elsewhere in the system and make sure that the bottleneck has all the resources it needs to stay busy. When a changeover or setup is made at a bottleneck, the number of units or customers processed before the next changeover should be large compared to the number processed at less critical operations. Maximizing the number of units processed per setup means fewer setups per year and, thus, less total time lost to setups. The number of setups also depends on the required product variety; more variety necessitates more frequent changeovers.

The long-term capacity of bottleneck operations can be expanded in various ways. Investments can be made in new equipment and in brick-and-mortar facility expansions. The bottleneck's capacity also can be expanded by operating it more hours per week, such as by hiring more employees and going from a one-shift operation to multiple shifts, or by hiring more employees and operating the plant six or seven days per week versus five days per week. Managers also might relieve the bottleneck by redesigning the process, either through *process reengineering* or *process improvement*, or by purchasing additional machines that can handle more capacity.

## Drum-Buffer-Rope Systems

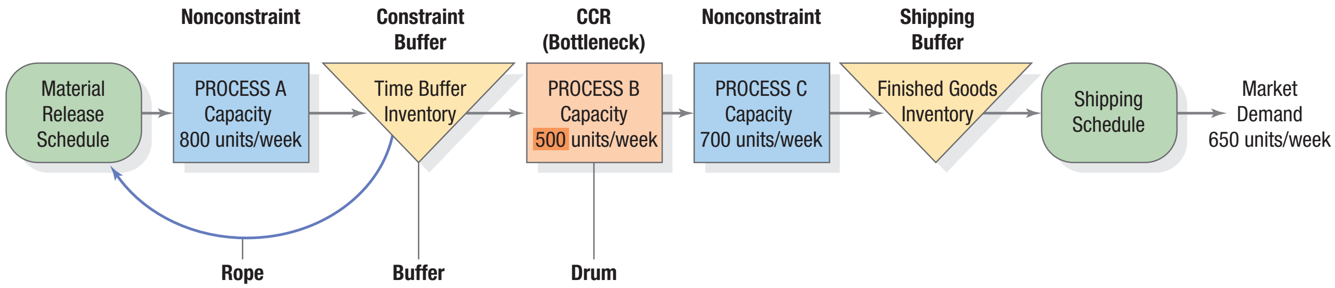
**drum-buffer-rope (DBR)**

A planning and control system that regulates the flow of work-in-process materials at the bottleneck or the capacity constrained resource (CCR) in a productive system.

**Drum-buffer-rope (DBR)** is a planning and control system based on the TOC that is often used in manufacturing firms to plan and schedule production. It works by regulating the flow of work-in-process materials at the bottleneck or the capacity constrained resource (CCR). The bottleneck schedule is the *drum* because it sets the beat or the production rate for the entire plant and is linked to the market demand. The *buffer* is a time buffer that plans early flows to the bottleneck and thus protects it from disruption. It also ensures that the bottleneck is never starved for work. A finished-goods inventory buffer can also be placed in front of the shipping point to protect customer shipping schedules. Finally, the *rope* represents the tying of material release to the drumbeat, which is the rate at which the bottleneck controls the throughput of the entire plant. It is thus a communication device to ensure that raw material is not introduced into the system at a rate faster than what the bottleneck can handle. Completing the loop, *buffer management* constantly monitors the execution of incoming bottleneck work. Working together, the drum, the buffer, and the rope can help managers create a production schedule that reduces lead times and inventories while simultaneously increasing throughput and on-time delivery.

To better understand the DBR system, consider the schematic layout shown in Figure 5.3. Process B, with a capacity of only 500 units per week, is the bottleneck because the upstream Process A and downstream Process C have capacities of 800 units per week and 700 units per week, respectively, and the market demand is 650 units per week, on average. In this case, because the capacity at Process B is less than the market demand, it is the bottleneck. A constraint time buffer, which can be in the form of materials arriving earlier than needed, is placed right in front of the bottleneck (Process B). A shipping buffer, in the form of finished goods inventory, can also be placed prior to the shipping schedule to protect customer orders that are firm. Finally, a rope ties the material release schedule to match the schedule, or drum beat, at the bottleneck. The material flow is pulled forward by the drumbeat prior to the bottleneck, while it is pushed downstream toward the customer subsequent to the bottleneck.

▼ **FIGURE 5.3**
Drum-Buffer-Rope System



DBR specifically strives to improve throughput by better utilizing the bottleneck resource and protecting it from disruption through the time buffer and protective buffer capacity elsewhere. So while the process batch in the DBR is any size that minimizes setups and improves utilization at the bottleneck, at nonconstrained resources the process batches are equal to what is needed for production at that time. The material can consequently be released in small batches known as transfer batches at the release point, which then combine at the constraint buffer to make a full process batch at the bottleneck. Transfer batches can be as small as one unit each, to allow a downstream workstation to start work on a batch before it is completely finished at the prior process. Using transfer batches typically facilitates a reduction in overall lead time.

DBR can be an effective system to use when the product the firm produces is relatively simple and the production process has more line flows. Planning is greatly simplified in this case and primarily revolves around scheduling the constrained resource and triggering other points to meet that bottleneck's schedule. Effectively implementing a DBR system requires an understanding of the TOC principles. However, such a system can be utilized in many different kinds of manufacturing and service organizations, either by itself or in conjunction with other planning and control systems.

## Applying the Theory of Constraints to Product Mix Decisions

Managers might be tempted to produce the products with the highest contribution margins or unit sales. *Contribution margin* is the amount each product contributes to profits and overhead; no fixed costs are considered when making the product mix decision. We call this approach the *traditional method.* The problem with this approach is that the firm's actual throughput and overall profitability depend more upon the contribution margin generated at the bottleneck than by the contribution margin of each individual product produced. We call this latter approach the *bottleneck method*. Example 5.3 illustrates both of these methods.

Linear programming (see Supplement D) could also be used to find the best product mix in Example 5.3. It must be noted, however, that the problem in Example 5.3 does not involve significant

### EXAMPLE 5.3 Determining the Product Mix Using Contribution Margin

The senior management at Diablo Electronics (see Example 5.2) wants to improve profitability by accepting the right set of orders, and so collected some additional financial data. Variable overhead costs are $8,500 per week. Each worker is paid $18 per hour and is paid for an entire week, regardless of how much the worker is used. Consequently, labor costs are fixed expenses. The plant operates one 8-hour shift per day, or 40 hours each week. Currently, decisions are made using the traditional method, which is to accept as much of the highest contribution margin product as possible (up to the limit of its demand), followed by the next highest contribution margin product, and so on until no more capacity is available. Pedro Rodriguez, the newly hired production supervisor, is knowledgeable about the TOC and bottleneck-based scheduling. He believes that profitability can indeed be improved if bottleneck resources were exploited to determine the product mix. What is the change in profits if, instead of the traditional method used by Diablo Electronics, the bottleneck method advocated by Pedro is used to select the product mix?

#### SOLUTION

**Decision Rule 1: Traditional Method**

Select the best product mix according to the highest overall contribution margin of each product.

**Step 1.** Calculate the contribution margin per unit of each product as shown here.

| | A | B | C | D |
|---|---|---|---|---|
| **Price** | $75.00 | $72.00 | $45.00 | $38.00 |
| **Raw material and purchased parts** | –10.00 | –5.00 | –5.00 | –10.00 |
| **= Contribution margin** | $65.00 | $67.00 | $40.00 | $28.00 |

When ordered from highest to lowest, the contribution margin per unit sequence of these products is B, A, C, D.

**Step 2.** Allocate resources V, W, X, Y, and Z to the products in the order decided in Step 1. Satisfy each demand until the bottleneck resource (workstation X) is encountered. Subtract minutes away from 2,400 minutes available for each week at each stage.

| Work Center | Minutes at the Start | Minutes Left After Making 80 B | Minutes Left After Making 60 A | Can Only Make 40 C | Can Still Make 100 D |
|---|---|---|---|---|---|
| **V** | 2,400 | 2,400 | 600 | 600 | 600 |
| **W** | 2,400 | 2,400 | 2,400 | 2,200 | 700 |
| **X** | 2,400 | 800 | 200 | 0 | 0 |
| **Y** | 2,400 | 1,600 | 1,000 | 800 | 300 |
| **Z** | 2,400 | 2,400 | 2,400 | 2,200 | 1,200 |

The best product mix according to this traditional approach is then 60 A, 80 B, 40 C, and 100 D.

**Step 3.** Compute profitability for the selected product mix.

| Profits | | |
|---|---|---|
| **Revenue** | $(60 \times \$75) + (80 \times \$72) + (40 \times \$45) + (100 \times \$38)$ | = $15,860 |
| **Materials** | $(60 \times \$10) + (80 \times \$5) + (40 \times \$5) + (100 \times \$10)$ | = −$2,200 |
| **Labor** | $(5 \text{ workers}) \times (8 \text{ hours/day}) \times (5 \text{ days/week}) \times (18 / \text{hour})$ | = −$3,600 |
| **Overhead** | | = −$8,500 |
| **Profit** | | = $1,560 |

Manufacturing the product mix of 60 A, 80 B, 40 C, and 100 D will yield a profit of **$1,560** per week.

### Decision Rule 2: Bottleneck Method

Select the best product mix according to the dollar contribution margin per minute of processing time at the bottleneck workstation X. This method would take advantage of the principles outlined in the TOC and get the most dollar benefit from the bottleneck.

**Step 1.** Calculate the contribution margin/minute of processing time at bottleneck workstation X:

| | Product A | Product B | Product C | Product D |
|---|---|---|---|---|
| **Contribution margin** | $65.00 | $67.00 | $40.00 | $28.00 |
| **Time at bottleneck** | 10 minutes | 20 minutes | 5 minutes | 0 minutes |
| **Contribution margin per minute** | $6.50 | $3.35 | $8.00 | Not defined |

When ordered from highest to lowest contribution margin/minute at the bottleneck, the manufacturing sequence of these products is D, C, A, B, which is reverse of the earlier order. Product D is scheduled first because it does not consume any resources at the bottleneck.

**Step 2.** Allocate resources V, W, X, Y, and Z to the products in the order decided in Step 1. Satisfy each demand until the bottleneck resource (workstation X) is encountered. Subtract minutes away from 2,400 minutes available for each week at each stage.

| Work Center | Minutes at the Start | Minutes Left After Making 100 D | Minutes Left After Making 80 C | Minutes Left After Making 60 A | Can Only Make 70 B |
|---|---|---|---|---|---|
| **V** | 2,400 | 2,400 | 2,400 | 600 | 600 |
| **W** | 2,400 | 900 | 500 | 500 | 500 |
| **X** | 2,400 | 2,400 | 2,000 | 1,400 | 0 |
| **Y** | 2,400 | 1,900 | 1,500 | 900 | 200 |
| **Z** | 2,400 | 1,400 | 1,000 | 1,000 | 1,000 |

The best product mix according to this bottleneck-based approach is then 60 A, 70 B, 80 C, and 100 D.

**Step 3.** Compute profitability for the selected product mix.

| Profits | | |
|---|---|---|
| **Revenue** | $(60 \times \$75) + (70 \times \$72) + (80 \times \$45) + (100 \times \$38)$ | $= \$16{,}940$ |
| **Materials** | $(60 \times \$10) + (70 \times \$5) + (80 \times \$5) + (100 \times \$10)$ | $= -\$2{,}350$ |
| **Labor** | (5 workers) × (8 hours/day) × (5 days/week) × (18/hour) | $= -\$3{,}600$ |
| **Overhead** | | $= -\$8{,}500$ |
| **Profit** | | $= \$2{,}490$ |

Manufacturing the product mix of 60 A, 70 B, 80 C, and 100 D will yield a profit of **$2,490** per week.

**DECISION POINT**

By focusing on the bottleneck resources in accepting customer orders and determining the product mix, the sequence in which products are selected for production is reversed from **B, A, C, D** to **D, C, A, B**. Consequently, the product mix is changed from 60 A, 80 B, 40 C, and 100 D to 60 A, 70 B, 80 C, and 100 D. The increase in profits by using the bottleneck method is **$930,** ($2,490 − $1,560), or almost 60 percent over the traditional approach.

setup times. Otherwise, they must be taken into consideration for not only identifying the bottleneck but also in determining the product mix. The experiential learning exercise of Min-Yo Garment Company at the end of this chapter provides an interesting illustration of how the product mix can be determined when setup times are significant. In this way, the principles behind the TOC can be exploited for making better decisions about a firm's most profitable product mix.

# Managing Constraints in Line Processes

As noted in Chapter 2, "Process Strategy and Analysis," products created by a line process include the assembly of computers, automobiles, appliances, and toys. Such assembly lines can exist in providing services as well. For instance, putting together a standardized hamburger with a fixed sequence of steps is akin to operating an assembly line. In this section, we explain in greater detail how constraints can be managed for line processes.

## Line Balancing

**Line balancing** is the assignment of work to stations in a line process so as to achieve the desired output rate with the smallest number of workstations. Normally, one worker is assigned to a station. Thus, the line that produces at the desired pace with the fewest workers is the most efficient one. Achieving this goal is much like the TOC, because both approaches are concerned about bottlenecks. Line balancing differs in how it addresses bottlenecks. Rather than (1) taking on new customer orders to best use bottleneck capacity or (2) scheduling so that bottleneck resources are conserved, line balancing takes a third approach. It (3) creates workstations with workloads as evenly balanced as possible. It seeks to create workstations so that the capacity utilization for the bottleneck is not much higher than for the other workstations in the line. Another difference is that line balancing applies only to line processes that do assembly work, or to work that can be bundled in many ways to create the jobs for each workstation in the line. The latter situation can be found both in manufacturing and service settings.

**line balancing**
The assignment of work to stations in a line process so as to achieve the desired output rate with the smallest number of workstations.

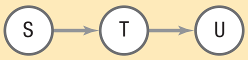
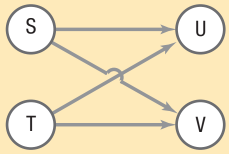
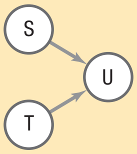
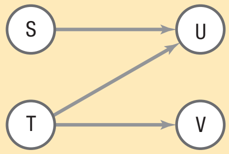
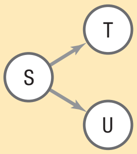
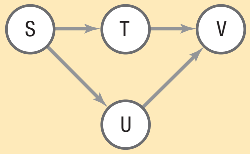
The goal of line balancing is to obtain workstations with well-balanced workloads (e.g., every station takes roughly 3 minutes per customer in a cafeteria line with different food stations). The analyst begins by separating the work into **work elements**, which are the smallest units of work that can be performed independently. The analyst then obtains the time standard for each element and identifies the work elements, called **immediate predecessors**, which must be done before the next element can begin.

**work elements**
The smallest units of work that can be performed independently.

**immediate predecessors**
Work elements that must be done before the next element can begin.

**Precedence Diagram** Most lines must satisfy some technological precedence requirements; that is, certain work elements must be done before the next can begin. However, most lines also allow for some latitude and more than one sequence of operations. To help you better visualize immediate predecessors,

**FIGURE 5.4** ▶
Diagramming Activity Relationships

| AON | Activity Relationships | AON | Activity Relationships |
|---|---|---|---|
|   | S precedes T, which precedes U. |   | U and V cannot begin until both S and T have been completed. |
|   | S and T must be completed before U can be started. |   | U cannot begin until both S and T have been completed; V cannot begin until T has been completed. |
|   | T and U cannot begin until S has been completed. |   | T and U cannot begin until S has been completed and V cannot begin until both T and U have been completed. |

**precedence diagram**

A diagram that allows one to visualize immediate predecessors better; work elements are denoted by circles, with the time required to perform the work shown below each circle.

let us run through the construction of a **precedence diagram**. The diagramming approach we use in this text is referred to as the **activity-on-node (AON) network**, in which nodes represent activities and arcs represent the precedence relationships between them. More specifically, we denote the work elements by nodes or circles, with the time required to perform the work shown below each circle. Arrows or arcs lead from immediate predecessors to the next work element. Some diagramming conventions must be used for AON networks. In cases of multiple activities with no predecessors, it is usual to show them emanating from a common node called *start*. For multiple activities with no successors, it is usual to show them connected to a node called *finish*. Figure 5.4 shows how to diagram several commonly encountered activity relationships.

Example 5.4 illustrates a manufacturing process, but a back office line-flow process in a service setting can be approached similarly.

## EXAMPLE 5.4 Constructing a Precedence Diagram

Green Grass, Inc., a manufacturer of lawn and garden equipment, is designing an assembly line to produce a new fertilizer spreader, the Big Broadcaster. Using the following information on the production process, construct a precedence diagram for the Big Broadcaster.

| Work Element | Description | Time (sec) | Immediate Predecessor(s) |
|---|---|---|---|
| A | Bolt leg frame to hopper | 40 | None |
| B | Insert impeller shaft | 30 | A |
| C | Attach axle | 50 | A |
| D | Attach agitator | 40 | B |
| E | Attach drive wheel | 6 | B |
| F | Attach free wheel | 25 | C |
| G | Mount lower post | 15 | C |
| H | Attach controls | 20 | D, E |
| I | Mount nameplate | 18 | F, G |
| | | Total 244 | |

**SOLUTION**

Figure 5.5 shows the complete diagram. We begin with work element A, which has no immediate predecessors. Next, we add elements B and C, for which element A is the only immediate predecessor. After entering time standards and arrows showing precedence, we add elements D and E, and so on. The diagram simplifies interpretation. Work element F, for example, can be done anywhere on the line after element C is completed. However, element I must await completion of elements F and G.

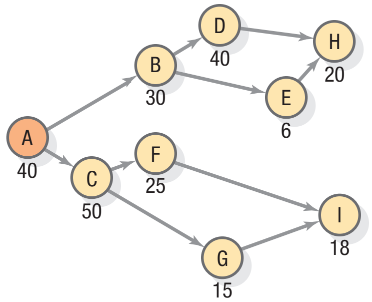



**FIGURE 5.5** Precedence Diagram for Assembling the Big Broadcaster

MyOMLab Animation

**DECISION POINT**

Management now has enough information to develop a line-flow layout that clusters work elements to form workstations, with a goal being to balance the workloads and, in the process, minimize the number of workstations required.

**Desired Output Rate** The goal of line balancing is to match the output rate to the staffing or production plan. For example, if the plan calls for 4,800 units or customers per week and the line operates 80 hours per week, the desired output rate ideally would be 60 units or customers (4,800/80) per hour. Matching output to the plan ensures on-time delivery and prevents buildup of unwanted inventory or customer delays. However, managers should avoid rebalancing a line too frequently because each time a line is rebalanced many workers' jobs on the line must be redesigned, temporarily hurting productivity and sometimes even requiring a new detailed layout for some stations.

**activity-on-node (AON) network**

An approach used to create a network diagram, in which nodes represent activities and arcs represent the precedence relationships between them.

**Cycle Time** After determining the desired output rate for a line, the analyst can calculate the line's cycle time. A line's **cycle time** is the maximum time allowed for work on a unit at each station.[2] If the time required for work elements at a station exceeds the line's cycle time, the station will be a bottleneck, preventing the line from reaching its desired output rate. The target cycle time is the reciprocal of the desired hourly output rate:

**cycle time**

The maximum time allowed for work on a unit at each station.

$$c = \frac{1}{r}$$

where

$c$ = cycle time in hours per unit

$r$ = desired output rate in units per hour

For example, if the line's desired output rate is 60 units per hour, the cycle time is $c = 1/60$ hour per unit, or 1 minute.

**Theoretical Minimum** To achieve the desired output rate, managers use line balancing to assign every work element to a station, making sure to satisfy all precedence requirements and to minimize the number of stations, $n$, formed. If each station is operated by a different worker, minimizing $n$ also maximizes worker productivity. Perfect balance is achieved when the sum of the work-element times at each station equals the cycle time, $c$, and no station has any idle time. For example, if the sum of each station's work-element times is 1 minute, which is also the cycle time, the line achieves perfect balance. Although perfect balance usually is unachievable in practice, owing to the unevenness of work-element times and the inflexibility of precedence requirements, it sets a benchmark, or goal, for the smallest number of stations possible. The **theoretical minimum (TM)** for the number of stations is

**theoretical minimum (TM)**

A benchmark or goal for the smallest number of stations possible, where the total time required to assemble each unit (the sum of all work-element standard times) is divided by the cycle time.

$$\text{TM} = \frac{\Sigma t}{c}$$

where

$\Sigma t$ = total time required to assemble each unit (the sum of all work-element standard times)

$c$ = cycle time

For example, if the sum of the work-element times is 15 minutes and the cycle time is 1 minute, TM = 15/1, or 15 stations. Any fractional values obtained for TM are rounded up because fractional stations are impossible.

[2]Except in the context of line balancing, *cycle time* has a different meaning. It is the elapsed time between starting and completing a job. Some researchers and practitioners prefer the term *lead time* in these non-line balancing applications.

**Idle Time, Efficiency, and Balance Delay** Minimizing $n$ automatically ensures (1) minimal idle time, (2) maximal efficiency, and (3) minimal balance delay. Idle time is the total unproductive time for all stations in the assembly of each unit:

$$\text{Idle time} = nc - \Sigma t$$

where

$$n = \text{number of stations}$$
$$c = \text{cycle time}$$
$$\Sigma t = \text{total standard time required to assemble each unit}$$

Efficiency is the ratio of productive time to total time, expressed as a percent:

$$\text{Efficiency (\%)} = \frac{\Sigma t}{nc}(100)$$

**balance delay**
The amount by which efficiency falls short of 100 percent.

**Balance delay** is the amount by which efficiency falls short of 100 percent:

$$\text{Balance delay (\%)} = 100 - \text{Efficiency}$$

As long as $c$ is fixed, we can optimize all three goals by minimizing $n$.

## EXAMPLE 5.5 Calculating the Cycle Time, Theoretical Minimum, and Efficiency

MyOMLab
Tutor 5.1 in MyOMLab provides another example to calculate these line-balancing measures.

Green Grass's plant manager just received marketing's latest forecasts of Big Broadcaster sales for the next year. She wants its production line to be designed to make 2,400 spreaders per week for at least the next three months. The plant will operate 40 hours per week.

**a.** What should be the line's cycle time?

**b.** What is the smallest number of workstations that she could hope for in designing the line for this cycle time?

**c.** Suppose that she finds a solution that requires only five stations. What would be the line's efficiency?

### SOLUTION

**a.** First, convert the desired output rate (2,400 units per week) to an hourly rate by dividing the weekly output rate by 40 hours per week to get $r = 60$ units per hour. Then, the cycle time is

$$c = 1/r = 1/60 \text{ (hour/unit)} = 1 \text{ minute/unit} = \mathbf{60} \text{ seconds/unit}$$

**b.** Now, calculate the theoretical minimum for the number of stations by dividing the total time, $\Sigma t$, by the cycle time, $c = 60$ seconds. Assuming perfect balance, we have

$$\text{TM} = \frac{\Sigma t}{c} = \frac{244 \text{ seconds}}{60 \text{ seconds}} = 4.067 \text{ or } \mathbf{5} \text{ stations}$$

**c.** Now, calculate the efficiency of a five-station solution, assuming for now that one can be found:

$$\text{Efficiency (\%)} = \frac{\Sigma t}{nc}(100) = \frac{244}{5(60)}(100) = \mathbf{81.3}\%$$

### DECISION POINT

If the manager finds a solution with five stations that satisfies all precedence constraints, then that is the optimal solution; it has the minimum number of stations possible. However, the efficiency (sometimes called the *theoretical maximum efficiency*) will be only 81.3 percent. Perhaps the line should be operated less than 40 hours per week (thereby adjusting the cycle time) and the employees transferred to other kinds of work when the line does not operate.

**Finding a Solution** Often, many assembly-line solutions are possible, even for such simple problems as Green Grass's. The goal is to cluster the work elements into workstations so that (1) the number of workstations required is minimized, and (2) the precedence and cycle-time requirements are not violated. The idea is to assign work elements to workstations subject to the precedence requirements so that the work content for the station is equal (or nearly so, but less than) the cycle time for the line. In this way, the number of workstations will be minimized.

Here we use the trial-and-error method to find a solution, although commercial software packages are also available. Most of these packages use different decision rules in picking which work element to assign next to a workstation being created. The ones used by POM for Windows are described in Table 5.3. The solutions can be examined for improvement, because there is no guarantee that they are optimal or even feasible. Some work elements cannot be assigned to the same station, some changes can be made to reduce the number of stations, or some shifts can provide better balance between stations.

**TABLE 5.3** HEURISTIC DECISION RULES IN ASSIGNING THE NEXT WORK ELEMENT TO A WORKSTATION BEING CREATED

**Create one station at a time. For the station now being created, identify the unassigned work elements that qualify for assignment: They are candidates if**

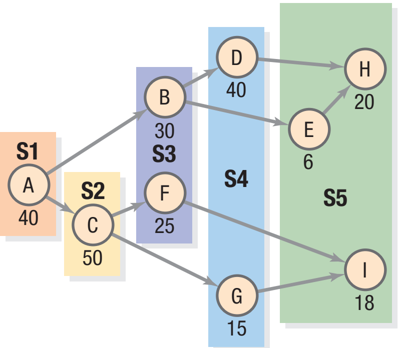
**1. All of their predecessors have been assigned to this station or stations already created.**

**2. Adding them to the workstation being created will not create a workload that exceeds the cycle time.**

| Decision Rule | Logic |
|---|---|
| *Longest work element* | Picking the candidate with the longest time to complete is an effort to fit in the most difficult elements first, leaving the ones with short times to “fill out” the station. |
| *Shortest work element* | This rule is the opposite of the longest work element rule because it gives preference in workstation assignments to those work elements that are quicker. It can be tried because no single rule guarantees the best solution. It might provide another solution for the planner to consider. |
| *Most followers* | When picking the next work element to assign to a station being created, choose the element that has the most *followers* (due to precedence requirements). In Figure 5.5, item C has three followers (F, G, and I) whereas item D has only one follower (H). This rule seeks to maintain flexibility so that good choices remain for creating the last few workstations at the end of the line. |
| *Fewest followers* | Picking the candidate with the fewest followers is the opposite of the most followers rule. |

Figure 5.6 shows a solution that creates just five workstations. We know that five is the minimum possible, because five is the theoretical minimum found in Example 5.5 All of the precedence and cycle-time requirements are also satisfied. Consequently, the solution is optimal for this problem. Each worker at each station must perform the work elements in the proper sequence. For example, workstation **S5** consists of one worker who will perform work elements E, H, and I on each unit that comes along the assembly line. The processing time per unit is 44 seconds (6 + 20 + 18) which does not exceed the cycle time of 60 seconds (see Example 5.5). Furthermore, the immediate predecessors of these three work elements are assigned to this workstation or upstream workstations, so their precedence requirements are satisfied. The worker at workstation S5 can do element I at any time but will not start element H until element E is finished.

**FIGURE 5.6**
Big Broadcaster Precedence Diagram Solution




## Rebalancing the Assembly Line

While the product mix or demand volumes do not change as rapidly for line processes as for job or batch processes, the load can shift between work centers in a line as the end product being assembled is changed from one product to another, or when the total output rate of the line is altered. Constraints arising out of such actions can be managed by either rebalancing the line, or as illustrated by Chrysler in Managerial Practice 5.1, by shifting workers across different lines in the manufacturing plant to reduce waste and create a more balanced allocation of workloads and available worker capacity.

## Managerial Considerations

In addition to balancing a line for a given cycle time, managers have four other considerations: (1) pacing, (2) behavioral factors, (3) number of models produced, and (4) different cycle times.

## MANAGERIAL PRACTICE 5.1 Assembly Line Balancing at Chrysler

**Headquartered** in Auburn Hills, Michigan, Chrysler Corporation was founded in 1925 and is currently owned by the Italian automaker Fiat since January 21, 2014. It is the smallest of the "Big Three" automobile manufacturers in the United States, and had sales of over 1.8 million vehicles in 2013. Especially well known for its industry leading pioneering designs of minivans, Chrysler was interested in reducing costs and improving efficiency through a better balancing of its assembly lines in the trim, chassis, and final (TCF) center. Such was the case at one of its manufacturing plants in Windsor, Ontario, which builds the popular minivan models Chrysler Town & Country and Dodge Grand Caravan among others. Instead of actually stopping the lines and experimenting with new ideas, the improvement team felt that it would be best to build simulation models that can identify system bottlenecks and evaluate the impact of line design and scheduling decisions associated with different cycle times, mean time to repair, and mean time between failures.

Using a commercially available Simul8 software, the simulation models included data on how many operators were available for each line, sequence and mix of products, cycle times for different delivery rates, and size of line buffers. After validating the model with historical data, the best performing as well as the worst performing bottlenecked lines were identified based on the process flow layouts of the system. Using different scenarios, it was determined that slowing down the best performing lines would not adversely affect the system throughput, which in turn would allow some workers to be transferred away to eliminate waste. Steve Lin, the throughput specialist at Chrysler leading the project, commented, "We reduced two people a shift on one line. So, with three shifts a day we effectively reduced manpower costs by six on that line, saving us $600,000 per year." This idea of using the simulation tool for slowing down the best performing lines to improve efficiency has now been rolled out to eight other Chrysler assembly plants, with cumulative savings projected to be around $5 million.

Understanding the impact of bottlenecks, cycle times, repair times, and product mix on the efficiency and throughputs of assembly lines can really pay off in managing line processes.

Rebecca Cook/Reuters/Corbis

A Chrysler auto worker uses an ergo-arm to load the seats into Chrysler minivans during the production launch of the new 2011 Dodge Grand Caravan's and Chrysler Town & Country minivans at the Windsor Assembly Plant in Windsor, Ontario.

*Source:* **http://en.wikipedia.org/wiki/Chrysler; http://en.wikipedia.org/wiki/Windsor_Assembly; http://www.simul8.com/our_customers/case_studies/Chrysler_line_balancing_case_study.pdf** (July 29, 2014).

**pacing**

The movement of product from one station to the next as soon as the cycle time has elapsed.

**Pacing** The movement of product from one station to the next as soon as the cycle time has elapsed is called **pacing**. Pacing manufacturing processes allows materials handling to be automated and requires less inventory storage area. However, it is less flexible in handling unexpected delays that require either slowing down the entire line or pulling the unfinished work off the line to be completed later.

**Behavioral Factors** The most controversial aspect of line-flow layouts is behavioral response. Studies show that installing production lines increases absenteeism, turnover, and grievances. Paced production and high specialization (say, cycle times of less than 2 minutes) lower job satisfaction. Workers generally favor inventory buffers as a means of avoiding mechanical pacing. One study even showed that productivity increased on unpaced lines.

**mixed-model line**

A production line that produces several items belonging to the same family.

**Number of Models Produced** A line that produces several items belonging to the same family is called a **mixed-model line**. In contrast, a single-model line produces one model with no variations. Mixed-model production enables a plant to achieve both high-volume production *and* product variety. However, it complicates scheduling and increases the need for good communication about the specific parts to be produced at each station.

**Cycle Times** A line's cycle time depends on the desired output rate (or sometimes on the maximum number of workstations allowed). In turn, the maximum line efficiency varies considerably with the cycle time selected. Thus, exploring a range of cycle times makes sense. A manager might go with a particularly efficient solution even if it does not match the desired output rate. The manager can compensate for the mismatch by varying the number of hours the line operates through overtime, extending shifts, or adding shifts. Multiple lines might even be the answer.

## LEARNING GOALS IN REVIEW

| Learning Goal | Guidelines for Review | MyOMLab Resources |
|---|---|---|
| 1 Explain the theory of constraints. | The section on "The Theory of Constraints (TOC)," pp. 199–201 explains that constraints or bottlenecks can exist in the form of internal resources or market demand in both manufacturing and service organizations, and in turn play an important role in determining system performance. Review opening vignette on BP Oil Spill cleanup for an application of TOC, and Table 5.2 for its key principles. | **Video:** Constraint Management at Southwest Airlines |
| 2 Identify and manage bottlenecks in service processes | The section "Managing Bottlenecks in Service Processes," pp. 201–202, shows you how to identify bottlenecks in manufacturing firms. Review Solved Problem 1 on p. 213 for an illustration of this approach. | |
| 3 Identify and manage bottlenecks in manufacturing processes | The section "Managing Bottlenecks in Manufacturing Processes," pp. 202–205, shows you how to identify and relieve bottlenecks in manufacturing firms, and links them to a planning and control system known as drum-buffer-rope on p. 204. | |
| 4 Applying the theory of constraints to product mix decisions. | The section "Applying Theory of Constraints to Product Mix Decisions," pp. 205–207, to understand how using a bottleneck based method for allocating resources and determining the product mix leads to greater profits. The experiential learning exercise Min-Yo Garment Company on p. 222 illustrates how product mix can be determined when set up times are significant. | **OM Explorer Solver:** Min-Yo Garment Company spreadsheet |
| 5 Describe how to manage constraints in line processes and balance assembly lines. | The section "Managing Constraints in Line Processes," pp. 207–212, shows you how to balance assembly lines and create workstations. It also positions assembly line balancing is a special form of a constraint in managing a line process within both manufacturing and services, and can also be an effective mechanism for matching output to a plan and running such processes more efficiently. Review Solved Problem 2 on p. 214 for an application of line-balancing principles. | **OM Explorer Tutor:** 5.1: Calculate Line-Balancing Measures<br>**POM for Windows**: Line Balancing |

# Key Equations

## Managing Constraints in Line Processes

1. Cycle time: $c = \dfrac{1}{r}$

2. Theoretical minimum number of workstations: $\text{TM} = \dfrac{\Sigma t}{c}$

3. Idle time: $nc - \Sigma t$

4. Efficiency(%): $\dfrac{\Sigma t}{nc}(100)$

5. Balance delay (%): $100 - \text{Efficiency}$

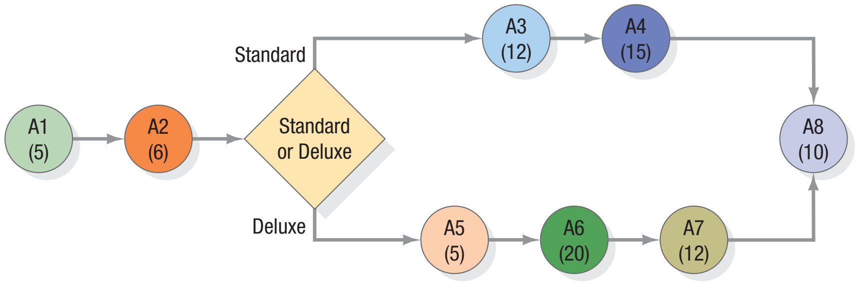
# Key Terms

activity-on-node (AON) network 209
balance delay 210
bottleneck 198
constraint 198
cycle time 209
drum-buffer-rope (DBR) 204
immediate predecessors 207
line balancing 207
mixed-model line 212
pacing 212
precedence diagram 208
theoretical minimum (TM) 209
theory of constraints (TOC) 199
throughput time 201
work elements 207

# Solved Problem 1

Bill's Car Wash offers two types of washes: Standard and Deluxe. The process flow for both types of customers is shown in Figure 5.7. Both wash types are first processed through Steps A1 and A2. The Standard wash then goes through Steps A3 and A4 while the Deluxe is processed through Steps A5, A6, and A7. Both offerings finish at the drying station (A8). The numbers in parentheses indicate the minutes it takes for that activity to process a customer.

**FIGURE 5.7 ▶**
Precedence Diagram




**a.** Which step is the bottleneck for the Standard car wash process? For the Deluxe car wash process?

**b.** What is the capacity (measured as customers served per hour) of Bill's Car Wash to process Standard and Deluxe customers? Assume that no customers are waiting at Step A1, A2, or A8.

**c.** If 60 percent of the customers are Standard and 40 percent are Deluxe, what is the average capacity of the car wash in customers per hour?

**d.** Where would you expect Standard wash customers to experience waiting lines, assuming that new customers are always entering the shop and that no Deluxe customers are in the shop? Where would the Deluxe customers have to wait, assuming no Standard customers?

**SOLUTION**

**a.** Step A4 is the bottleneck for the Standard car wash process, and Step A6 is the bottleneck for the Deluxe car wash process, because these steps take the longest time in the flow.

**b.** The capacity for Standard washes is four customers per hour because the bottleneck Step A4 can process one customer every 15 minutes (60/15). The capacity for Deluxe car washes is three customers per hour (60/20). These capacities are derived by translating the "minutes per customer" of each bottleneck activity to "customers per hour."

**c.** The average capacity of the car wash is $(0.60 \times 4) + (0.40 \times 3) =$ **3.6** customers per hour.

**d.** Standard wash customers would wait before Steps A1, A2, A3, and A4 because the activities that immediately precede them have a higher rate of output (i.e., smaller processing times). Deluxe wash customers would experience a wait in front of Steps A1, A2, and A6 for the same reasons. A1 is included for both types of washes because the arrival rate of customers could always exceed the capacity of A1.

# Solved Problem 2

MyOMLab Video

A company is setting up an assembly line to produce 192 units per 8-hour shift. The following table identifies the work elements, times, and immediate predecessors:

| Work Element | Time (Sec) | Immediate Predecessor(s) |
|---|---|---|
| A | 40 | None |
| B | 80 | A |
| C | 30 | D, E, F |
| D | 25 | B |
| E | 20 | B |
| F | 15 | B |
| G | 120 | A |
| H | 145 | G |
| I | 130 | H |
| J | 115 | C, I |
| | Total 720 | |

**a.** What is the desired cycle time (in seconds)?
**b.** What is the theoretical minimum number of stations?
**c.** Use trial and error to work out a solution, and show your solution on a precedence diagram.
**d.** What are the efficiency and balance delay of the solution found?

### SOLUTION

**a.** Substituting in the cycle-time formula, we get

$$c = \frac{1}{r} = \frac{8 \text{ hours}}{192 \text{ units}}(3{,}600 \text{ seconds / hour}) = \mathbf{150} \text{ seconds / unit}$$

**b.** The sum of the work-element times is 720 seconds, so

$$\text{TM} = \frac{\Sigma t}{c} = \frac{720 \text{ seconds / unit}}{150 \text{ seconds / unit-station}} = 4.8 \text{ or } \mathbf{5} \text{ stations}$$

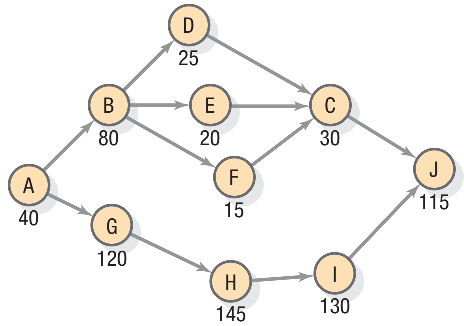
which may not be achievable.

**c.** The precedence diagram is shown in Figure 5.8. Each row in the following table shows work elements assigned to each of the five workstations in the proposed solution.

**d.** Calculating the efficiency, we get

$$\text{Efficiency} = \frac{\Sigma t}{nc}(100) = \frac{720 \text{ seconds / unit}}{5[150 \text{ seconds / unit}]}(100) = \mathbf{96\%}$$

Thus, the balance delay is only 4 percent (100–96).




▲ **FIGURE 5.8**
Precedence Diagram

| Station | Candidate(s) | Choice | Work-Element Time (Sec) | Cumulative Time (Sec) | Idle Time ($c = 150$ Sec) |
|---|---|---|---|---|---|
| S1 | A | A | 40 | 40 | 110 |
| | B | B | 80 | 120 | 30 |
| | D, E, F | D | 25 | 145 | 5 |
| S2 | E, F, G | G | 120 | 120 | 30 |
| | E, F | E | 20 | 140 | 10 |
| S3 | F, H | H | 145 | 145 | 5 |
| S4 | F, I | I | 130 | 130 | 20 |
| | F | F | 15 | 145 | 5 |
| S5 | C | C | 30 | 30 | 120 |
| | J | J | 115 | 145 | 5 |

# Discussion Questions

1. Take a process that you encounter on a daily basis, such as the lunch cafeteria or the journey from your home to school or work, and identify the bottlenecks that limit the throughput of this process.
2. Using the same process as in question 1, identify conditions that would lead to the bottlenecks changing or shifting away from the existing bottleneck.
3. How could the efficiency of the redesigned process be improved further?

# Problems

The OM Explorer and POM for Windows software is available to all students using the 11th edition of this textbook. Go to **http://www.pearsonglobaleditions.com/krajewski** to download these computer packages. If you purchased MyOMLab, you also have access to Active Models software and significant help in doing the following problems. Check with your instructor on how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decision, the software entirely replaces the manual calculations.

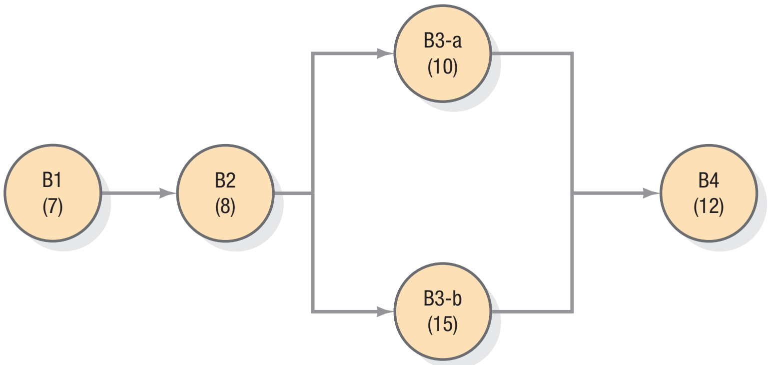
## Managing Bottlenecks in Service Processes

**1.** Bill's Barbershop has two barbers available to cut customers' hair. Both barbers provide roughly the same experience and skill, but one is just a little bit slower than the other. The process flow in Figure 5.9 shows that all customers go through steps B1 and B2 and then can be served at either of the two barbers at step B3. The process ends for all customers at step B4. The numbers in parentheses indicate the minutes it takes that activity to process a customer.

**a.** How long does it take the average customer to complete this process?

**b.** What single activity is the bottleneck for the entire process?

**c.** How many customers can this process serve in an hour?



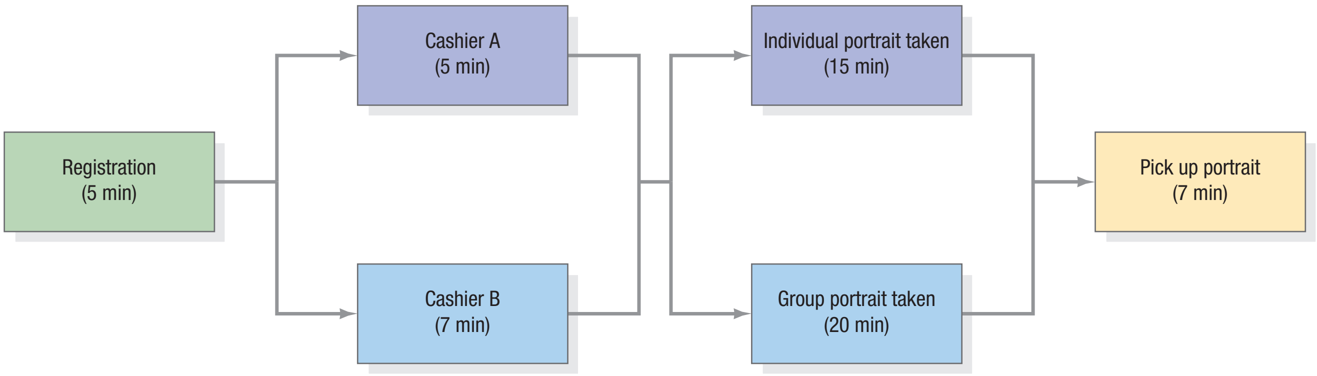

▲ **FIGURE 5.9**
Process Flow for Bill's Barbershop

**2.** Melissa's Photo Studio offers both individual and group portrait options. The process flow diagram in Figure 5.10 shows that all customers must first register and then pay at one of two cashiers. Then, depending on whether they want a single or group portrait they go to different rooms. Finally, everyone picks up their own finished portrait.

**a.** How long does it take to complete the entire process for a group portrait?

**b.** What single activity is the bottleneck for the entire process, assuming the process receives equal amounts of both groups and individuals?

**c.** What is the capacity of the bottleneck for both groups and individuals?



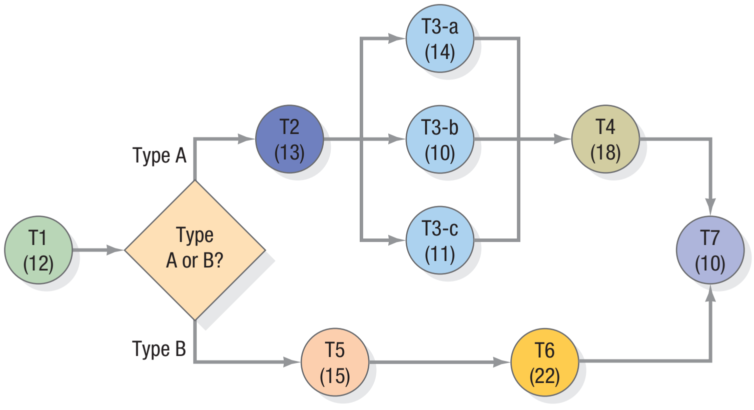

▲ **FIGURE 5.10**
Process Flow for Melissa's Photo Studio

**3.** Figure 5.11 details the process flow for two types of customers who enter Barbara's Boutique shop for customized dress alterations. After Step T1, Type A customers proceed to Step T2 and then to any of the three workstations at T3, followed by Steps T4 and T7. After Step T1, Type B customers proceed to Step T5 and then Steps T6 and T7. The numbers in parentheses are the minutes it takes to process a customer.

**a.** What is the capacity of Barbara's shop in terms of the numbers of Type A customers who can be served in an hour? Assume no customers are waiting at Steps T1 or T7.

**b.** If 30 percent of the customers are Type A customers and 70 percent are Type B customers, what is the average capacity of Barbara's shop in customers per hour?

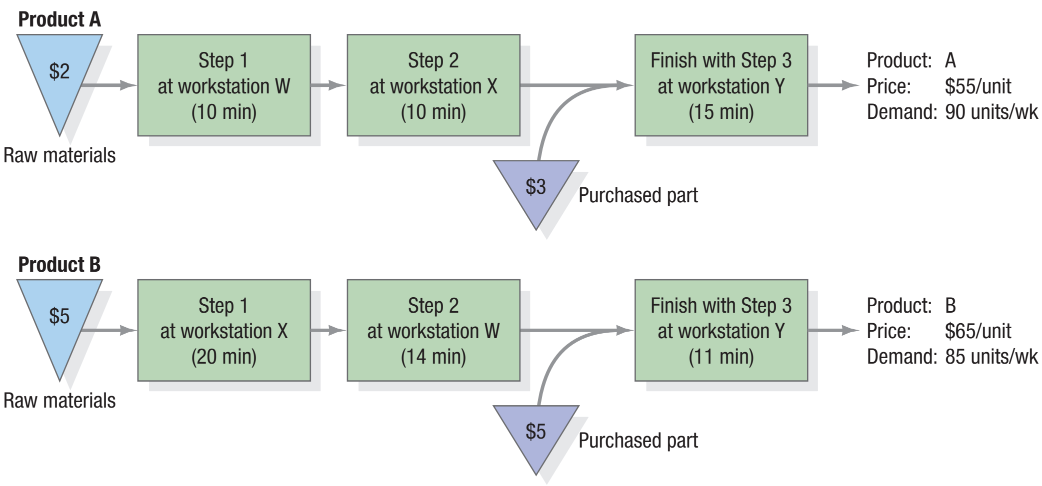
**c.** Assuming that the arrival rate is greater than five customers per hour, when would you expect Type A customers to experience waiting lines, assuming no Type B customers in the shop? Where would the Type B customers have to wait, assuming no Type A customers?




▲ **FIGURE 5.11**
Process Flow for Barbara's Boutique Customers

## Managing Bottlenecks in Manufacturing Processes

**4.** Canine Kernels Company (CKC) manufactures two different types of dog chew toys (A and B, sold in 1,000-count boxes) that are manufactured and assembled on three different workstations (W, X, and Y) using a small-batch process (see Figure 5.12). Batch setup times are negligible. The flowchart denotes the path each product follows through the manufacturing process, and each product's price, demand per week, and processing times per unit are indicated as well. Purchased parts and raw materials consumed during production are represented by inverted triangles. CKC can make and sell up to the limit of its demand per week; no penalties are incurred for not being able to meet all the demand. Each workstation is staffed by a worker who is dedicated to work on that workstation alone, and is paid \$6 per hour. Total labor costs per week are fixed. Variable overhead costs are \$3,500/week. The plant operates one 8-hour shift per day, or 40 hours/week. Which of the three workstations, W, X, or Y, has the highest aggregate workload, and thus serves as the bottleneck for CKC?




▲ **FIGURE 5.12**
Flowchart for Canine Kernels Company (CKC)

**5.** Super Fun Industries manufactures four top-selling toys code named A-148, B-356, B-457, and C-843. The following table shows how long it takes to process each toy through each required station. Note that all times are in minutes. Super Fun's manufacturing plant is open 16 hours a day, 5 days a week, and 8 hours on Saturday.

| | A-148 | B-356 | B-457 | C-843 |
|---|---|---|---|---|
| Processing Time Station 1 | 6 min | 5 min | 0 min | 8 min |
| Processing Time Station 2 | 4 min | 4 min | 5 min | 2 min |
| Processing Time Station 3 | 5 min | 7 min | 4 min | 2 min |
| Processing Time Station 4 | 3 min | 0 min | 10 min | 1 min |

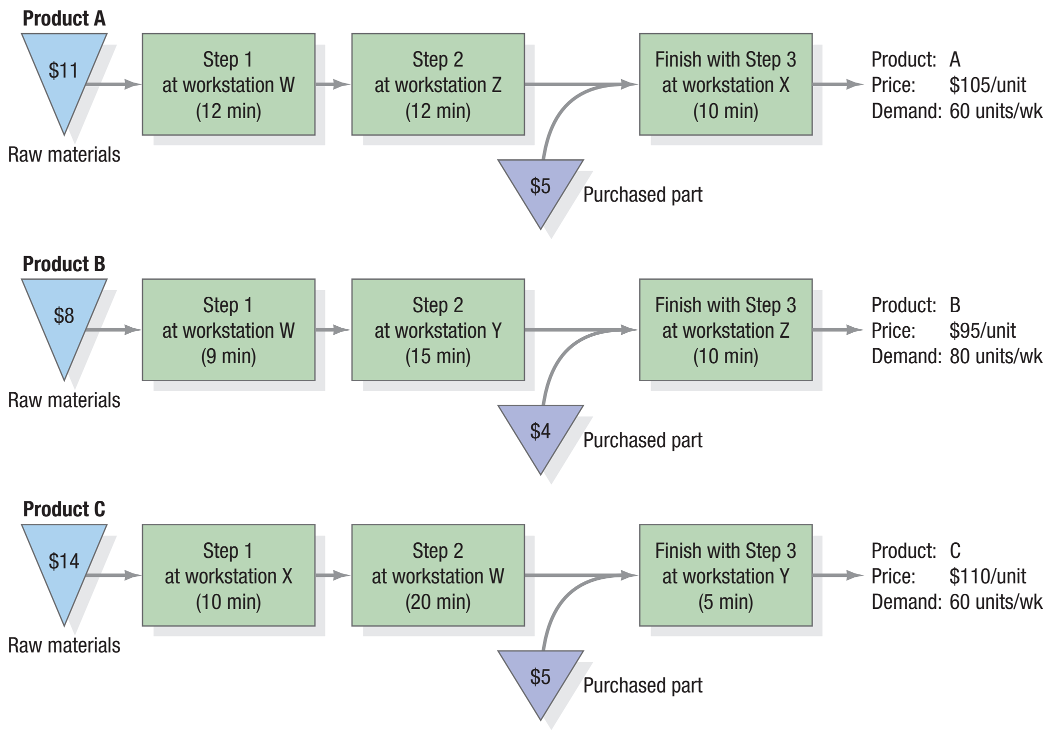
a. If only toy A-148 is produced during a specific week, how many units could be produced?

b. If weekly demand for the four products are A-148 = 200 units, B-356 = 250 units, B-457 = 250 units, and C-843 = 300 units, which station is the bottleneck, and is it capable of producing all the toys demanded?

6. Returning to problem 5, if weekly demand for the four products are A-148 = 100 units, *B*-356 = 400 units, *B*-457 = 250 units, and C-843 = 100 units, which station is the bottleneck now, and is it capable of producing all the toys demanded? If so, how many additional units of C-843 could be produced? Under this condition, does the bottleneck change?

7. Yost-Perry Industries (YPI) manufactures a mix of affordable guitars (A, B, C) that are fabricated and assembled at four different processing stations (W, X, Y, Z). The operation is a batch process with small setup times that can be considered negligible. The product information (price, weekly demand, and processing times) and process sequences are shown in Figure 5.13. Raw materials and purchased parts (shown as a per-unit consumption rate) are represented by inverted triangles. YPI is able to make and sell up to the limit of its demand per week with no penalties incurred for not meeting the full demand. Each workstation is staffed by one highly skilled worker who is dedicated to work on that workstation alone and is paid $15 per hour. The plant operates one 8-hour shift per day and operates on a 5-day work week (i.e., 40 hours of production per person per week). Overhead costs are $9,000/week. Which of the four workstations, W, X, Y, or Z, has the highest aggregate workload, and thus serves as the bottleneck for YPI?

**FIGURE 5.13 ▶**
Flowchart for Yost-Perry Industries (YPI)




## Applying the Theory of Constraints to Product Mix Decisions

8. The senior management at Canine Kernels Company (CKC) mentioned in problem 4 is concerned with the existing capacity limitation, so they want to accept the mix of orders that maximizes the company's profits. Traditionally, CKC has utilized a method whereby decisions are made to produce as much of the product with the highest contribution margin as possible (up to the limit of its demand), followed by the next highest contribution margin product, and so on until no more capacity is available. Because capacity is limited, choosing the proper product mix is crucial. Troy Hendrix, the newly hired production supervisor, is an avid follower of the TOC philosophy and the bottleneck method for scheduling. He believes that profitability can indeed be approved if bottleneck resources are exploited to determine the product mix.

a. What is the profit if the traditional contribution margin method is used for determining CKC's product mix?

b. What is the profit if the bottleneck method advocated by Troy is used for selecting the product mix?

c. Calculate the profit gain, both in absolute dollars as well as in terms of percentage gains, by using TOC principles for determining product mix.

9. Yost-Perry Industries' (YPI) senior management team wants to improve the profitability of the firm by accepting the right set of orders. Currently, decisions are made using the traditional method, which is to accept as much of the highest contribution margin product as possible (up to the limit of its demand), followed by the next highest contribution margin product, and so on until all available capacity is utilized. Because the firm cannot satisfy all the demand, the product mix must be chosen carefully. Jay Perry, the newly promoted production supervisor, is knowledgeable about the TOC and the bottleneck-based method for scheduling. He believes

that profitability can indeed be improved if bottleneck resources are exploited to determine the product mix. What is the change in profits if, instead of the traditional method that YPI has used thus far, the bottleneck method advocated by Jay is used for selecting the product mix?

**10.** A.J.'s Wildlife Emporium manufactures two unique birdfeeders (Deluxe and Super Duper) that are manufactured and assembled in up to three different workstations (X, Y, Z) using a small batch process. Each of the products is produced according to the flowchart in Figure 5.14. Additionally, the flowchart indicates each product's price, weekly demand, and processing times per unit. Batch setup times are negligible. A.J. can make and sell up to the limit of its weekly demand and there are no penalties for not being able to meet all of the demand. Each workstation is staffed by a worker who is dedicated to work on that workstation alone and is paid $16 per hour. The plant operates 40 hours per week, with no overtime. Overhead costs are $2,000 per week. Based on the information provided, as well as the information contained in the flowchart, answer the following questions.

**a.** Using the traditional method, which bases decisions solely on a product's contribution to profits and overhead, what is the optimal product mix and what is the overall profitability?

**b.** Using the bottleneck-based method, what is the optimal product mix and what is the overall profitability?

**11.** Cooper River Glass Works (CRGW) produces four different models of desk lamps as shown in Figure 5.15. The operations manager knows that total monthly demand exceeds the capacity available for production. Thus, she is interested in determining the product mix which will maximize profits. Each model's price, routing, processing times, and material cost are provided in Figure 5.15. Demand next month is estimated to be 200 units of model Alpha, 250 units of model Bravo, 150 units of model Charlie, and 225 units of model Delta. CRGW operates only one 8-hour shift per day and is scheduled to work 20 days next month (no overtime). Further, each station requires a 10 percent capacity cushion.

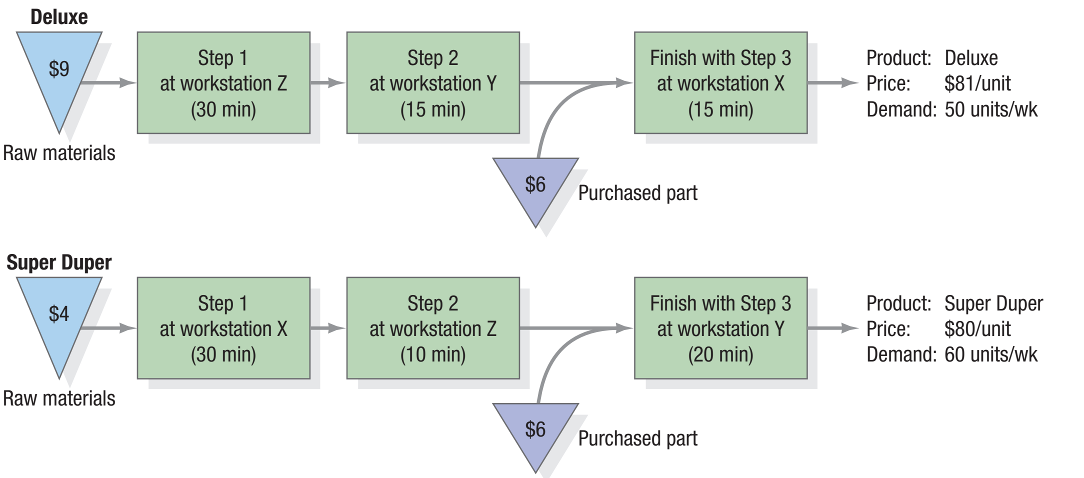



**FIGURE 5.14**
A.J.'s Wildlife Emporium Flowchart

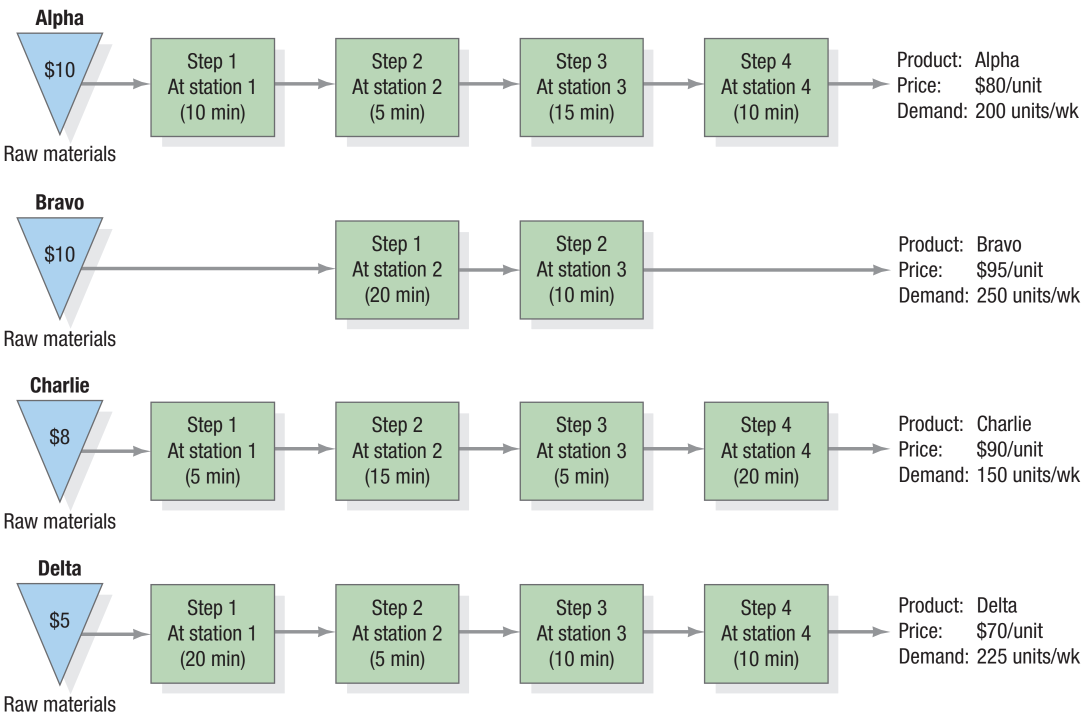



**FIGURE 5.15**
Cooper River Glass Works Flowchart

a. Which station is the bottleneck?

b. Using the traditional method, which bases decisions solely on a product's contribution to profits and overhead, what is the optimal product mix and what is the overall profitability?

c. Using the bottleneck-based method, what is the optimal product mix and what is the overall profitability?

12. The senior management at Davis Watercraft would like to determine if it is possible to improve firm profitability by changing their existing product mix. Currently, the product mix is determined by giving resource priority to the highest contribution margin watercraft. Davis Watercraft always has a contingent of 10 workers on hand; each worker is paid $25 per hour. Overhead costs are $35,000 per week. The plant operates 18 hours per day and 6 days per week. Labor is considered a fixed expense because workers are paid for their time regardless of their utilization. The production manager has determined that workstation 1 is the bottleneck. Detailed production information is provided below.

| | MODEL | | |
|---|---|---|---|
| | A | B | C |
| Price | $450 | $400 | $500 |
| Material Cost | $50 | $40 | $110 |
| Weekly Demand | 100 | 75 | 40 |
| Processing Time Station 1 | 60 min | 0 min | 30 min |
| Processing Time Station 2 | 0 min | 0 min | 60 min |
| Processing Time Station 3 | 10 min | 60 min | 0 min |
| Processing Time Station 4 | 20 min | 30 min | 40 min |

a. Using the traditional method, which bases decisions solely on a product's contribution to profits and overhead, what is the product mix that yields the highest total profit? What is the resulting profit?

b. Using the bottleneck-based method, what is the product mix that yields the highest total profit? What is the resulting profit?

## Managing Constraints in Line Processes

13. Quick Stop Pharmacy is a small family-owned drug compounding business in Portland Oregon that is trying to perfect its customer service operations. John Suleiman, the owner wants to maximize the productivity of his staff as well as serve customers well. One area of concern is the drive-thru operation during the 7:30–8:30 morning rush hour. The process of fulfilling an order is as follows:

| | Work Element | Time (Sec.) | Immediate Predecessor(s) |
|---|---|---|---|
| (A) | Greet patient and take prescription | 40 | — |
| (B) | Check patient information on system | 45 | A |
| (C) | Gather compounding materials | 55 | A |
| (D) | Perform compounding | 55 | C |
| (E) | Package and label | 65 | D |
| (F) | Instruct patient on use | 40 | B |
| (G) | Collect payment | 25 | B |

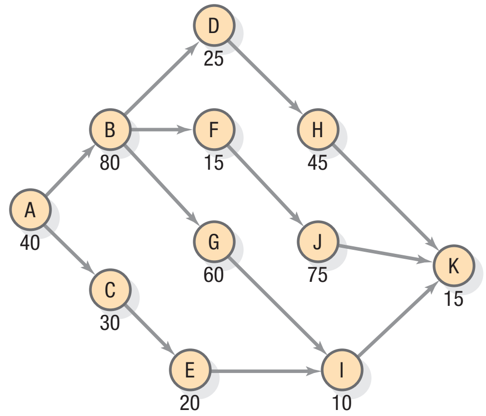
a. If all the steps are handled by one employee, how many patients could be served per hour?

b. If James wants to process 30 patients per hour, how many employees will he need?

c. How many stations are required using the longest work element decision rule?

d. Using the solution developed in part c, which station is the bottleneck and how large is its capacity cushion?

14. Use the longest work element rule to balance the assembly line described in the following table and Figure 5.16 so that it will produce 40 units per hour.




▲ FIGURE 5.16
Precedence Diagram

a. What is the cycle time?

b. What is the theoretical minimum number of workstations?

c. Which work elements are assigned to each workstation?

d. What are the resulting efficiency and balance delay percentages?

e. Use the shortest work element rule to balance the assembly line. Do you note any changes in solution?

| Work Element | Time (Sec) | Immediate Predecessor(s) |
|---|---|---|
| A | 40 | None |
| B | 80 | A |
| C | 30 | A |

| Work Element | Time (Sec) | Immediate Predecessor(s) |
|---|---|---|
| D | 25 | B |
| E | 20 | C |
| F | 15 | B |
| G | 60 | B |
| H | 45 | D |
| I | 10 | E, G |
| J | 75 | F |
| K | 15 | H, I, J |
| | Total 415 | |

**15.** Johnson Cogs wants to set up a line to serve 60 customers per hour. The work elements and their precedence relationships are shown in the following table.

**a.** What is the theoretical minimum number of stations?

**b.** How many stations are required using the longest work element decision rule?

**c.** Suppose that a solution requiring five stations is obtained. What is its efficiency?

| Work Element | Time (Sec) | Immediate Predecessor(s) |
|---|---|---|
| A | 21 | None |
| B | 20 | A |
| C | 30 | A |
| D | 20 | B |
| E | 4 | B |
| F | 15 | C |
| G | 10 | C |
| H | 8 | D, E |
| I | 12 | F, G |
| J | 20 | H, I |
| | Total 160 | |

**16.** The *trim line* at PW is a small subassembly line that, along with other such lines, feeds int1, o the final chassis line. The entire assembly line, which consists of more than 900 workstations, is to make PW's new E cars. The trim line itself involves only 13 work elements and must handle 20 cars per hour. Work-element data are as follows:

| Work Element | Time (Sec) | Immediate Predecessor(s) |
|---|---|---|
| A | 2.4 | None |
| B | 0.5 | None |
| C | 2.1 | None |
| D | 1.8 | C |
| E | 1.1 | B |
| F | 0.9 | A |
| G | 2 | A |
| H | 0.7 | F |
| I | 0.7 | D |
| J | 1.8 | H, E |
| K | 1.3 | J |
| L | 1.9 | G |
| M | 1.1 | L, I, K |

**a.** Draw a precedence diagram.

**b.** What cycle time (in minutes) results in the desired output rate?

**c.** What is the theoretical minimum number of stations?

**d.** Use the longest work element decision rule to balance the line and calculate the efficiency of your solution.

**e.** Use the most followers work element decision rule to balance the line and calculate the efficiency of your solution.

**17.** Refer back to problem 16. Suppose that in addition to the usual precedence constraints, there are two zoning constraints within the trim line. First, work elements K and L should be assigned to the same station; both use a common component, and assigning them to the same station conserves storage space. Second, work elements H and J cannot be performed at the same station.

**a.** Using trial and error, balance the line as best you can.

**b.** What is the efficiency of your solution?

**18.** To meet holiday demand, Penny's Pie Shop requires a production line that is capable of producing 50 pecan pies per week, while operating only 40 hours per week. There are only four steps required to produce a single pecan pie with respective processing times of 5 minutes, 5 minutes, 45 minutes, and 15 minutes.

**a.** What should be the line's cycle time?

**b.** What is the smallest number of workstations Penny could hope for in designing the line considering this cycle time?

**c.** Suppose that Penny finds a solution that requires only four stations. What would be the efficiency of this line?

**19.** A paced assembly line has been devised to manufacture calculators, as the following data show:

| Station | Work Element Assigned | Work Element Time (min) |
|---|---|---|
| S1 | A | 2.7 |
| S2 | D, E | 0.6, 0.9 |
| S3 | C | 3.0 |
| S4 | B, F, G | 0.7, 0.7, 0.9 |
| S5 | H, I, J | 0.7, 0.3, 1.2 |
| S6 | K | 2.4 |

a. What is the maximum hourly output rate from this line? (*Hint:* The line can go only as fast as its slowest workstation.)

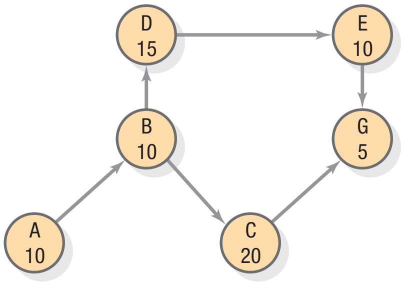
b. What cycle time corresponds to this maximum output rate?

c. If a worker is at each station and the line operates at this maximum output rate, how much idle time is lost during each 10-hour shift?

d. What is the line's efficiency?

**20.** Jane produces custom greeting cards using six distinct work elements. She would like to produce 10 cards in each 8-hour card-making session. Figure 5.17 details each work element and its associated durations in minutes as well as their precedence relationships.

**FIGURE 5.17** ▶
Precedence Diagram for Custom Greeting Cards




a. What cycle time is required to satisfy the required output rate?

b. What is the theoretical minimum number of workstations required?

c. If Jane identifies a five-station solution, what is the associated efficiency and balance delay?

d. If the cycle time increased by 100 percent, would the theoretical minimum number of workstations also increase by 100 percent?

**21.** Greg Davis, a business major at the University of South Carolina (USC), has opened Six Points Saco (SPS), a specialty subs–taco restaurant, at the rim of the USC campus. SPS has grown in popularity over the one year that it has been in operation, and Greg is trying to perfect the business model before making it into a franchise. He wants to maximize the productivity of his staff, as well as serve customers well in a timely fashion. One area of concern is the drive-thru operation during the 11:30 A.M. to 12:30 P.M. lunch hour.

The process of fulfilling an order involves fulfilling the tasks listed below.

Greg is interested in getting a better understanding of the staffing patterns that will be needed to operate his restaurant. After taking a course in operations management at the university, he knows that fulfilling a customer order at SPS is very similar to operating an assembly line. He has also used the POM for Windows software before, and wants to apply it for examining different demand scenarios for serving his customers.

a. If all the seven tasks are handled by one employee, how many customers could be served per hour?

b. If Greg wants to process 45 customers per hour, how many employees will he need during the peak period?

c. With the number of employees determined in part b, what is the maximum number of customers who could be served every hour (i.e., what is the maximum output capacity)?

d. Assuming that no task is assigned to more than one employee, what is the maximum output capacity from this assembly line? How many employees will be needed to actually accomplish this maximum output capacity?

e. Beyond the output accomplished in part d, if Greg decides to add one additional worker to help out with a bottleneck task, where should he add that worker? With that addition, would he be able to process more customers per hour? If so, what is the new maximum output capacity for the drive-thru?

| Task | Time (Seconds) | Immediate Predecessors |
|---|---|---|
| A. Take an order at the booth. Most orders are for a taco and a sub. | 25 | |
| B. Collect money at the window. | 20 | A |
| C. Gather drinks. | 35 | B |
| D. Assemble taco order. | 32 | B |
| E. Assemble sub order. | 30 | B |
| F. Put drinks, taco, and sub in a bag. | 25 | C, D, E |
| G. Give the bag to the customer. | 10 | F |

## EXPERIENTIAL LEARNING Min-Yo Garment Company

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

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

### Products

Min-Yo has divided its product line into three categories: licensed brands, subcontracted brands, and special garments.

### Licensed Brands

Licensed brands are brands that are owned by one company but, through a licensing agreement, are produced by another firm that also markets the brand in a specific geographic region. The licenser may have licensees all over the world. The licensee pays the licenser a fee for the privilege of marketing the brand in its region, and the licenser agrees to provide some advertising for the product, typically through media outlets that have international exposure. A key aspect of the licensing agreement is that the licensee must agree to provide sufficient quantities of product at the retail level. Running out of stock hurts the image of the brand name.

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

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

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

### Subcontracted Brands

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

| Week | Demand | Week | Demand |
|---|---|---|---|
| 1* | 700 | 7 | 1,100 |
| 2 | 800 | 8 | 1,100 |
| 3 | 900 | 9 | 900 |
| 4 | 900 | 10 | 900 |
| 5 | 1,000 | 11 | 800 |
| 6 | 1,100 | 12 | 700 |

*In other words, the company expects to sell 700 Muscle Shirts at the end of week 1.

Currently, Min-Yo manufactures only one subcontracted brand, called the Thunder Shirt because of its bright colors. Thunder Shirts are manufactured to order for a company in Singapore. Min-Yo's price to this company is $7 per shirt. When orders are placed, usually twice a month, the customer specifies the delivery of certain quantities in each of the next 2 weeks. The last order the customer placed is overdue, forcing Min-Yo to pay a penalty charge. To avoid another penalty, 200 shirts must be shipped in week 1. The Singapore company is expected to specify the quantities it requires for weeks 2 and 3 at the beginning of week 1. The delivery schedule containing the orders for weeks 4 and 5 is expected to arrive at the beginning of week 3, and so on. The customer has estimated its average weekly needs for the year to be 200 shirts per week, although its estimates are frequently inaccurate.

Because of the importance of this large customer to Min-Yo and the lengthy negotiations of the sales department to get the business, management always tries to satisfy its needs. Management believes that if Min-Yo Garment ever refuses to accept an order from this customer, Min-Yo will lose the Thunder Shirt business. Under the terms of the sales contract, Min-Yo agreed to pay this customer $1 for every shirt not shipped on time for each week the shipment of the shirt is delinquent. Delinquent shipments must be made up.

### Special Garments

Special garments are made only to customer order because of their low volume and specialized nature. Customers come to Min-Yo Garment to manufacture shirts for special promotions or special company occasions. Min-Yo's special garments are known as Dragon Shirts because of the elaborate embroidery and oriental flair of the designs. Because each shirt is made to a particular customer's specifications and requires a separate setup, special garments cannot be produced in advance of a firm customer order.

Although price is not a major concern for the customers of special garments, Min-Yo sells Dragon Shirts for $8 a shirt to ward off other companies seeking to enter the custom shirt market. Its customers come to Min-Yo because the company can produce almost any design with high quality and deliver an entire order on time. When placing an order for a Dragon Shirt, a customer specifies the design of the shirt (or chooses from Min-Yo's catalog), supplies specific designs for logos, and specifies the quantity of the order and the delivery date. In the past, management checked to see whether such an order would fit into the schedule, and then either accepted or rejected it on that basis. If Min-Yo accepts an order for delivery at the *end* of a certain week and fails to meet this commitment, it pays a penalty of $2 per shirt for each week delivery is delayed. This penalty is incurred weekly until the delinquent order is delivered. The company tried to forecast demand for specific designs of Dragon Shirts but has given up. Last week, Min-Yo had four Dragon Shirt opportunities of 50, 75, 200, and 60 units but chose not to accept any of the orders. Dragon Shirt orders in the past ranged from 50 units to 300 units with varying lead times.

Figure 5.18, Min-Yo's current open-order file, shows that in some prior week Min-Yo accepted an order of 400 Thunder Shirts for delivery last week. The open-order file is important because it contains the commitment management made to customers. Commitments are for a certain quantity and a date of delivery. As customer orders are accepted, management enters the quantity in the green cell representing the week that they are due. Because Dragon Shirts are unique unto themselves, they each have their own order number for future use. No Dragon Shirt orders appear in the open-order file because Min-Yo has not committed to any in the past several weeks.

### Manufacturing Process

The Min-Yo Garment Company has the latest process technology in the industry—a machine, called a garment maker, that is run by one operator on each of three shifts. This single machine process can make every garment Min-Yo produces; however, the changeover times consume a substantial amount of capacity. Company policy is to run the machine three shifts a day, five days a week. If business is insufficient to keep the machine busy, the workers are idle because Min-Yo is committed to never fire or lay off a worker. By the same token, the firm has a policy of never working on weekends. Thus, the capacity of the process is 5 days $\times$ 24 hours $=$ 120 hours per week. The hourly wage is $10 per hour, so the firm is committed to a fixed labor cost of $10 $\times$ 120 $=$ $1,200 per week. Once the machine has been set up to make a particular type of garment, it can produce that garment at the rate of 10 garments per hour, regardless of type. The cost of the material in each garment, regardless of type, is $4. Raw materials are never a problem and can be obtained overnight.

### Scheduling the Garment Maker

Scheduling at Min-Yo is done once each week, after production for the week has been completed and shipped, after new orders from customers have arrived, and before production for the next week has started. Scheduling results in two documents.

**MIN-YO GARMENT COMPANY**

**Open Order File (Record of commitments)**

| | *Week Order is Due* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Product* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Thunder Orders | 400 | | | | | | | | | |
| Dragon Order 1 | | | | | | | | | | |
| Dragon Order 2 | | | | | | | | | | |
| Dragon Order 3 | | | | | | | | | | |
| Dragon Order 4 | | | | | | | | | | |
| Dragon Order 5 | | | | | | | | | | |
| Dragon Order 6 | | | | | | | | | | |
| Dragon Order 7 | | | | | | | | | | |
| Dragon Order 8 | | | | | | | | | | |
| Dragon Order 9 | | | | | | | | | | |
| Dragon Order 10 | | | | | | | | | | |
| Dragon Order 11 | | | | | | | | | | |
| Dragon Order 12 | | | | | | | | | | |
| Dragon Order 13 | | | | | | | | | | |
| Dragon Order 14 | | | | | | | | | | |
| Dragon Order 15 | | | | | | | | | | |

Intro | Open Order File | Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 | Week 7 | Week 8 | Week 9 | Week 10 | S

▲ **FIGURE 5.18**

Min-Yo's Open Order File

Note: All orders are to be delivered at the end of the week indicated, after production for the week has been completed and before next week's production is started.

The first is a production schedule, shown in Figure 5.19. The schedule shows what management wants the garment maker process to produce in a given week. Two spreadsheet entries are required for each product that is to be produced in a given week. They are in the green shaded cells. The first is the production quantity. In Figure 5.19, the schedule shows that Min-Yo produced quantities of 800 units for Muscle and 200 units for Thunder last week. The second input is a "1" if the machine is to be set up for a given product or a "blank" if no changeover is required. Figure 5.19 shows that last week changeovers were required for the Muscle and Thunder production runs. The changeover information is important because, at the end of a week, the garment maker process will be set up for the last product produced. If the same product is to be produced first the following week, no new changeover will be required. Management must keep track of the sequence of production each week to take advantage of this savings. The only exception to this rule is Dragon Shirts, which are unique orders that always require a changeover. In week 0, Min-Yo did not produce any Dragon Shirts; however, it did produce 800 Muscle Shirts, followed by 200 Thunder Shirts. Finally, the spreadsheet calculates the hours required for the proposed schedule. Changeover times for Muscle, Thunder, and Dragon Shirts are 8, 10, and 25 hours, respectively. Because the garment maker process produces 10 garments per hour regardless of type, the production hours required for Muscle Shirts is $8 + 800/10 = 88$ hours, and the production hours for Thunder Shirts is $10 + 200/10 = 30$ hours, as shown in Figure 5.19. The total time spent on the garment maker process on all products in a week cannot exceed 120 hours. The spreadsheet will not allow you to proceed if this constraint is violated.

The second document is a weekly profit and loss (P&L) statement that factors in sales and production costs, including penalty charges and inventory carrying costs, as shown in Figure 5.20. The inventory carrying cost for *any type of product* is $0.10 per shirt per week left in inventory after shipments for the week have been made. The spreadsheet automatically calculates the P&L statement, which links to the open-order file and the production schedule, after the demand for Muscle Shirts is known. Figure 5.20 shows that the actual demand for Muscle Shirts last week was 750 shirts.

### Notes

- The past due quantity of shirts are those shirts not shipped as promised, and appear as a negative number in the "End Inv" column.
- Available = Beginning inventory + Production
- Sales = Demand × Production < available; Available × Price, otherwise
- Inventory cost = $0.10 times number of shirts in inventory. Past due cost equals past due quantity times the penalty ($1 for Thunder Shirts; $2 for Dragon Shirts). These costs are combined in the "Inv/Past Due Costs" column.

### The Simulation

At Min-Yo Garment Company, the executive committee meets weekly to discuss the new order possibilities and the load on the garment maker process. The executive committee consists of top management representatives from finance, marketing, and operations. You will be asked to participate on a team and play the role of a member of the executive committee in class. During this exercise, you must decide how far into the future to plan. Some decisions, such as the markets you want to exploit, are long-term in nature. Before class, you may want to think about the markets and their implications for manufacturing. Other decisions are short-term and have an

## MIN-YO GARMENT COMPANY

### PRODUCTION SCHEDULE

The two inputs to the Production Schedule table are:
1. The quantity you decide to produce this time period
2. Whether there is a setup/changover required (1 or 0)

| PRODUCT | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Changeover | Quantity | | | | | | |
| Muscle | 1 | 800 | | | | | | |
| Hours | | 88 | | | | | | |
| | | | | | | | | |
| Thunder | 1 | 200 | | | | | | |
| Hours | | 30 | | | | | | |
| | | | | Changeover | Quantity | | Changeover | Quantity |
| Dragon Order 1 | | | Dragon Order 11 | | | Dragon Order 21 | | |
| Dragon Order 2 | | | Dragon Order 12 | | | Dragon Order 22 | | |
| Dragon Order 3 | | | Dragon Order 13 | | | Dragon Order 23 | | |
| Dragon Order 4 | | | Dragon Order 14 | | | Dragon Order 24 | | |
| Dragon Order 5 | | | Dragon Order 15 | | | Dragon Order 25 | | |
| Dragon Order 6 | | | Dragon Order 16 | | | Dragon Order 26 | | |
| Dragon Order 7 | | | Dragon Order 17 | | | Dragon Order 27 | | |
| Dragon Order 8 | | | Dragon Order 18 | | | Dragon Order 28 | | |
| Dragon Order 9 | | | Dragon Order 19 | | | Dragon Order 29 | | |
| Dragon Order 10 | | | Dragon Order 20 | | | Dragon Order 30 | | |
| | | | | | | | | |
| Total Dragon Hours | | 0 | | | | | | |
| Total Dragon Production | | 0 | | | | | | |
| | | | | | | | | |
| Total Hours scheduled | | 118 | | | | | | |

Is production within capacity? Yes

▲ **FIGURE 5.19**
Min-Yo's Production Schedule

### P&L STATEMENT

| Product | Price | Beg Inv | Production | Available | Demand | Sales | End Inv | Inv/Past due costs |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| Muscle | $6 | 550 | 800 | 1350 | 750 | 4500 | 600 | 60 |
| Thunder | $7 | | 200 | 200 | 400 | 1400 | -200 | 200 |
| Dragon Orders | $8 | | 0 | 0 | 0 | 0 | 0 | 0 |
| Totals | | | **1000** | | | **5900** | | **260** |

| | | Current | Cumulative |
|---|---|---|---|
| Sales Total | | $5,900 | $5,900 |
| Labor | $1,200 | | |
| Materials | $4,000 | | |
| Inv/Past due | $260 | | |
| Total Cost | | $5,460 | |
| Profit Contribution | | **$440** | **$440** |

▲ **FIGURE 5.20**
Min-Yo's P&L Schedule

impact on the firm's ability to meet its commitments. In class, the simulation will proceed as follows.

1. Use the Min-Yo Tables spreadsheet in OM Explorer in MyOMLab. It is found in the Solver menu, under Constraint Management. You will start by specifying the production schedule for week 1, based on the forecasts for week 1 in the case narrative for Muscle Shirts and additional information on new and existing orders for the customized shirts from your instructor. *You may assume that your managerial predecessors left the garment machine set up for Thunder Shirts*. The production schedule decision is to be made in collaboration with your executive committee colleagues in class.
2. When all the teams have finalized their production plans for week 1, the instructor will supply the actual demands for Muscle Shirts in week 1. Enter that quantity in the P&L statement in the spreadsheet for week 1.
3. After the P&L statement for week 1 is completed, the instructor will announce the new order requests for Thunder Shirts and Dragon Shirts to be shipped in week 2 and the weeks beyond.
4. You should look at your order requests, accept those that you want, and reject the rest. Add those that you accept for delivery in future periods to your open-order file. Enter the quantity in the cell representing the week the order is due. You are then irrevocably committed to them and their consequences.
5. You should then make out a new production schedule, specifying what you want your garment-maker process to do in the next week (it will be for week 2 at that time).
6. The instructor will impose a time limit for each period of the simulation. When the time limit for one period has been reached, the simulation will proceed to the next week. Each week the spreadsheet will automatically update your production and financial information in the Summary Sheet.

## VIDEO CASE Constraint Management at Southwest Airlines

What if you could take a commercial airline flight any time and anywhere you wanted to go? Just show up at the airport without the need to consider time schedules or layovers. Aside from the potentially cost-prohibitive nature of such travel, there are also constraints in the airline system that preclude this kind of operation. From the lobby check-in process through to boarding at the gate and processing plane turnaround, the process of operating the airline is filled with constraints that must be managed in order for them to be successful and profitable. Flight schedules are tightly orchestrated and controlled, departure and arrival gates at airports are limited, and individual aircraft have seating capacities in each section of the plane, to name a few.

Southwest Airlines is one company that has figured out how to manage its constraints and generate positive customer experiences in the process. No other airline can claim the same level of profitability and customer satisfaction Southwest regularly achieves. What is its secret?

Talk to any loyal Southwest customer and you will hear rave reviews about its low fares, great customer service, and lack of assigned seating that gives customers a chance to choose who they sit next to onboard. From an operations perspective, it is much more than what the customer sees. Behind the scenes, operations managers carefully manage and execute—3,400 times a day in over 60 cities in the United States—a process designed to manage all potential bottleneck areas.

Southwest's famous rapid gate-turnaround of 25 minutes or less demonstrates how attention to the activities that ground operations must complete to clean, fuel, and prepare a plane for flight can become bottlenecks if not properly scheduled. In the terminal at the gate, passenger boarding also can be a bottleneck if the boarding process itself is not carefully managed. Since the individual mix of passengers presents a different set of issues with each flight that often are not evident until the passengers actually arrive at the gate, ranging from families with kids and strollers to large quantities of carry-on bags and passengers needing wheelchair assistance, operations managers must be ready for any and all situations to avoid a boarding bottleneck while also ensuring a pleasant and stress-free gate experience for all passengers.

Pearson

Passengers boarding a Southwest Airlines flight.

In 2007, as part of the company's continuous improvement activities, Southwest focused its attention on the passenger boarding process to determine whether there was a better way to board. Its existing process consisted of three groups, A, B, C, with no assigned seating. Depending on passenger check-in and arrival time, passengers were given a spot in a group. Those first to check-in received choice places in the A group. The last to check in ended up in the C group and usually had a choice of only middle seats in the back of the plane upon boarding. As passengers arrived at the gate, they queued up in their respective boarding group areas to await the boarding call.

Seven different alternate boarding scenarios were designed and tested. They included

- New family pre-boarding behind the "A" group of first-to-board passengers
- Family pre-boarding before anyone else, but seating choices limited onboard to behind the wing
- Six boarding groups (within A-B-C groups) instead of the original three A-B-C groups
- Assigned boarding gate line positions based on both boarding group and gate arrival time
- Single boarding chute at the gate, but up to nine groups all in one queue
- Boarding with a countdown clock to give customers an incentive to get in line and board quickly; incentives given out if everyone was on time
- Educational boarding video to make the boarding process fun, inform passengers how to board efficiently, and provide the company another way to promote its brand.

### QUESTIONS

1. Analyze Southwest's passenger boarding process using the TOC.
2. Which boarding scenario among the different ones proposed would you recommend for implementation? Why?
3. How should Southwest evaluate the gate boarding and plane turnaround process?
4. How will Southwest know that the bottleneck had indeed been eliminated after the change in the boarding process?

Kristoffer Tripplaar/Alamy


An Aldi discount grocery store.

# 6

# DESIGNING LEAN SYSTEMS

## Aldi

Aldi is a discount supermarket chain with headquarters in Germany and over 8000 stores worldwide including Australia, Europe, Great Britain, Ireland, and the United States. With roots and distribution in several countries throughout Europe, it is a different kind of retailer that prides itself in displaying key dietary and nutritional information on the front of their packaging to enable customers to make informed choices about their food. Aldi also makes its packaging from recycled materials to keep the planet green. Its emphasis on core values of simplicity, consistency, and corporate responsibility are closely tied to the principles of lean production, which Aldi uses to keep costs down in all areas, provide customers more value for their money, and remain more competitive in a business with razor thin margins.

Aldi's waste reduction efforts start with training its employees to do many different tasks, which improves flexibility and lowers staff costs. In addition, consistent with total quality management (TQM) principles, all workers have the responsibility to get it right the first time, whether it is accurate pricing or ordering the appropriate replenishment stocks. In return, they are paid some of the better wages in the United States in the grocery industry. In the stores, all items have bar codes in a number of places to save time in finding them, which makes the checkout process more efficient. Aldi is also known for having smaller stores, which are made possible by the fact that it sells fewer variations of each product and so less space is used for display. It also means that Aldi can get quantity discounts and economies of scale in sourcing products. Holding only the stock that is needed for each product is further facilitated through a just-in-time ordering and delivery system. Products are delivered as needed in display-ready cases; some of them are even sold directly from a pallet or a platform to minimize handling and increase the efficiency of getting a large volume into the store quickly. In contrast to several of its 24-hour competitors, Aldi stores are only open from 8 A.M. to 8 P.M. on most days, which reduces the use of energy and staff salary costs. By limiting the use of credit cards, except Discover in some stores in the United States and Visa and MasterCard in Ireland, and using only cash or debit cards saves Aldi the surcharge fees levied by most credit card companies. Finally, Aldi's shopping carts utilize a 25¢ (in the United States) or a €1 (in Europe) coin system to make sure that customers return them to the parking stations near the store, which saves labor costs in collecting the carts that would otherwise be left scattered across the parking lots or potentially be lost or stolen.

Aldi's lean philosophy extends into the supply chain as well. Up to 60 percent of its fruits and vegetables are sourced locally to save on transportation costs and time. As part of its inventory reduction policies, suppliers are not allowed to hold more than one month of normal orders and requirements of Aldi's private label products in inventory at any given point of time, unless Aldi submits a written authorization for a temporary or permanent change in suppliers' inventory levels. Due to its relentless focus on lean principles, it is no wonder that Aldi is a clear leader in prices among leading grocery brands according to a study of 6,200 consumers conducted in May 2014 by Market Force Information, a customer intelligence solutions firm. Aldi's products can be as much as 30 percent cheaper than its competitors in some cases. In addition, Publix and Aldi were ranked second and third in customer satisfaction in North America after Trader Joe's due to their courteous service, fast checkouts, and the quality of their private label brand products. All these initiatives have contributed to Aldi's explosive growth globally—a new store opens roughly every week in the United Kingdom alone.

*Sources:* "Competitive Advantage through Efficiency: An Aldi Case Study," **http://businesscasestudies.co.uk/aldi/competitive-advantage-through-efficiency/introduction.html#axzz39GsjgbiQ**; **http://en.wikipedia.org/wiki/Aldi**; **https://corporate.aldi.us**; **http://www.producenews.com/news-dep-menu/test-featured/13168-consumer-study-reveals-top-grocery-stores** (August 2, 2014).



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

1. Describe how lean systems can facilitate the continuous improvement of processes.
2. Identify the strategic supply chain and process characteristics of lean systems.
3. Explain the differences between one-worker, multiple-machine (OWMM) and group technology (GT) approaches to lean system layouts.
4. Understand value stream mapping and its role in waste reduction.
5. Understand *kanban* systems for creating a production schedule in a lean system.
6. Explain the implementation issues associated with the application of lean systems.

**lean systems**

Operations systems that maximize the value added by each of a company's activities by removing waste and delays from them.

Aldi is a learning organization and an excellent example of an approach for designing supply chains known as lean systems, which allow firms like Aldi to continuously improve its operations and spread the lessons learned across the entire corporation. **Lean systems** are operations systems that maximize the value added by each of a company's activities by removing waste and delays from them. They encompass the company's operations strategy, process design, quality management, constraint management, layout design, supply chain design, and technology and inventory management and can be used by both service and manufacturing firms. Like a manufacturer, each service business takes an order from a customer, delivers the service, and then collects revenue. Each service business purchases services or items, receives and pays for them, and hires and pays employees. Each of these activities bears considerable similarity to those in manufacturing firms. They also typically contain huge amounts of waste.

Lean systems affect a firm's internal linkages between its core and supporting processes and its external linkages with its customers and suppliers. The design of supply chains using the lean systems approach is important to various departments and functional areas across the organization. Marketing relies on lean systems to deliver high-quality services or products on time and at reasonable prices. Human resources must put in place the right incentive systems that reward teamwork and also recruit, train, and evaluate the employees needed to create a flexible workforce that can successfully operate a lean system. Engineering must design products that use more common parts, so that fewer setups are required and focused factories can be used. Operations is responsible for maintaining close ties with suppliers, designing the lean system, and using it in the production of services or goods. Accounting must adjust its billing and cost accounting practices to provide the support needed to manage lean systems. Finally, top management must embrace the lean philosophy and make it a part of organizational culture and learning, as was done by Aldi in the opening vignette.

Thus far in the text, we have discussed many ways to improve manufacturing and service processes. We take that further in this chapter by showing how process improvement techniques can be used to make a firm lean by first discussing the continuous improvement aspect of lean systems, followed by a discussion of the characteristics of lean systems, and the design of layouts needed to achieve these characteristics. We also address different types of lean systems used in practice and some of the implementation issues that companies face.

## Continuous Improvement Using a Lean Systems Approach

One of the most popular systems that incorporate the generic elements of lean systems is the just-in-time (JIT) system. According to Taiichi Ohno, one of the earlier pioneers at Toyota Corporation, the **just-in-time (JIT) philosophy** is simple but powerful—eliminate waste or muda by cutting excess capacity or inventory and removing non-value-added activities. Table 6.1 shows the eight types of waste that often occur in firms in an interrelated fashion and which must be eliminated in implementing lean systems.

**just-in-time (JIT) philosophy**

The belief that waste can be eliminated by cutting unnecessary capacity or inventory and removing non-value-added activities in operations.

**TABLE 6.1** THE EIGHT TYPES OF WASTE OR *MUDA*[1]

| Waste | Definition |
|---|---|
| 1. Overproduction | Manufacturing an item before it is needed, making it difficult to detect defects and creating excessive lead times and inventory. |
| 2. Inappropriate Processing | Using expensive high-precision equipment when simpler machines would suffice. It leads to overutilization of expensive capital assets. Investment in smaller flexible equipment, immaculately maintained older machines, and combining process steps where appropriate reduce the waste associated with inappropriate processing. |
| 3. Waiting | Wasteful time incurred when product is not being moved or processed. Long production runs, poor material flows, and processes that are not tightly linked to one another can cause over 90 percent of a product's lead time to be spent waiting. |
| 4. Transportation | Excessive movement and material handling of product between processes, which can cause damage and deterioration of product quality without adding any significant customer value. |
| 5. Motion | Unnecessary effort related to the ergonomics of bending, stretching, reaching, lifting, and walking. Jobs with excessive motion should be redesigned. |
| 6. Inventory | Excess inventory hides problems on the shop floor, consumes space, increases lead times, and inhibits communication. Work-in-process inventory is a direct result of overproduction and waiting. |
| 7. Defects | Quality defects result in rework and scrap and add wasteful costs to the system in the form of lost capacity, rescheduling effort, increased inspection, and loss of customer goodwill. |
| 8. Underutilization of Employees | Failure of the firm to learn from and capitalize on its employees' knowledge and creativity impedes long-term efforts to eliminate waste. |

[1]David McBride, "The Seven Manufacturing Wastes," August 29, 2003, **http://www.emsstrategies.com** by permission of EMS Consulting Group, Inc. © 2003.

laorsomsri/Thinkstock/Getty Images

Stacks of bags at a coffee bean warehouse indicate that too much inventory can result from overproduction.

The goals of a lean system are thus to eliminate these eight types of waste, produce services and products only as needed, and to continuously improve the value-added benefits of operations. A **JIT system** organizes the resources, information flows, and decision rules that enable a firm to realize the benefits of JIT principles.

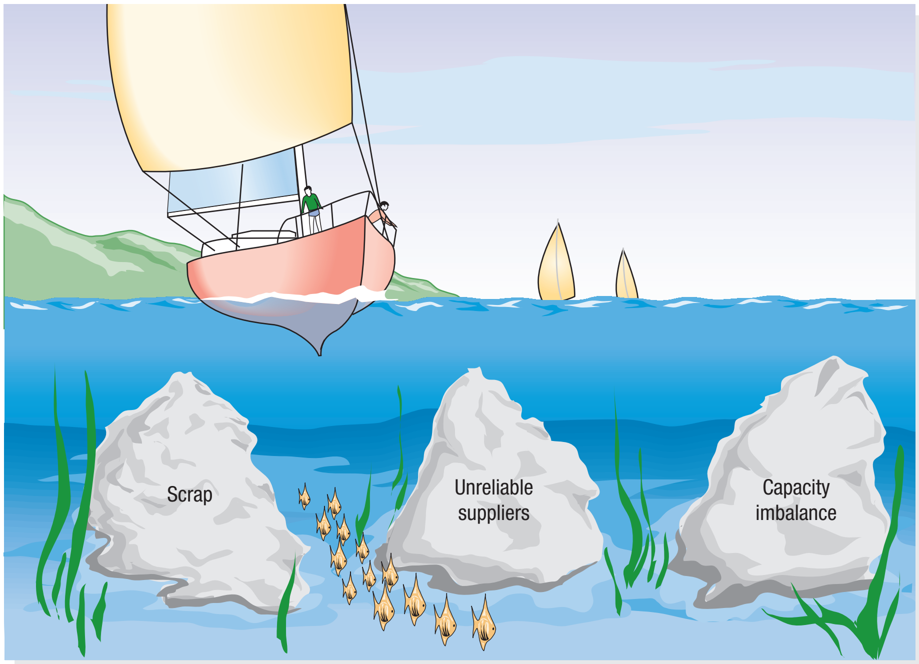
By spotlighting areas that need improvement, lean systems lead to continuous improvement in quality and productivity. The Japanese term for this approach to process improvement is kaizen. The key to kaizen is the understanding that excess capacity or inventory hides underlying problems with the processes that produce a service or product. Lean systems provide the mechanism for management to reveal the problems by systematically lowering capacities or inventories until the problems are exposed. For example, Figure 6.1 characterizes the philosophy behind continuous improvement with lean systems. In services, the water surface represents service system capacity, such as staff levels. In manufacturing, the water surface represents product and component inventory levels. The rocks represent problems encountered in the fulfillment of services or products. When the water surface is high enough, the boat passes over the rocks because the high level of capacity or inventory covers up problems. As capacity or inventory shrinks, rocks are exposed. Ultimately, the boat will hit a rock if the water surface falls far enough. Through lean systems, workers, supervisors, engineers, and analysts apply methods for continuous improvement to demolish the exposed rock. The coordination required to achieve smooth material flows in lean systems identifies problems in time for corrective action to be taken.

**JIT system**

A system that organizes the resources, information flows, and decision rules that enable a firm to realize the benefits of JIT principles.

Maintaining low inventories, periodically stressing the system to identify problems, and focusing on the elements of the lean system lie at the heart of continuous improvement. For example, plants may periodically cut its safety stocks almost to zero. The problems at the plant are exposed, recorded, and later assigned to employees as improvement projects. After improvements are made, inventories are permanently cut to the new level. Many firms use this trial-and-error process to develop more efficient manufacturing operations. In addition, workers using special presses often fabricate parts on the assembly line in exactly the quantities needed. Service processes, such as scheduling, billing, order taking, accounting, and financial planning, can be improved with lean systems, too. In service operations, a common approach used by managers is to place stress on the system by reducing the number of employees doing a particular activity or series of activities until the process begins to slow or come to a halt. The problems can be identified, and ways for overcoming them explored. Other kaizen tactics can be used as well. Eliminating the problem of too much scrap might require improving the firm's work processes, providing employees with additional training, or finding higher-quality suppliers. Eliminating capacity imbalances might involve revising the firm's master production schedule and improving the flexibility of its workforce. Irrespective of which problem is solved, there are always new ones that can be addressed to enhance system performance.

▼ **FIGURE 6.1**
Continuous Improvement with Lean Systems




Oftentimes, continuous improvement occurs with the ongoing involvement and input of new ideas from employees, who play an important role in implementing the JIT philosophy. In one year alone, about 740,000 corporate-wide improvement suggestions were received at Toyota. A large majority of them got implemented, and employees making those suggestions received rewards ranging from 500 yen (about $5) to upwards of 50,000 yen (about $500) depending upon their bottom line impact.

# Strategic Characteristics of Lean Systems

The philosophy of lean systems, applicable at the process level, is also applicable at the supply chain level. Factors, both within and outside the firm, arising from supply chain and process considerations that have an important impact in creating and implementing lean systems are discussed next in this section.

## Supply Chain Considerations in Lean Systems

In this section, we discuss the two salient characteristics of lean systems that are related to creating and managing material flows in a supply chain: close supplier ties and small lot sizes.

**Close Supplier Ties** Because lean systems operate with low levels of capacity slack or inventory, firms that use them need to have a close relationship with their suppliers. Supplies must be shipped frequently, have short lead times, arrive on schedule, and be of high quality. A contract might even require a supplier to deliver goods to a facility as often as several times per day.

The lean system philosophy is to look for ways to improve efficiency and reduce inventories throughout the supply chain. Close cooperation between companies and their suppliers can be a win–win situation for everyone. Better communication of component requirements, for example, enables more efficient inventory planning and delivery scheduling by suppliers, thereby improving supplier profit margins. Customers can then negotiate lower component prices. Close supplier relations cannot be established and maintained if companies view their suppliers as adversaries whenever contracts are negotiated. Rather, they should consider suppliers to be partners in a venture, wherein both parties have an interest in maintaining a long-term, profitable relationship. Consequently, one of the first actions undertaken when a lean system is implemented is to pare down the number of suppliers, and make sure they are located in close geographic proximity to promote strong partnerships and better synchronize product flows.

A particularly close form of supplier partnerships through lean systems is the JIT II system, which was conceived and implemented by Bose Corporation, a producer of high-quality professional sound and speaker systems. In a JIT II system, also called *vendor-managed inventories*, the supplier is brought into the plant to be an active member of the purchasing office of the customer. The in-plant representative is on site full-time at the supplier's expense and is empowered to plan and schedule the replenishment of materials from the supplier. Thus, JIT II fosters extremely close interaction with suppliers. The qualifications for a supplier to be included in the program are stringent.

In general, JIT II can offer benefits to both buyers and suppliers because it provides the organizational structure needed to improve supplier coordination by integrating the logistics, production, and purchasing processes together. We have more to say about supplier relationships and vendor-managed inventories in Chapter 14, "Integrating the Supply Chain."

**Small Lot Sizes** Lean systems use lot sizes that are as small as possible. A **lot** is a quantity of items that are processed together. Small lots have the advantage of reducing the average level of inventory relative to large lots. Small lots pass through the system faster than large lots since they do not keep materials waiting. In addition, if any defective items are discovered, large lots cause longer delays because the entire lot must be examined to find all the items that need rework. Finally, small lots help achieve a uniform workload on the system and prevent overproduction. Large lots consume large chunks of capacity at workstations and, therefore, complicate scheduling. Small lots can be juggled more effectively, enabling schedulers to efficiently utilize capacities.

**lot**
A quantity of items that are processed together.

Although small lots are beneficial to operations, they have the disadvantage of increased setup frequency. A setup is the group of activities needed to change or readjust a process between successive lots of items, sometimes referred to as a changeover. This changeover in itself is a process that can be made more efficient. Setups involve trial runs, and the material waste can be substantial as the machines are fine tuned for the new parts. Typically, a setup takes the same time regardless of the size of the lot. Consequently, many small lots, in lieu of several large lots, may result in waste in the form of idle employees, equipment, and materials. Setup times must be brief to realize the benefits of small-lot production.

Achieving brief setup times often requires close cooperation among engineering, management, and labor. For example, changing dies on large presses to form automobile parts from sheet metal can take 3 to 4 hours. At Honda's Marysville, Ohio, plant—where four stamping lines stamp all the exterior and major interior body panels for Accord production—teams worked on ways to reduce the changeover time for the massive dies. As a result, a complete change of dies for a giant 2,400-ton press now takes less than 8 minutes. The goal of **single-digit setup** means having setup times of less than 10 minutes. Some techniques used to reduce setup times at the Marysville plant include using conveyors for die storage, moving large dies with cranes, simplifying dies, enacting machine controls, using microcomputers to automatically feed and position work, and preparing for changeovers while a job currently in production is still being processed.

**single-digit setup**
The goal of having a setup time of less than 10 minutes.

Paula Solloway/Alamy

A diner at a Chinese restaurant buffet. Because the food items must be prepared in advance, the restaurant uses a push method of workflow.

## Process Considerations in Lean Systems

In this section, we discuss the following characteristics of lean systems: pull method of work flow, quality at the source, uniform workstation loads, standardized components and work methods, flexible workforce, automation, Five S (5S) practices, and total preventive maintenance (TPM).

**Pull Method of Work Flow** Managers have a choice as to the nature of the material flows in a process or supply chain. Most firms using lean operations use the **pull method**, in which customer demand activates the production of a good or service. In contrast, a method often used in conventional systems that do not emphasize lean systems is the **push method**, which involves using forecasts of demand and producing the item before the customer orders it. To differentiate between these two methods, let us use a service example that involves a favorite pastime, eating.

**pull method**

A method in which customer demand activates production of the service or item.

**push method**

A method in which production of the item begins in advance of customer needs.

For an illustration of the pull method, consider a five-star restaurant in which you are seated at a table and offered a menu of exquisite dishes, appetizers, soups, salads, and desserts. You can choose from filet mignon, porterhouse steak, yellow fin tuna, grouper, and lamb chops. Your choice of several salads is prepared at your table. Although some appetizers, soups, and desserts can be prepared in advance and brought to temperature just before serving, the main course and salads cannot. Your order for the salad and the main course signals the chef to begin preparing your specific requests. For these items, the restaurant is using the pull method. Firms using the pull method must be able to fulfill the customer's demands within an acceptable amount of time.

For an understanding of the push method, consider a cafeteria on a busy downtown corner. During the busy periods around 12 P.M. and 5 P.M. lines develop, with hungry patrons eager to eat and then move on to other activities. The cafeteria offers choices of chicken (roasted or deep fried), roast beef, pork chops, hamburgers, hot dogs, salad, soup (chicken, pea, and clam chowder), bread (three types), beverages, and desserts (pies, ice cream, and cookies). Close coordination is required between the cafeteria's "front office," where its employees interface with customers, and its "back office," the kitchen, where the food is prepared and then placed along the cafeteria's buffet line. Because it takes substantial time to cook some of the food items, the cafeteria uses a push method. The cafeteria would have a difficult time using the pull method because it could not wait until a customer asked for an item before asking the kitchen to begin processing it. After all, shortages in food could cause riotous conditions (recall that customers are hungry), whereas preparing an excess amount of food will be wasteful because it will go uneaten. To make sure that neither of these conditions occurs, the cafeteria must accurately forecast the number of customers it expects to serve. A Chinese restaurant buffet as shown above would similarly follow a push method for serving its customers.

The choice between the push and pull methods is often situational. Firms using an assemble-to-order strategy sometimes use both methods: the push method to produce the standardized components, and the pull method to fulfill the customer's request for a particular combination of the components.

**Quality at the Source** Consistently meeting the customer's expectations is an important characteristic of lean systems. One way to achieve this goal is by adhering to a practice called quality at the source, which is a philosophy whereby defects are caught and corrected where they are created. The goal for workers is to act as their own quality inspectors and never pass on defective units to the next process. Automatically stopping the process when something is wrong and then fixing the problems on the line itself as they occur is also known as ***jidoka***. Jidoka tends to separate worker and machine activities by freeing workers from tending to machines all the time, thus allowing them to staff multiple operations simultaneously. Jidoka represents a visual management system whereby status of the system in terms of safety, quality, delivery, and cost performance relative to the goals for a given fabrication cell or workstation in an assembly line is clearly visible to workers on the floor at all times.

***jidoka***

Automatically stopping the process when something is wrong and then fixing the problems on the line itself as they occur.

An alternative to jidoka or quality at the source is the traditional practice of pushing problems down the line to be resolved later. This approach is often ineffective. For example, a soldering operation at the Texas Instruments antenna department had a defect rate that varied from 0 to 50 percent on a daily basis, averaging about 20 percent. To compensate, production planners increased the lot sizes, which only increased inventory levels and did nothing to reduce the number of defective items. The company's engineers then discovered through experimentation that gas temperature was a critical variable in producing defect-free items. They subsequently devised statistical control charts for the firm's equipment operators to use to monitor the temperature and adjust it themselves. Process yields immediately improved and stabilized at 95 percent, and Texas Instruments was eventually able to implement a lean system.

One successful approach for implementing quality at the source is to use ***poka-yoke***, or mistake-proofing methods aimed at designing fail-safe systems that attack and minimize human error. Poka-yoke systems work well in practice. Consider, for instance, a company that makes modular products. The company could use the *poka-yoke* method by making different parts of the modular product in such a way that allows them to be assembled in only one way—the correct way. Similarly, a company's shipping boxes could be designed to be packed only in a certain way to minimize damage and eliminate all chances of mistakes. At Toyota plants, every vehicle being assembled is accompanied by an RFID chip containing information on how many nuts and bolts need to be tightened on that vehicle for an operation at a given workstation. A green light comes on when the right numbers of nuts have been tightened. Only then does the vehicle move forward on the assembly line.


zmostock/Alamy

An example of poka-yoke is the design of new fuel doors in automobiles. They are mistake proof since the filling pipe insert keeps larger, leaded-fuel nozzle from being inserted. In addition, a gas cap tether does not allow the motorist to drive off without the cap, and is also fitted with a ratchet to signal proper tightness and prevent over-tightening.

***poka-yoke***

Mistake-proofing methods aimed at designing fail-safe systems that minimize human error.

Another tool for implementing quality at the source is *andon*, which is a system that gives machines and machine operators the ability to signal the occurrence of any abnormal condition such as tool malfunction, shortage of parts, or the product being made outside the desired specifications. It can take the form of audio alarms, blinking lights, LCD text displays, or cords that can be pulled by workers to ask for help or stop the production line if needed. Stopping a production line can, however, cost a company thousands of dollars each minute production is halted. Needless to say, management must realize the enormous responsibility this method puts on employees and must prepare them properly.

**Uniform Workstation Loads** A lean system works best if the daily load on individual workstations is relatively uniform. Service processes can achieve uniform workstation loads by using reservation systems. For example, hospitals schedule surgeries in advance of the actual service so that the facilities and facilitating goods can be ready when the time comes. The load on the surgery rooms and surgeons can be evened out to make the best use of these resources. Another approach is to use differential pricing of the service to manage the demand for it. Uniform loads are the rationale behind airlines promoting weekend travel or red-eye flights that begin late in the day and end in the early morning. Efficiencies can be realized when the load on the firm's resources can be managed.

For manufacturing processes, uniform loads can be achieved by assembling the same type and number of units each day, thus creating a uniform daily demand at all workstations. Capacity planning, which recognizes capacity constraints at critical workstations, and line balancing are used to develop the master production schedule. For example, at Toyota's plant the production plan may call for 4,500 vehicles per week for the next month. That requires two full shifts, 5 days per week, producing 900 vehicles each day, or 450 per shift. Three models are produced: Camry (C), Avalon (A), and Venza (V). Suppose that Toyota needs 200 Camrys, 150 Avalons, and 100 Venzas per shift to satisfy market demand. To produce 450 units in one shift of 480 minutes, the line must roll out a vehicle every $480/450 = 1.067$ minutes. The 1.067 minutes, or 64 seconds, represents the **takt time** of the process, defined as the cycle time needed to match the rate of production to the rate of sales or consumption.

**takt time**

Cycle time needed to match the rate of production to the rate of sales or consumption.

With traditional big-lot production, all daily requirements of a model are produced in one batch before another model is started. The sequence of 200 Cs, 150 As, and 100 Vs would be repeated once per shift. Not only would these big lots increase the average inventory level, but they also would cause lumpy requirements on all the workstations feeding the assembly line.

But there are other two options for devising a production schedule for the vehicles. These options are based on the Japanese concept of ***heijunka***, which is the leveling of production load by both volume and product mix. It does not build products according to the actual flow of customer orders but levels out the total volume of orders in a period so that the same amount and mix are being made each day.[2]

***heijunka***

The leveling of production load by both volume and product mix.

[2]David McBride, "Heijunka, Leveling the Load," September 1, 2004, **http://www.emsstrategies.com**.

**mixed-model assembly**

A type of assembly that produces a mix of models in smaller lots.

Let us explore two possible heijunka options. The first option uses leveled **mixed-model assembly**, producing a mix of models in smaller lots. Note that the production requirements at Toyota are in the ratio of 4 Cs to 3 As to 2 Vs, found by dividing the model's production requirements by the greatest common divisor, or 50. Thus, the Toyota planner could develop a production cycle consisting of 9 units: 4 Cs, 3 As, and 2 Vs. The cycle would repeat in $9(1.067) = 9.60$ minutes, for a total of 50 times per shift $(480 \text{ min}/9.60 \text{ min} = 50)$.

The second heijunka option uses a lot size of one, such as the production sequence of C–V–C–A–C–A–C–V–A repeated 50 times per shift. The sequence would achieve the same total output as the other options; however, it is feasible only if the setup times are brief. The sequence generates a steady rate of component requirements for the various models and allows the use of small lot sizes at the feeder workstations. Consequently, the capacity requirements at those stations are greatly smoothed. These requirements can be compared to actual capacities during the planning phase, and modifications to the production cycle, production requirements, or capacities can be made as necessary.

**Standardized Components and Work Methods** In highly repetitive service operations, analyzing work methods and documenting the improvements to use can gain great efficiencies. For example, UPS consistently monitors its work methods, from sorting packages to delivering them, and revises them as necessary to improve service. In manufacturing, the standardization of components increases the total quantity that must be produced for that component. For example, a firm producing 10 products from 1,000 different components could redesign its products so that they consist of only 100 different components with larger daily requirements. Because the requirements per component increase, each worker performs a standardized task or work method more often each day. Productivity tends to increase because workers learn to do their tasks more efficiently with increased repetition. Standardizing components and work methods help a firm achieve the high-productivity, low-inventory objectives of a lean system.

**Flexible Workforce** The role of workers is elevated in lean systems. Workers in flexible workforces can be trained to perform more than one job. A benefit of flexibility is the ability to shift workers among workstations to help relieve bottlenecks as they arise without the need for inventory buffers—an important aspect of the uniform flow of lean systems. Also, workers can step in and do the job for those who are on vacation or who are out sick. Although assigning workers to tasks they do not usually perform can temporarily reduce their efficiency, some job rotation tends to relieve boredom and refreshes workers. At some firms that have implemented lean systems, cross-trained workers may switch jobs every 2 hours.

The more customized the service or product is, the greater the firm's need for a multiskilled workforce. For example, stereo repair shops require broadly trained personnel who can identify a wide variety of component problems when the customer brings the defective unit into the shop and who then can repair the unit. Alternatively, back-office designs, such as the mail-processing operations at a large post office, have employees with more narrowly defined jobs because of the repetitive nature of the tasks they must perform. These employees do not have to acquire as many alternative skills. In some situations, shifting workers to other jobs may require them to undergo extensive, costly training.

**five S (5S)**

A methodology consisting of five workplace practices—sorting, straightening, shining, standardizing, and sustaining—that are conducive to visual controls and lean production.

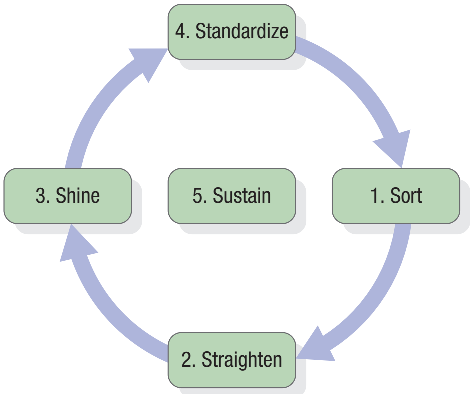
Molly McMillin/MCT/Newscom

Spirit AeroSystems' plant in Prestwick, Scotland, has seen some big changes. For one, it has invested in automation on the A320 production line.

**Automation** Automation plays a big role in lean systems and is a key to low-cost operations. Money freed up because of inventory reductions or other efficiencies can be invested in automation to reduce costs. The benefits, of course, are greater profits, greater market share (because prices can be cut), or both. Automation can play a big role when it comes to providing lean services. For example, banks offer ATMs that provide various bank services on demand 24 hours a day. Automation should be planned carefully, however. Many managers believe that if some automation is good, more is better, which is not always the case. At times, humans can do jobs better than robots and automated assembly systems. In other instances, especially when production volumes are high, automation can result in higher quality, precision, and productivity.

**Five S Practices** **Five S (5S)** is a methodology for organizing, cleaning, developing, and sustaining a productive work environment. It represents five related terms, each beginning with an S, that describe workplace practices conducive to visual controls and lean production. As shown in Figure 6.2, these five practices of sort, straighten, shine, standardize, and sustain build upon one another and are done systematically to achieve lean systems. These practices are interconnected and are not something that can be done as a stand-alone program. As such, they serve as an enabler and an essential foundation of lean systems. Table 6.2 shows the terms[3] that represent the 5S and what they imply.

It is commonly accepted that 5S forms an important cornerstone of waste reduction and removal of unneeded tasks, activities, and materials. 5S practices can enable workers to visually see everything differently, prioritize tasks, and achieve a greater degree of focus. They can also be applied to a diverse range of manufacturing and service settings including organizing work spaces, offices, tool rooms, shop floors, and the like. Implementation of 5S practices have been shown to lead to lowered costs, improved on-time delivery and productivity, higher product quality, better use of floor space, and a safe working environment. It also builds the discipline needed to make the lean systems work well.




▲ FIGURE 6.2
5S Practices

**TABLE 6.2 | 5S DEFINED**

| 5S Term | Definition |
|---|---|
| 1. Sort | Separate needed items from unneeded items (including tools, parts, materials, and paperwork), and discard the unneeded. |
| 2. Straighten | Neatly arrange what is left, with a place for everything and everything in its place. Organize the work area so that it is easy to find what is needed. |
| 3. Shine | Clean and wash the work area and make it shine. |
| 4. Standardize | Establish schedules and methods of performing the cleaning and sorting. Formalize the cleanliness that results from regularly doing the first three S practices so that perpetual cleanliness and a state of readiness are maintained. |
| 5. Sustain | Create discipline to perform the first four S practices, whereby everyone understands, obeys, and practices the rules when in the plant. Implement mechanisms to sustain the gains by involving people and recognizing them through a performance measurement system. |

**Total Preventive Maintenance (TPM)** Because lean systems emphasize finely tuned flows of work and little capacity slack or buffer inventory between workstations, unplanned machine downtime can be disruptive. Total Preventive Maintenance (TPM), which is also sometimes referred to as total *productive* maintenance, can reduce the frequency and duration of machine downtime. After performing their routine maintenance activities, technicians can test other machine parts that might need to be replaced. Replacing parts during regularly scheduled maintenance periods is easier and quicker than dealing with machine failures during production. Maintenance is done on a schedule that balances the cost of the preventive maintenance program against the risks and costs of machine failure. Routine preventive maintenance is important for service businesses that rely heavily on machinery, such as the rides at Walt Disney World or Universal Studios.

Another tactic is to make workers responsible for routinely maintaining their own equipment, which will develop employee pride in keeping the machines in top condition. This tactic, however, typically is limited to general housekeeping chores, minor lubrication, and adjustments. Maintaining high-tech machines requires trained specialists. Nonetheless, performing even simple maintenance tasks goes a long way toward improving the performance of machines.


Nerthuz/Thinkstock/Getty Images

5S Kaizen Cycle

[3]The Japanese words for these 5S terms are *seiri, seiton, seiso, seiketsu,* and *shitsuke,* respectively.

For long-term improvements, data can be collected for establishing trends in failure pattern of machines, which can subsequently be analyzed to establish better standards and procedures for preventive maintenance. The data can also provide failure history and costs incurred to maintain the systems.

## Toyota Production System

If you were to select one company that regularly invokes the above-mentioned features of lean systems and also exemplifies excellence in automobile manufacturing, it would probably be Toyota. Despite its recent problems with quality and product recalls, as well as component shortages and delayed new model launches caused by the Japanese earthquake in March 2011, Toyota has become one of the largest car manufacturers in the world and also one of its most admired. Worldwide in its presence, Toyota has 11 manufacturing plants in North America alone producing over 1.86 million vehicles per year. Much of this success is attributed to the famed Toyota Production System (TPS), which is one of the most admired lean manufacturing systems in existence. Replicating the system, however, is fraught with difficulties. What makes the system tick, and why has Toyota been able to use it so successfully in many different plants?

Most outsiders see the TPS as a set of tools and procedures that are readily visible during a plant tour. Even though they are important for the success of the TPS, they are not the key. What most people overlook is that through the process of continuous improvement, Toyota built a learning organization over the course of 50 years. Lean systems require constant improvements to increase efficiency and reduce waste. Toyota's system stimulates employees to experiment to find better ways to do their jobs. In fact, Toyota sets up all of its operations as "experiments" and teaches employees at all levels how to use the scientific method of problem solving.

Four principles form the basis of the TPS. First, all work must be completely specified as to content, sequence, timing, and outcome. Detail is important; otherwise, a foundation for improvements is missing. Second, every customer–supplier connection must be direct, unambiguously specifying the people involved, the form and quantity of the services or goods to be provided, the way the requests are made by each customer, and the expected time in which the requests will be met. Customer–supplier connections can be internal (employee to employee) or external (company to company). Third, the pathway for every service and product must be simple and direct. That is, services and goods do not flow to the next available person or machine but to a specific person or machine. With this principle, employees can determine, for example, whether a capacity problem exists at a particular workstation and then analyze ways to solve it.

The first three principles define the system in detail by specifying how employees do work and interact with each other and how the work flows are designed. However, these specifications actually are "hypotheses" about the way the system should work. For example, if something goes wrong at a workstation enough times, the hypothesis about the methods the employee uses to do work is rejected. The fourth principle, then, is that any improvement to the system must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible organizational level. The scientific method involves clearly stating a verifiable hypothesis of the form, "If we make the following specific changes, we expect to achieve this specific outcome." The hypothesis must then be tested under a variety of conditions. Working with a teacher, who is often the employees' supervisor, is a key to becoming a learning organization. Employees learn the scientific method and eventually become teachers of others. Finally, making improvements at the lowest level of the organization means that the employees who are actually doing the work are actively involved in making the improvements. Managers are advised only to coach employees—not to fix their problems for them.

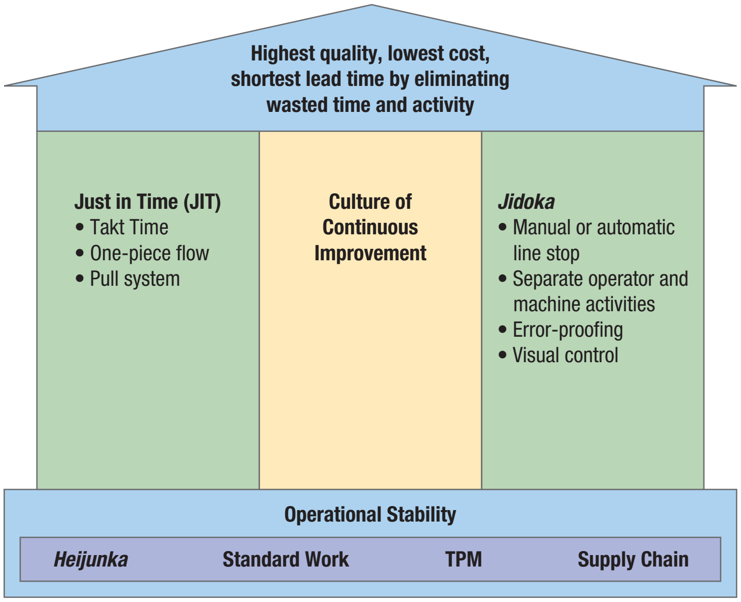
Chang-Ran Kim/Reuters/Corbis

An employee helps assemble a vehicle in Toyota City, located in central Japan. Toyota's production system is among the most-admired lean manufacturing systems in the world.

These four principles are deceptively simple. However, they are difficult but not impossible to replicate. Those organizations that successfully implement them enjoy the benefits of a lean system that adapts to change. Toyota's lean system made it an innovative leader in the auto industry and served as an important cornerstone of its success.

**House of Toyota** Taiichi Ohno and Eiji Toyoda created a graphic representation shown in Figure 6.3

to define the TPS to its employees and suppliers, and which is now known as the House of Toyota. It captures the four principles of TPS described above, and represents all the essential elements of lean systems that make the TPS work well. The house conveys stability. The twin pillars of JIT and *jidoka* support the roof, representing the primary goals of high quality, low cost, waste elimination, and short lead-times. Within JIT, TPS uses a pull system that focuses on one-piece work flow methods that can change and match the takt time of the process to the actual market demand because setup reductions and small changeover times are facilitated by cross-trained workers in cellular layouts. Implementing various tools of jidoka ensures that quality is built into the product rather than merely inspected at the end. Finally, within an environment of continuous improvement, operational stability to the House of Toyota is provided at the base by leveraging other lean concepts such as heijunka, standard work methods, 5S practices, total preventive maintenance, and elimination of waste throughout the supply chain within which the Toyota products flow to reach their eventual customers.




▲ **FIGURE 6.3**
House of Toyota[5]

## Designing Lean System Layouts

Line flows are recommended in designing lean system layouts because they eliminate waste by reducing the frequency of setups. If volumes of specific products are large enough, groups of machines and workers can be organized into a line-flow layout to eliminate setups entirely. In a service setting, managers of back-office service processes can similarly organize their employees and equipment to provide uniform work flows through the process and, thereby, eliminate wasted employee time. Banks use this strategy in their check-processing operations, as does UPS in its parcel-sorting process.

When volumes are not high enough to justify dedicating a single line of multiple workers to a single customer type or product, managers still may be able to derive the benefits of line-flow layout—simpler materials handling, low setups, and reduced labor costs—by creating line-flow layouts in some portions of the facility. Two techniques for creating such layouts are one-worker, multiple-machines (OWMM) cells, and group technology (GT) cells.

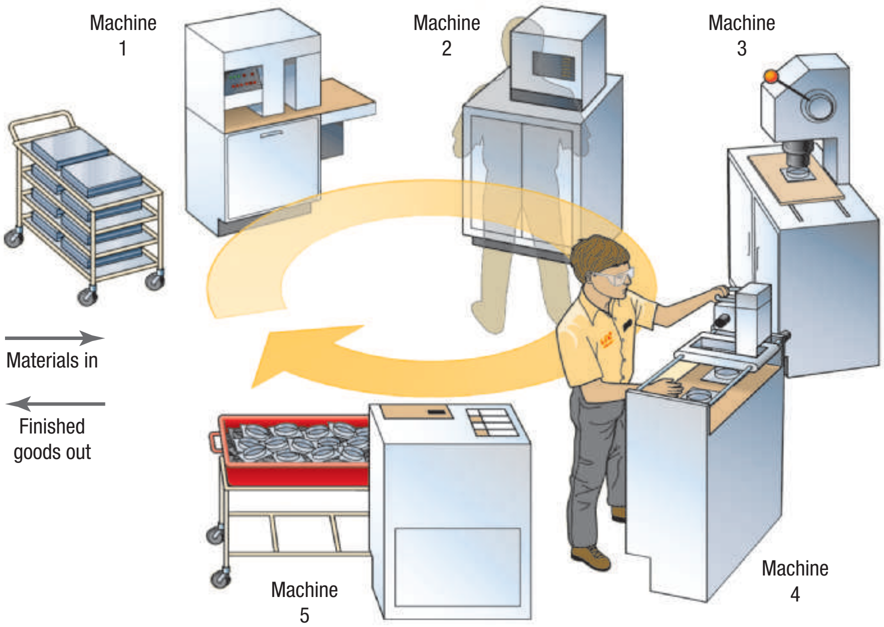
**one-worker, multiple-machines (OWMM) cell**
A one-person cell in which a worker operates several different machines simultaneously to achieve a line flow.

### One Worker, Multiple Machines

If volumes are not sufficient to keep several workers busy on one production line, the manager might set up a line small enough to keep one worker busy. The **one-worker, multiple-machines (OWMM) cell** is a workstation in which a worker operates several different machines simultaneously to achieve a line flow. Having one worker operate several identical machines is not unusual. However, with an OWMM cell, several different machines are in the line.

Figure 6.4 illustrates a five-machine OWMM cell that is being used to produce a flanged metal part, with the machines encircling one operator in the center. (A U-shape also is common.) The operator moves around the circle, performing tasks (typically loading and unloading) that have not been automated. Different products or parts can be produced in an OWMM cell by changing the

▼ **FIGURE 6.4**
One-Worker, Multiple-Machines (OWMM) Cell




[5]TBM Consulting Group; **http://www.tbmcg.com/about/ourroots/house_toyota.php**

machine setups. If the setup on one machine is especially time-consuming for a particular part, management can add a duplicate machine to the cell for use whenever that part is being produced.

An OWMM arrangement reduces both inventory and labor requirements. Inventory is cut because, rather than piling up in queues waiting for transportation to another part of the plant, materials move directly into the next operation. Labor is cut because more work is automated. The addition of several low-cost automated devices can maximize the number of machines included in an OWMM arrangement: automatic tool changers, loaders and unloaders, start and stop devices, and fail-safe devices that detect defective parts or products. Manufacturers are applying the OWMM concept widely because of their desire to achieve low inventories.

## Group Technology

**group technology (GT)**

An option for achieving line-flow layouts with low volume processes; this technique creates cells not limited to just one worker and has a unique way of selecting work to be done by the cell.

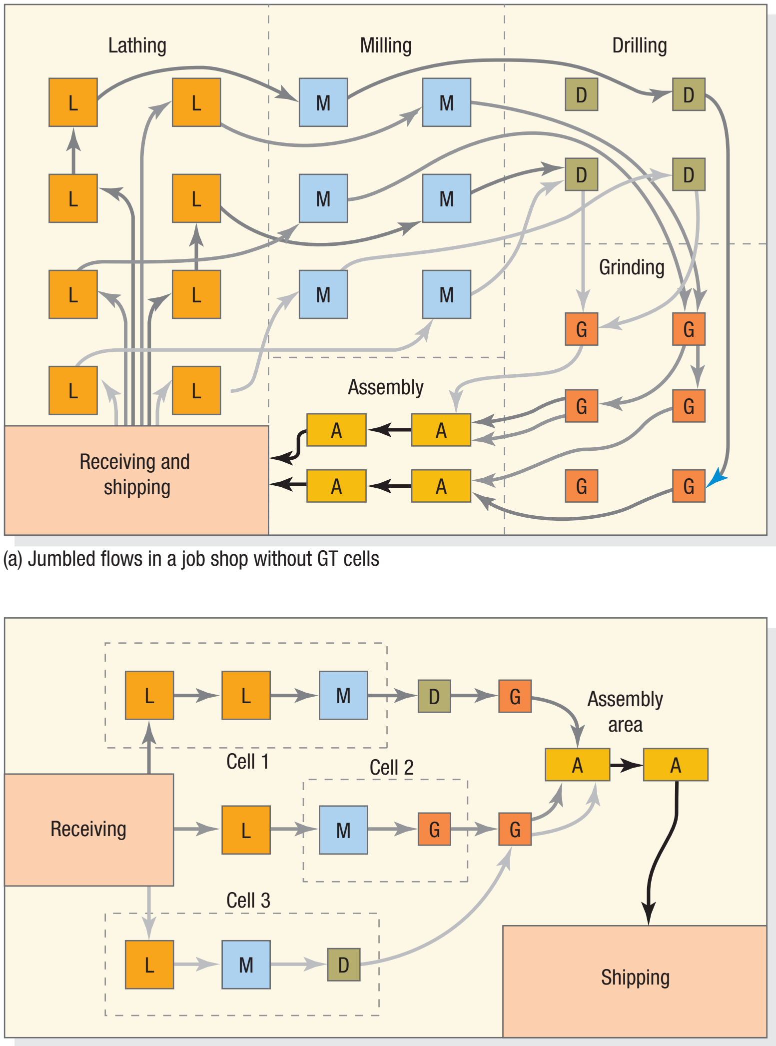
A second option for achieving line-flow layouts with low volume processes is **group technology (GT)**. This manufacturing technique creates cells not limited to just one worker and has a unique way of selecting work to be done by the cell. The GT method groups parts or products with similar characteristics into families and sets aside groups of machines for their production. Families may be based on size, shape, manufacturing or routing requirements, or demand. The goal is to identify a set of products with similar processing requirements and minimize machine changeover or setup. For example, all bolts might be assigned to the same family because they all require the same basic processing steps regardless of size or shape.

Once parts have been grouped into families, the next step is to organize the machine tools needed to perform the basic processes on these parts into separate cells. The machines in each cell require only minor adjustments to accommodate product changeovers from one part to the next in the same family. By simplifying product routings, GT cells reduce the time a job is in the shop. Queues of materials waiting to be worked on are shortened or eliminated. Frequently, materials handling is automated so that, after loading raw materials into the cell, a worker does not handle machined parts until the job has been completed.

Figure 6.5 compares process flows before and after creation of GT cells. Figure 6.5(a) shows a shop floor where machines are grouped according to function: lathing, milling, drilling, grinding, and assembly. After lathing, a part is moved to one of the milling machines, where it waits in line until it has a higher priority than any other job competing for the machine's capacity. When the milling operation on the part has been finished, the part is moved to a drilling machine, and so on. The queues can be long, creating significant time delays. Flows of materials are jumbled because the parts being processed in any one area of the shop have so many different routings.

By contrast, the manager of the shop shown in Figure 6.5(b) identified three product families that account for a majority of the firm's production. One family always requires two lathing operations followed by one operation at the milling machines. The second family always requires a milling operation followed by a grinding operation. The third family requires the use of a lathe, a milling machine, and a drill press. For simplicity, only the flows of parts assigned to these three families are shown. The remaining parts are produced at machines outside the cells and still have jumbled routings. Some equipment might have to be duplicated, as when a machine is required for one or more cells and for operations outside the cells. However, by creating three GT cells, the manager has definitely created more line flows and simplified routings.

Managerial Practice 6.1 illustrates how along with adopting principles of continuous flow processes, standardized work methods, and cellular layouts, Panasonic Corporation used robots and automation to increase throughput and reduce costs in its manufacturing plant.




(a) Jumbled flows in a job shop without GT cells

(b) Line flows in a job shop with three GT cells

**FIGURE 6.5**

Process Flows Before and After the Use of GT Cells

*Source:* Groover, Automation, Production Systems & Computer-Aided Manufacturing, 1st Ed., © 1980. Reprinted and Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.

## MANAGERIAL PRACTICE 6.1 Panasonic Corporation

**Panasonic Corporation**, which was originally founded as Matsushita Corporation in 1918 to produce lamps, has grown to become one of the largest electronic manufacturing firms in the world. As of March 31, 2014, Panasonic had 271,789 employees and over 500 consolidated companies creating net sales of about $75 billion per year. While the last few years have been challenging in terms of reduction in sales and workforce, Panasonic continues to be one of the largest producers in Japan of electronic products. Renowned for its global focus on efficiency and lean operations, its pursuit of excellence is exemplified nowhere better than at the Matsushita Electric Company's factory in Saga on Japan's southern island of Kyushu, where cordless phones, fax machines, and security cameras are made in record time by machines in a spotless facility.

Even though the plant's efficiency had doubled over a four-year span, managers saw opportunities for "trimming the fat" and improving further. A cluster of robots that could seamlessly hand off work to one another, flexibly substitute for a broken robot, and use software to synchronize production replaced the plant's conveyor belts. As a result, throughput time declined from 2.5 days to 40 minutes, allowing the Saga plant to make twice as many phones per week, which in turn allowed a reduction in inventory because components such as chips and circuit boards spend much less time in the factory. Being able to make things faster means that the plant can quickly change the product mix even as customer demands shift and new products are introduced, thus allowing Panasonic to keep ahead of low-cost rivals in other Asian countries.

Panasonic has used the lessons learned from the Saga mother plant to change layouts and setups at six other plants in China, Malaysia, Mexico, and Great Britain. These plants have been able to similarly cut their inventories and improve productivity, even as ideas from local staff at each plant were incorporated into the change effort. The next sets of improvements are focused on breaking assembly lines into cells and better utilizing the idle robots. In addition, standardized circuit board designs that are common to a large variety of end products are being used to minimize the retooling of robots for every type of board. By relentlessly focusing on minimizing waste and continuously improving efficiency, Panasonic has been able to weather severe business challenges and downturn better than what would have been the case otherwise.


Lain Masterton/Alamy

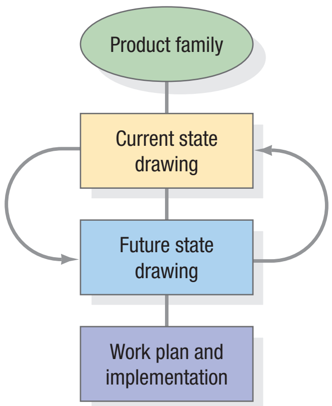
Panasonic stand with many 3D television screens at IFA consumer electronics trade fair in Berlin, Germany.

*Source:* Kenji Hall, "No One Does Lean Like the Japanese," Business Week (July 10, 2006), pp. 40–41; **http://panasonic.net/corporate/info/** (August 4, 2014).

# Value Stream Mapping

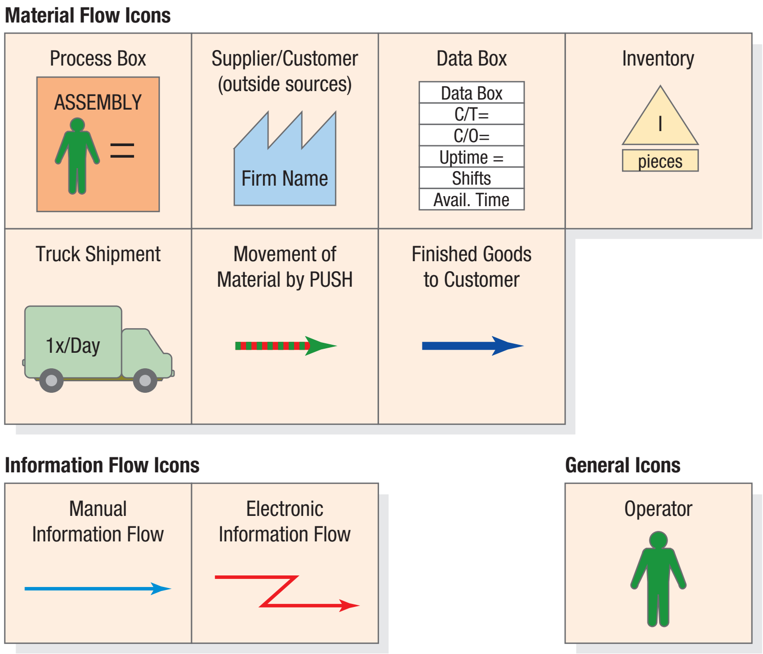
**Value stream mapping (VSM)** is a widely used qualitative lean tool aimed at eliminating waste or muda. Waste in many processes can be as high as 60 percent. Value stream mapping is helpful because it creates a visual map of every process involved in the flow of materials and information in a product's value chain. These maps consist of a current state drawing, a future state drawing, and an implementation plan. Value stream mapping spans the supply chain from the firm's receipt of raw materials or components to the delivery of the finished good to the customer. Thus, it tends to be broader in scope, displaying far more information than a typical process map or a flowchart used with Six Sigma process improvement efforts. Creating such a big picture representation helps managers identify the source of wasteful non-value-added activities.

Value stream mapping follows the steps shown in Figure 6.6. The first step is to focus on one product family for which mapping can be done. It is then followed by drawing a current state map of the existing production situation: Analysts start from the customer end and work upstream to draw the map by hand and record actual process times rather than rely on information not obtained by firsthand observation. Information for drawing the material and information flows can be gathered from the shop floor, including the data related to each process: cycle time (C/T), setup or changeover time (C/O), uptime (on-demand available machine time expressed as a percentage), production batch sizes, number of people required to operate the process, number of product variations, pack size (for moving the product to the next stage), working time (minus breaks), and scrap rate. Value stream mapping uses a standard set of icons for material flow, information flow, and general information (to denote operators, safety stock buffers, etc.). Even though the complete glossary is extensive, a representative set of these icons is shown in Figure 6.7. These icons provide a common language for describing in detail how a facility should operate to create a better flow.




▲ **FIGURE 6.6**
Value Stream Mapping Steps
*Source:* © Copyright 2003 Lean Enterprise Institute, Inc. Cambridge, MA, lean.org. All rights reserved.

**FIGURE 6.7** ▶
Selected Set of Value Stream Mapping Icons




**value stream mapping (VSM)**
A qualitative lean tool for eliminating waste or muda that involves a current state drawing, a future state drawing, and an implementation plan.

## EXAMPLE 6.1 Determining the Value Stream Map, Takt Time, and Total Capacity

Jensen Bearings Incorporated, a ball bearing manufacturing company located in Lexington, South Carolina, receives raw material sheets from Kline Steel Company once a week every Monday for a product family of retainers (casings in which ball bearings are held), and then ships its finished product on a daily basis to a second-tier automotive manufacturing customer named GNK Enterprises. The product family of the bearing manufacturing company under consideration consists of two types of retainers—large (L) and small (S)—that are packaged for shipping in returnable trays with 40 retainers in each tray. The manufacturing process consists of a cell containing pressing operation; a piercing and forming cell, and a finish grind operation, after which the two types of retainers are staged for shipping. The information collected by the operations manager at Jensen Bearings Inc. is shown in Table 6.3.

**TABLE 6.3** OPERATIONS DATA FOR A FAMILY OF RETAINERS AT JENSEN BEARINGS, INC.

| | | |
|---|---|---|
| **Overall Process Attributes** | **Average demand: 3,200/week (1,000 "L"; 2,200 "S")**<br>**Batch size: 40**<br>**Number of shifts per day: 1**<br>**Availability: 8 hours per shift with two 30-minute lunch breaks** | |
| **Process Step 1** | Press | Cycle time = 12 seconds<br>Setup time = 10 min<br>Up time = 100%<br>Operators = 1<br>WIP = 5 days of sheets (Before Press) |
| **Process Step 2** | Pierce & Form | Cycle time = 34 seconds<br>Setup time = 3 minutes<br>Up time = 100%<br>Operators = 1<br>WIP = 1,000 "L," 1,250 "S" (Before Pierce & Form) |
| **Process Step 3** | Finish Grind | Cycle time = 35 seconds<br>Setup time = 0 minutes<br>Up time = 100%<br>Operators = 1<br>WIP = 1,050 "L," 2,300 "S" (Before Finish Grind) |
| **Process Step 4** | Shipping | WIP = 500 "L," 975 "S" (After Finish Grind) |

| | |
|---|---|
| **Overall Process Attributes** | **Average demand: 3,200/week (1,000 "L"; 2,200 "S")**<br>**Batch size: 40**<br>**Number of shifts per day: 1**<br>**Availability: 8 hours per shift with two 30-minute lunch breaks** |
| **Customer Shipments** | One shipment of 3,200 units each week in trays of 40 pieces |
| **Information Flow** | All communications from customer are electronic:<br>180/90/60/30/day Forecasts<br>Daily Order<br>All communications to supplier are electronic<br>4-Week Forecast<br>Weekly Fax<br>There is a weekly schedule manually delivered to Press, Pierce & Form, and Finish Grind and a Daily Ship Schedule manually delivered to Shipping<br>All material is pushed |

**a.** Using data shown in Table 6.3; create a value stream map for Jensen Bearings Inc. and show how the data box values are calculated.

**b.** What is the takt time for this manufacturing cell?

**c.** What is the production lead time at each process in the manufacturing cell?

**d.** What is the total processing time of this manufacturing cell?

**e.** What is the capacity of this manufacturing cell?

## SOLUTION

**a.** We use the VSM icons to illustrate in Figure 6.8 what a current state map would look like for Jensen Bearings Inc. The process characteristics and inventory buffers in front of each process are shown in the current state map of Figure 6.8. One worker occupies each station. The process flows shown at the bottom of Figure 6.8 are similar to the flowcharts discussed in Chapter 2, "Process Strategy and Analysis," except that more detailed information is presented here for each process. However, what really sets the

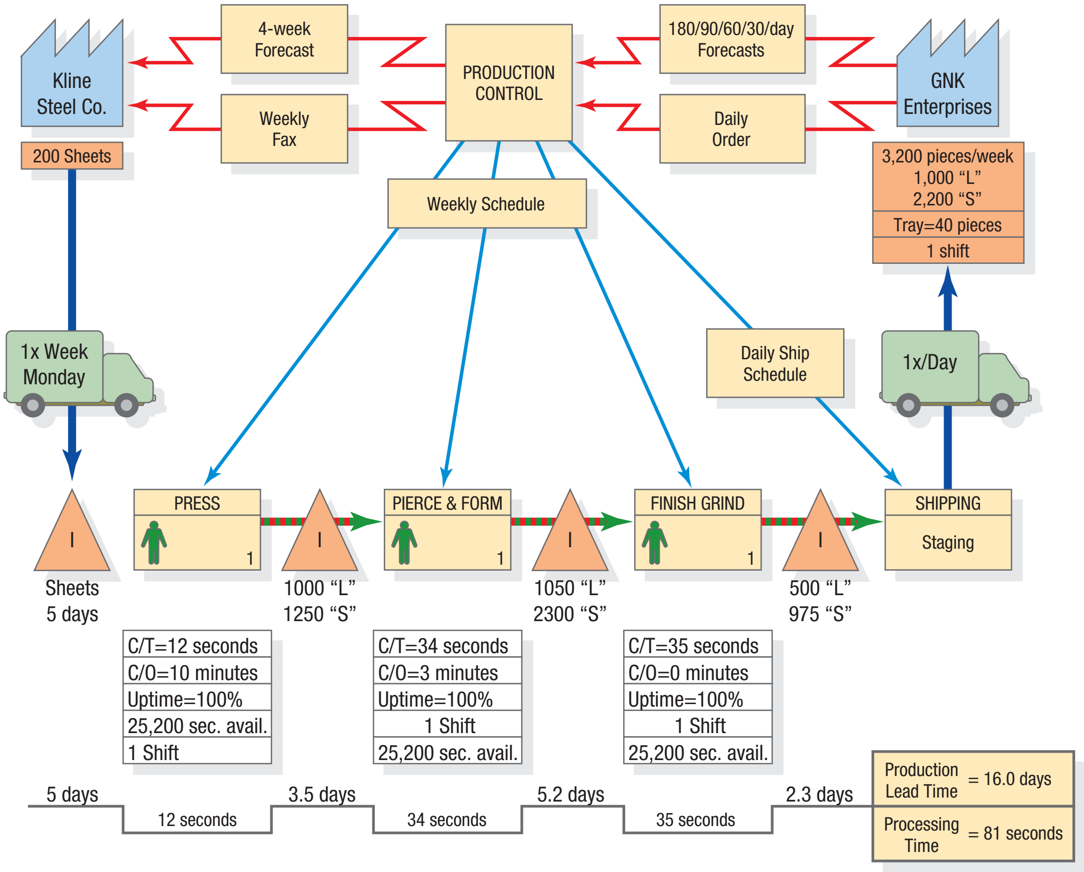



**FIGURE 6.8**
Current State Map for a Family of Retainers at Jensen Bearings Incorporated

value stream maps apart from flowcharts is the inclusion of information flows at the top of Figure 6.8, which plan and coordinate all the process activities. The value stream maps are more comprehensive than process flowcharts and meld together planning and control systems (discussed in detail in Chapter 11, "Efficient Resource Planning") with detailed flowcharts (discussed in Chapter 2) to create a comprehensive supply chain view that includes both information and material flows between the firm and its suppliers and customers.

**b.** The cell's takt time is the rate at which the cell must produce units to match demand.

Daily Demand $= [(1{,}000 + 2{,}200)$ pieces per week$]/5$ working days per week
$= 640$ pieces per day

Daily Availability $=$ (7 hours per day) $\times$ (3,600 seconds per hour) $=$ 25,200 seconds per day

Takt Time $=$ Daily Availability/Daily Demand $=$ (25,200 seconds per day)/640 pieces per day
$=$ **39.375** seconds per piece

**c.** The production lead time (in days) is calculated by summing the inventory held between each processing step divided by daily demand.

Raw Material lead time $= 5.0$ days

WIP lead time between Press and Pierce & Form $= (2{,}250/640) = 3.5$ days

WIP lead time between Pierce & Form and Finish Grind $= (3{,}350/640) = 5.2$ days

WIP lead time between Finish Grind and Shipping $= (1{,}475/640) = 2.3$ days

Total Production Lead time $= (5 + 3.5 + 5.2 + 2.3) =$ **16** days

**d.** The cycle time at each process is added to compute total processing time. The manufacturing cell's total processing time is $(12 + 34 + 35) =$ **81** seconds.

**e.** The cell's capacity may be calculated by locating the bottleneck and computing the number of units that it can process in the available time per day at that bottleneck with the given batch size of 40 units.

| Capacity at Press | Capacity at Pierce & Form | Capacity at Finish Grind |
|---|---|---|
| Cycle time = 12 seconds | Cycle time = 34 seconds | Cycle time = 35 seconds |
| Setup Time = (10 min * 60 seconds per min)/40 units per batch = **15.0 seconds** | Setup Time = (3 minutes * 60 seconds per minute)/40 units per batch = **4.5 seconds** | Setup Time = (0 minutes * 60 seconds per minute)/40 units per batch = **0.0 seconds** |
| Per Unit Processing Time = (12 + 15) = **27 seconds** | Per Unit Processing Time = (34 + 4.5) = **38.5 seconds** | Per Unit Processing Time = (35 + 0.0) = **35.0 seconds** |

At a batch size of 40 units, Pierce & Form process is the bottleneck.

Availability at Pierce & Form $=$ 25,200 seconds per day

Time at bottleneck (with setup) $=$ 38.5 seconds

Capacity (Availability/Time at bottleneck) $= 25{,}200/38.5 =$ **654** units per day

### DECISION POINT

Although the total processing time for each retainer is only 81 seconds, it takes 16 days for the cumulative production lead time. Clearly *muda* or waste is present, and opportunities exist for reconfiguring the existing processes with the goal of eliminating inventories and reducing cumulative production lead time.

Once the current state map is done, the analysts can then use principles of lean systems to create a future state map with more streamlined product flows. The future state drawing highlights sources of waste and how to eliminate them. The developments of the current and future state maps are overlapping efforts. Finally, the last step is aimed at preparing and actively using an implementation plan to achieve the future state. It may take only a couple of days from the creation of a future state map to the point where implementation can begin for a single product family. At this stage, the future state map becomes a blueprint for implementing a lean system and is fine-tuned as implementation progresses. As the future state becomes reality, a new future state map is drawn, thus denoting continuous improvement at the value stream level.

Unlike the theory of constraints (see Chapter 5, "Managing Process Constraints"), which accepts the existing system bottlenecks and then strives to maximize the throughput given that set of constraint(s), value stream mapping endeavors to understand through current state and future state maps how existing processes can be altered to eliminate bottlenecks and other wasteful activities. The goal is to bring the production rate of the entire process closer to the customer's desired demand rate. The benefits of applying this tool to the waste-removal process include reduced lead times and work-in-process inventories, reduced rework and scrap rates, and lower indirect labor costs.

# The *Kanban* System

One of the most publicized aspects of lean systems, and the TPS in particular, is the *kanban* system developed by Toyota. ***Kanban***, meaning "card" or "visible record" in Japanese, refers to cards used to control the flow of production through a factory. In the most basic *kanban* system, a card is attached to each container of items produced. The container holds a given percent of the daily production requirements for an item. When the user of the parts empties a container, the card is removed from the container and put on a receiving post. The empty container is then taken to the storage area, and the card signals the need to produce another container of the part. When the container has been refilled, the card is put back on the container, which is then returned to a storage area. The cycle begins again when the user of the parts retrieves the container with the card attached.

***kanban***

A Japanese word meaning "card" or "visible record" that refers to cards used to control the flow of production through a factory.

Figure 6.9 shows how a single-card *kanban* system works when a fabrication cell feeds two assembly lines. As an assembly line needs more parts, the *kanban* card for those parts is taken to the receiving post, and a full container of parts is removed from the storage area. The receiving post accumulates cards for assembly lines and a scheduler sequences the production of replenishment parts. In this example, the fabrication cell will produce product 2 (red) before it produces product 1 (green). The cell consists of three different operations, but operation 2 has two workstations. Once production has been initiated in the cell, the product begins on operation 1 but could be routed to either of the workstations performing operation 2, depending on the workload at the time. Finally, the product is processed on operation 3 before being taken to the storage area.

## General Operating Rules

The operating rules for the single-card system are simple and are designed to facilitate the flow of materials while maintaining control of inventory levels.

1. Each container must have a card.
2. The assembly line always withdraws materials from the fabrication cell. The fabrication cell never pushes parts to the assembly line because, sooner or later, parts will be supplied that are not yet needed for production.
3. Containers of parts must never be removed from a storage area without a *kanban* first being posted on the receiving post.
4. The containers should always contain the same number of good parts. The use of nonstandard containers or irregularly filled containers disrupts the production flow of the assembly line.

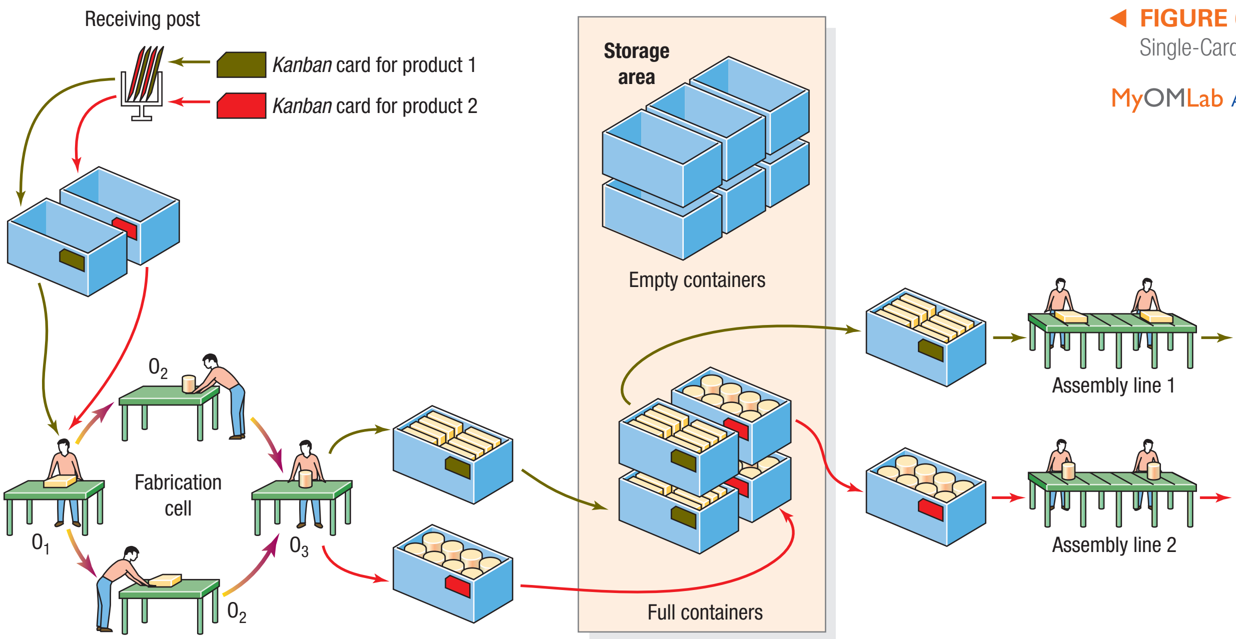



**FIGURE 6.9**
Single-Card *Kanban* System

MyOMLab Animation

5. Only nondefective parts should be passed along to the assembly line to make the best use of materials and worker's time. This rule reinforces the notion of building quality at the source, which is an important characteristic of lean systems.
6. Total production should not exceed the total amount authorized on the *kanbans* in the system.

Toyota uses a two-card system, based on a withdrawal card and a production-order card, to control inventory quantities more closely. The withdrawal card specifies the item and the quantity the user of the item should withdraw from the producer of the item, as well as the stocking locations for both the user and the producer. The production-order card specifies the item and the quantity to be produced, the materials required and where to find them, and where to store the finished item. Materials cannot be withdrawn without a withdrawal card, and production cannot begin without a production-order card. The cards are attached to containers when production commences. By manipulating the number of withdrawal and production cards in play at any time, management can control the flow of materials in the production system.

## Determining the Number of Containers

The number of authorized containers in the TPS determines the amount of authorized inventory. Management must make two determinations: (1) the number of units to be held by each container, and (2) the number of containers flowing back and forth between the supplier station and the user station. The first decision amounts to determining the size of the production lot.

The number of containers flowing back and forth between two stations directly affects the quantities of work-in-process inventory, which includes any safety stock inventory to cover for unexpected requirements.[4] The containers spend some time in production, in a line waiting, in a storage location, or in transit. The key to determining the number of containers required is to estimate the average lead time needed to produce a container of parts. The lead time is a function of the processing time per container at the supplier station, the waiting time during the production process, and the time required for materials handling. Little's Law, which says that the average work-in-process inventory (WIP) equals the average demand rate multiplied by the average time a unit spends in the manufacturing process, can be used to determine the number of containers needed to support the user station (see Supplement B, "Waiting Line Models").

$$\text{WIP} = (\text{average demand rate})(\text{average time a container spends in the manufacturing process}) + \text{safety stock}$$

In this application of determining the number of containers needed for a part, WIP is the product of $\kappa$, the number of containers, and $c$, the number of units in each container. Consequently,

$$\kappa c = \bar{d}(\bar{\omega} + \bar{\rho})(1 + \alpha)$$

$$\kappa = \frac{\bar{d}(\bar{\omega} + \bar{\rho})(1 + \alpha)}{c}$$

where

$\kappa$ = number of containers for a part

$\bar{d}$ = expected daily demand for the part, in units

$\bar{\omega}$ = average waiting time during the production process plus materials handling time per container, in fractions of a day

$\bar{\rho}$ = average processing time per container, in fractions of a day

$c$ = quantity in a standard container of the part

$\alpha$ = a policy variable that adds safety stock to cover for unexpected circumstances (Toyota uses a value of no more than 10 percent)

The number of containers must, of course, be an integer. Rounding $\kappa$ up provides more inventory than desired, whereas rounding $\kappa$ down provides less.

The container quantity, $c$, and the efficiency factor, $\alpha$, are variables that management can use to control inventory. Adjusting $c$ changes the size of the production lot, and adjusting $\alpha$ changes the amount of safety stock. The *kanban* system allows management to fine-tune the flow of materials in the system in a straightforward way. For example, removing cards from the system reduces the number of authorized containers of the part thus reducing the inventory of the part. Thus, a major benefit is the simplicity of the system, whereby product mix or volume changes can easily be accomplished by adjusting the number of *kanbans* in the system.

[4]We discuss safety stocks, and their use, in more detail in Chapter 9, "Managing Inventories," and Chapter 12 "Designing Effective Supply Chains."

**EXAMPLE 6.2** **Determining the Appropriate Number of Containers**

The Westerville Auto Parts Company produces rocker-arm assemblies for use in the steering and suspension systems of four-wheel-drive trucks. A typical container of parts spends 0.02 day in processing and 0.08 day in materials handling and waiting during its manufacturing cycle. The daily demand for the part is 2,000 units. Management believes that demand for the rocker-arm assembly is uncertain enough to warrant a safety stock equivalent of 10 percent of its authorized inventory.

**a.** If each container contains 22 parts, how many containers should be authorized?

**b.** Suppose that a proposal to revise the plant layout would cut materials handling and waiting time per container to 0.06 day. How many containers would be needed?

**Solver-Number of Containers**
Enter data in yellow-shaded area.

| | |
|---|---|
| Daily Expected Demand | 2000 |
| Quantity in Standard Container | 22 |
| Container Waiting Time (days) | 0.06 |
| Processing Time (days) | 0.02 |
| Policy Variable | 10% |
| Containers Required | 8 |

▲ **FIGURE 6.10**
OM Explorer Solver for Number of Containers

### SOLUTION

**a.** If $\bar{d} = 2{,}000$ units/day, $\bar{p} = 0.02$ day, $\alpha = 0.10$, $\bar{w} = 0.08$ day, and $c = 22$ units,

$$\kappa = \frac{2{,}000(0.08 + 0.02)(1.0)}{22} = \frac{220}{22} = \mathbf{10} \text{ containers}$$

**b.** Figure 6.10 from OM Explorer shows that the number of containers drops to **8**.

### DECISION POINT

The average lead time per container is $\bar{w} + \bar{p}$. With a lead time of 0.10 day, 10 containers are needed. However, if the improved facility layout reduces the materials handling time and waiting time to $\bar{w} = 0.06$ day, only 8 containers are needed. The maximum authorized inventory of the rocker-arm assembly is $\kappa c$. Thus, in part (a), the maximum authorized inventory is 220 units, but in part (b), it is only 176 units. Reducing $\bar{w} + \bar{p}$ by 20 percent reduces the inventory of the part by 20 percent. Management must balance the cost of the layout change (a one-time charge) against the long-term benefits of inventory reduction.

## Other *Kanban* Signals

Cards are not the only way to signal the need for more production of a part. Other, less formal methods are possible, including container and containerless systems.

**Container System** Sometimes, the container itself can be used as a signal device: An empty container signals the need to fill it. Unisys took this approach for low-value items. Adding or removing containers adjusts the amount of inventory of the part. This system works well when the container is specially designed for a particular part and no other parts could accidentally be put in the container. Such is the case when the container is actually a pallet or fixture used to position the part during precision processing.

**Containerless System** Systems requiring no containers have been devised. In assembly-line operations, operators use their own workbench areas to put completed units on painted squares, one unit per square. Each painted square represents a container, and the number of painted squares on each operator's bench is calculated to balance the line flow. When the subsequent user removes a unit from one of the producer's squares, the empty square signals the need to produce another unit. McDonald's uses a containerless system. Information entered by the order taker at the cash register is transmitted to the cooks and assemblers, who produce the sandwiches requested by the customer.

# Operational Benefits and Implementation Issues

To gain competitive advantage and to make dramatic improvements, a lean system can be the solution. Lean systems can be an integral part of a corporate strategy based on speed because they cut cycle times, improve inventory turnover, and increase labor productivity. Recent studies also show that practices representing different components of lean systems such as JIT, TQM, Six Sigma, total preventive maintenance (TPM), and human resource management (HRM), individually as well as cumulatively, improve the performance of manufacturing plants as well as service facilities. Lean systems also involve a considerable amount of employee participation through small-group interaction sessions, which have resulted in improvements in many aspects of operations, not the least of which is service or product quality.

Even though the benefits of lean systems can be outstanding, problems can still arise after a lean system has long been operational, which was witnessed recently in product recalls and a perceived shift away from tightly controlled quality that has always been the standard at Toyota. In addition, implementing a


wunkley/Alamy

After the pathology lab at the University of Pittsburgh Medical Center adopted a lean operations approach based on a line system versus a batch-and-queue system, the time it took to process samples dropped from days to just hours. Diagnoses were made more quickly as a result, and patients' stays at the hospital were shortened.

lean system can take a long time. We address below some of the issues managers should be aware of when implementing a lean system.

## Organizational Considerations

Implementing a lean system requires management to consider issues of worker stress, cooperation and trust among workers and management, and reward systems and labor classifications.

**The Human Costs of Lean Systems** Lean systems can be coupled with statistical process control (SPC) to reduce variations in output. However, this combination requires a high degree of regimentation and sometimes stresses the workforce. For example, in the TPS, workers must meet specified cycle times, and with SPC, they must follow prescribed problem-solving methods. Such systems might make workers feel pushed and stressed, causing productivity losses or quality reductions. In addition, workers might feel a loss of some autonomy because of the close linkages in work flows between stations with little or no excess capacity or safety stocks. Managers can mitigate some of these effects by allowing for some slack in the system—either safety stock inventories or capacity slack—and by emphasizing work flows instead of worker pace. Managers also can promote the use of work teams and allow them to determine their task assignments within their domains of responsibility.

**Cooperation and Trust** In a lean system, workers and first-line supervisors must take on responsibilities formerly assigned to middle managers and support staff. Activities such as scheduling, expediting, and improving productivity become part of the duties of lower-level personnel. Consequently, the work relationships in the organization must be reoriented in a way that fosters cooperation and mutual trust between the workforce and management. However, this environment can be difficult to achieve, particularly in light of the historical adversarial relationship between the two groups.

**Reward Systems and Labor Classifications** In some instances, the reward system must be revamped when a lean system is implemented. At General Motors, for example, a plan to reduce stock at one plant ran into trouble because the production superintendent refused to cut back on the number of unneeded parts being made. Why? Because his or her salary was based on the plant's production volume.

The realignment of reward systems is not the only hurdle. Labor contracts traditionally crippled a company's ability to reassign workers to other tasks as the need arose. For example, a typical automobile plant in the United States has several unions and dozens of labor classifications. Generally, the people in each classification are allowed to do only a limited range of tasks. In some cases, companies have managed to give these employees more flexibility by agreeing to other types of union concessions and benefits. In other cases, however, companies relocated their plants to take advantage of nonunion or foreign labor.

## Process Considerations

Firms using lean systems typically have some dominant work flows. To take advantage of lean practices, firms might have to change their existing layouts. Certain workstations might have to be moved closer together, and cells of machines devoted to particular component families may have to be established. However, rearranging a plant to conform to lean practices can be costly. For example, many plants currently receive raw materials and purchased parts by rail, but to facilitate smaller and more frequent shipments, truck deliveries would be preferable. Loading docks might have to be reconstructed or expanded and certain operations relocated to accommodate the change in transportation mode and quantities of arriving materials.

## Inventory and Scheduling

Manufacturing firms need to have stable master production schedules, short setups, and frequent, reliable supplies of materials and components to achieve the full potential of the lean systems concept.

**Schedule Stability** Daily production schedules in high-volume, make-to-stock environments must be stable for extended periods. At Toyota, the master production schedule is stated in fractions of days over a 3-month period and is revised only once a month. The first month of the schedule is frozen to avoid disruptive changes in the daily production schedule for each workstation; that is, the workstations execute the same work schedule each day of the month (see Chapter 11, "Efficient Resource Planning," for more details on master production schedules and freezing). At the beginning of each month, *kanbans* are reissued for the new daily production rate. Stable schedules are needed so that production lines can be balanced and new assignments found for employees who otherwise would be underutilized. Lean systems used in high-volume, make-to-stock environments cannot respond quickly to scheduling changes because little slack inventory or capacity is available to absorb these changes.

**Setups** If the inventory advantages of a lean system are to be realized, small lot sizes must be used. However, because small lots require a large number of setups, companies must significantly reduce setup times. Some companies have not been able to achieve short setup times and, therefore, have to use large-lot production, negating some of the advantages of lean practices. Also, lean systems are vulnerable to lengthy changeovers to new products because the low levels of finished goods inventory will be insufficient to cover demand while the system is down. If changeover times cannot be reduced, large finished goods inventories of the old product must be accumulated to compensate. In the automobile industry, every week that a plant is shut down for new-model changeover costs between $16 million and $20 million in pretax profits.

**Purchasing and Logistics** If frequent, small shipments of purchased items cannot be arranged with suppliers, large inventory savings for these items cannot be realized. For example, in the United States, such arrangements may prove difficult because of the geographic dispersion of suppliers.

The shipments of raw materials and components must be reliable because of the low inventory levels in lean systems. A plant can be shut down because of a lack of materials. Similarly, recovery becomes more prolonged and difficult in a lean system after supply chains are disrupted, which is what happened immediately after 9/11.

Process design and continuous improvement are key elements of a successful operations strategy. In this chapter, we focused on lean systems as a directive for efficient process design and an approach to achieve continuous improvement. We showed how JIT systems, a popular lean systems approach, can be used for continuous improvement and how a *kanban* system can be used to control the amount of work-in-process inventory. Transforming a current process design to one embodying a lean systems philosophy is a constant challenge for management, often fraught with implementation issues. However, adopting appropriate tools and management approaches can facilitate such a transformation, as exemplified by firms like Aldi, Panasonic, and Toyota among others.

## LEARNING GOALS IN REVIEW

| Learning Goal | Guidelines for Review | MyOMLab Resources |
|---|---|---|
| 1 Describe how lean systems can facilitate the continuous improvement of processes. | See the section on "Continuous Improvement using a Lean Systems Approach," pp. 229–230. Review Figure 6.1 and the opening vignette on Aldi Corporation. | |
| 2 Identify the strategic supply chain and process characteristics of lean systems. | See the sub-sections on "Supply Chain Considerations in Lean Systems," p. 231, and "Process Considerations in Lean Systems," pp. 232–236. The subsection on "Toyota Production System," pp. 236–237, illustrates how one firm implements lean characteristics to gain strategic advantage over its competition. | **Video**: Lean Systems at Autoliv |
| 3 Explain the differences between one worker, multiple machine (OWMM) and group technology (GT) approaches to lean system layouts. | The section "Designing Lean System Layouts," pp. 237–239, shows you how to differentiate between two different types of layouts used to implement line flows, when volumes are not high to justify a single line of multiple workers to a single product. | |
| 4 Understand value stream mapping and its role in waste reduction. | The section "Value Stream Mapping," pp. 239–243, shows you how to construct value stream maps and identify waste in the processes. Review Example 6.1 for details on mapping and creating data boxes. | |
| 5 Understand *kanban* systems for creating a production schedule in a lean system. | The section "The *Kanban* System," pp. 243–245, shows how firms like Toyota use simple visual systems to pull production and make exactly what the market demands. Example 6.2 shows how to calculate the number of *kanban* cards needed. | **OM Explorer Tutor:** 6.1: Calculate Number of Containers in a *Kanban* System<br>**OM Explorer Solver**: Number of Containers |
| 6 Explain the implementation issues associated with the application of lean systems. | The section "Operational Benefits and Implementation Issues," pp. 245–247, reviews organizational and process considerations needed to successfully deploy lean systems and gain their benefits. | **Video**: Lean Systems at Autoliv |

# Key Equations

## The *Kanban* System

Number of containers:

$$\kappa = \frac{\overline{d}(\overline{\omega} + \overline{\rho})(1 + \alpha)}{c}$$

# Key Terms

five S (5S) 234
group technology (GT) 238
*heijunka* 233
*jidoka* 232
JIT system 230
just-in-time (JIT) philosophy 229
*kanban* 243
lean systems 228
lot 231
mixed-model assembly 234
one worker, multiple machines (OWMM) cell 237
*poka-yoke* 233
pull method 232
push method 232
single-digit setup 231
takt time 233
value stream mapping (VSM) 240

# Solved Problem 1

MyOMLab Video

Metcalf, Inc., manufacturers engine assembly brackets for two major automotive customers. The manufacturing process for the brackets consists of a cell containing a forming operation, a drilling operation, a finish grinding operation, and packaging, after which the brackets are staged for shipping. The information collected by the operations manager at Metcalf, Inc., is shown in Table 6.4.

**TABLE 6.4 | OPERATIONS DATA FOR BRACKETS AT METCALF, INC.**

| | | |
|---|---|---|
| **Overall Process Attributes** | **Average demand: 2700/day**<br>**Batch size: 50**<br>**Number of shifts per day: 2**<br>**Availability: 8 hours per shift with a 30-minute lunch break** | |
| **Process Step 1** | Forming | Cycle time = 11 seconds<br>Setup time = 3 minutes<br>Up time = 100%<br>Operators = 1<br>WIP = 4000 units (Before Forming) |
| **Process Step 2** | Drilling | Cycle time = 10 seconds<br>Setup time = 2 minutes<br>Up time = 100%<br>Operators = 1<br>WIP = 5,000 units (Before Drilling) |
| **Process Step 3** | Grinding | Cycle time = 17 seconds<br>Setup time = 0 minutes<br>Up time = 100%<br>Operators = 1<br>WIP = 2,000 units (Before Grinding) |
| **Process Step 4** | Packaging | Cycle time = 15 seconds<br>Setup time = 0 minutes<br>Up time = 100%<br>Operators = 1<br>WIP = 1,600 units (Before Packaging)<br>WIP = 15,700 units (Before Shipping) |
| **Customer Shipments** | One shipment of 13,500 units each week | |
| **Information Flow** | All communications with customer are electronic<br>There is a weekly order release to Forming<br>All material is pushed | |

**a.** Using data shown in Table 6.4; create a value stream map for Metcalf, Inc., and show how the data box values are calculated.
**b.** What is the takt time for this manufacturing cell?
**c.** What is the production lead time at each process in the manufacturing cell?
**d.** What is the total processing time of this manufacturing cell?
**e.** What is the capacity of this manufacturing cell?

## SOLUTION

**a.** Figure 6.11 shows the current value stream state map for Metcalf, Inc.

**b.** Daily Demand = 2,700 units per day

Daily Availability = (7.5 hours per day) × (3,600 seconds per hour) × (2 shifts per day) = 54,000 seconds per day

Takt Time = Daily Availability/Daily Demand = 54,000 seconds per day/2,700 units per day = **20** seconds per unit

**c.** The production lead time (in days) is calculated by summing the inventory held between each processing step divided by daily demand.

Raw Material lead time = [4,000/2,700] = 1.48 days

WIP lead time between Forming and Drilling = [5,000/2,700] = 1.85 days

WIP lead time between Drilling and Grinding = [2,000/2,700] = 0.74 day

WIP lead time between Grinding and Packaging = [1,600/2,700] = 0.59 day

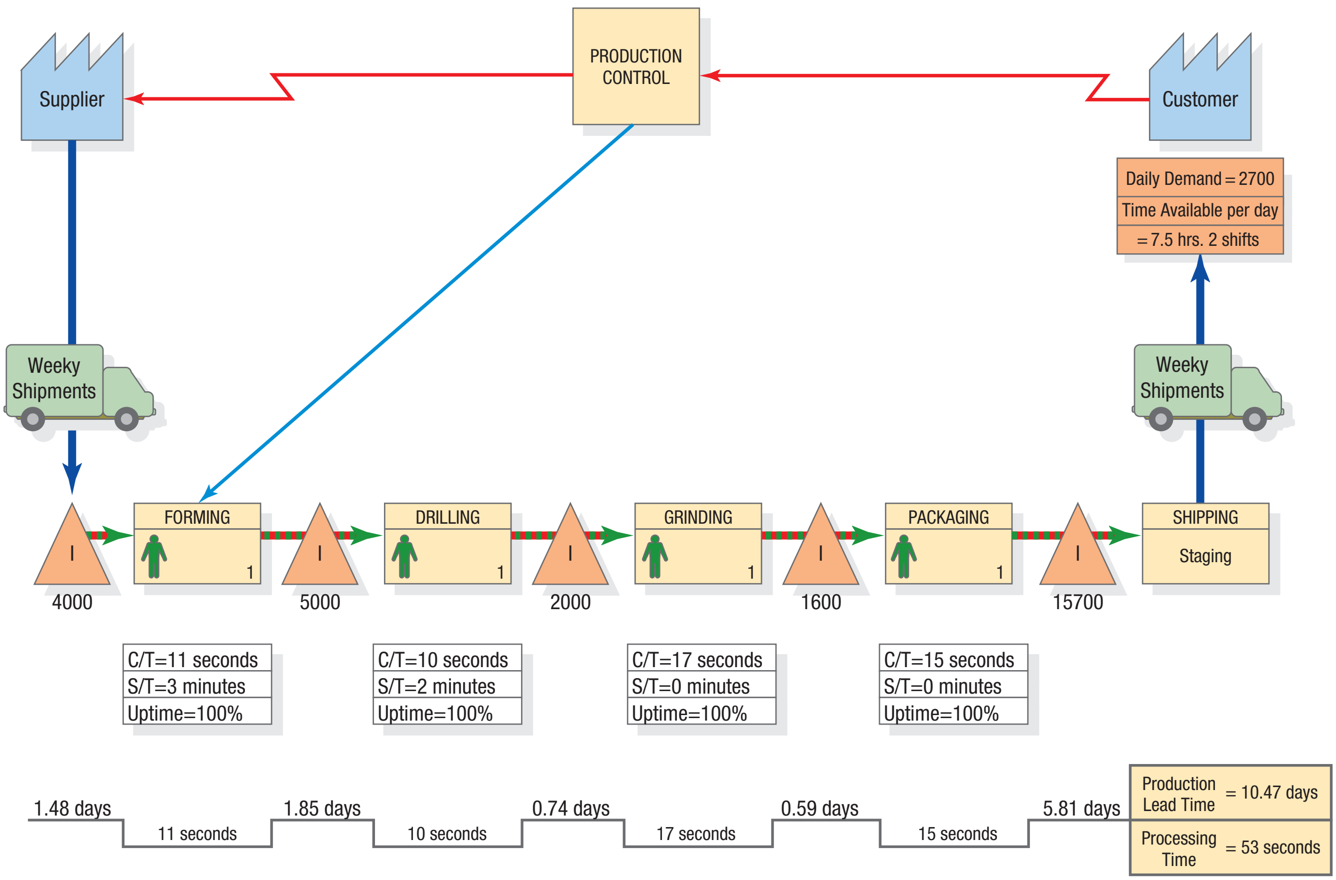
Finished Goods lead time before Shipping = [15,700/2,700] = 5.81 days

The cell's total production lead time is: 1.48 + 1.85 + 0.74 + 0.59 + 5.81 = **10.47** days

**d.** The manufacturing cell's total processing time is (11 + 10 + 17 + 15) = **53** seconds.

**e.** The cell's capacity may be calculated by locating the bottleneck and computing the number of units that it can process in the available time per day at that bottleneck.

**FIGURE 6.11**
Current State Value Stream Map for Metcalf, Inc.



| Capacity at Forming | Capacity at Drilling | Capacity at Grinding | Capacity at Packaging |
|---|---|---|---|
| Cycle time = 11 seconds | Cycle time = 10 seconds | Cycle time = 17 seconds | Cycle time = 15 seconds |
| Setup Time = (3 minutes * 60 seconds per minute)/ 50 units per batch = **3.6 seconds** | Setup Time = (2 minutes * 60 seconds per minute)/ 50 units per batch = **2.4 seconds** | Setup Time = **zero seconds** | Setup Time = **zero seconds** |
| Per Unit Processing Time = (11 + 3.6) = **14.6 seconds** | Per Unit Processing Time = (10 + 2.4) = **12.4 seconds** | Per Unit Processing Time = (17 + 0) = **17.0 seconds** | Per Unit Processing Time = (15 + 0) = **15.0 seconds** |

**a.** At a batch size of 50 units, Finish Grinding process is the bottleneck

**b.** Availability at Grinding = 54,000 seconds per day

**c.** Time at bottleneck (with setup) = 17.0 seconds

**d.** Capacity (Availability/Time at bottleneck) = 54,000/17 = **3,176** units per day

# Solved Problem 2

A company using a *kanban* system has an inefficient machine group. For example, the daily demand for part L105A is 3,000 units. The average waiting time for a container of parts is 0.8 day. The processing time for a container of L105A is 0.2 day, and a container holds 270 units. Currently, 20 containers are used for this item.

**a.** What is the value of the policy variable, $\alpha$?

**b.** What is the total planned inventory (work-in-process and finished goods) for item L105A?

**c.** Suppose that the policy variable, $\alpha$, was 0. How many containers would be needed now? What is the effect of the policy variable in this example?

### SOLUTION

**a.** We use the equation for the number of containers and then solve for $\alpha$:

$$\kappa = \frac{\bar{d}(\bar{\omega} + \bar{\rho})(1 + \alpha)}{c}$$

$$20 = \frac{3{,}000(0.8 + 0.2)(1 + \alpha)}{270}$$

and

$$(1 + \alpha) = \frac{20(270)}{3{,}000(0.8 + 0.2)} = 1.8$$

$$\alpha = 1.8 - 1 = \mathbf{0.8}$$

**b.** With 20 containers in the system and each container holding 270 units, the total planned inventory is $20(270) =$ **5,400** units.

**c.** If $\alpha = 0$

$$\kappa = \frac{3{,}000(0.8 + 0.2)(1 + 0)}{270} = 11.11, \text{ or } \mathbf{12} \text{ containers}$$

The policy variable adjusts the number of containers. In this case, the difference is quite dramatic because $\bar{\omega} + \bar{\rho}$ is fairly large and the number of units per container is small relative to daily demand.

# Discussion Questions

1. Charming Fashion, a Spanish company that manufactures handbags and shoes for young customers, has decided to introduce aspects of lean systems into its processes. It is especially interested in the *Kanban* system since some of its more important buyers are Japanese department stores that favor this aspect of lean systems. The company has two choices, one is to introduce the single-card *Kanban* system, which has the advantage of simplicity and it's designed to facilitate the flow of materials while maintaining control of inventory levels. The other, which would be suitable for its differentiated and articulated product lines, is the two-card system. This will be based on a withdrawal card and a production-order card. While this is more complex, it will allow Charming Fashion to control inventory quantities more closely.
   a. What should the company do? Explain the reasoning process.
   b. Apart from applying the *Kanban* card system, what other options are available to the company?
2. Which elements of lean systems would be most troublesome for manufacturers to implement? Why?
3. List the pressures that lean systems pose for supply chains, whether in the form of process failures due to inventory shortages or labor stoppages, and so forth. Reflect on how these pressures may apply to a firm that is actually implementing lean philosophy in their operations.
4. Identify a service or a manufacturing process that you are familiar with, and draw a current state value stream map to depict its existing information and material flows.

# Problems

The OM Explorer and POM for Windows software is available to all students using the 11th edition of this textbook. Go to **http://www.pearsonglobaleditions.com/krajewski** to download these computer packages. If you purchased MyOMLab, you also have access to Active Models software and significant help in doing the following problems. Check with your instructor on how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software replaces entirely the manual calculations.

## Strategic Characteristics of Lean Systems

1. Swenson Saws produces bow, frame, dovetail, and tenon saws used by craft furniture makers. During an 8-hour shift, a saw is produced every 6 minutes. The demand for bow, frame, and dovetail saws is about the same, but the demand for tenon saws is twice the demand for the other three.
   a. If mixed-model scheduling is used, how many of each saw will be produced before the cycle is repeated?
   b. Determine a satisfactory production sequence for one unit production. How often is this sequence repeated?
   c. How many of each saw does Swenson produce in one shift?
2. The Harvey Motorcycle Company produces three models: the Tiger, a sure-footed dirt bike; the LX2000, a nimble café racer; and the Golden, a large interstate tourer. This month's master production schedule calls for the production of 54 Goldens, 42 LX2000s, and 30 Tigers per 7-hour shift.
   a. What average cycle time is required for the assembly line to achieve the production quota in 7 hours?
   b. If mixed-model scheduling is used, how many of each model will be produced before the production cycle is repeated?
   c. Determine a satisfactory production sequence for the ultimate in small-lot production: one unit.
   d. The design of a new model, the Cheetah, includes features from the Tiger, LX2000, and Golden models. The resulting blended design has an indecisive character and is expected to attract some sales from the other models. Determine a mixed-model schedule resulting in 52 Goldens, 39 LX2000s, 26 Tigers, and 13 Cheetahs per 7-hour shift. Although the total number of motorcycles produced per day will increase only slightly, what problem might be anticipated in implementing this change from the production schedule indicated in part (b)?
3. The Farm-4-Less tractor company produces a grain combine (GC) in addition to both a large (LT) and small size tractor (SM). Its production manager desires to produce to customer demand using a mixed-model production line. The current sequence of production, which is repeated 30 times during a shift, is SM-GC-SM-LT-SM-GC-LT-SM. A new machine is produced every 2 minutes. The plant operates two 8-hour shifts. There is no downtime because the 4 hours between each shift are dedicated to maintenance and restocking raw material. Based on this information, answer the following questions.
   a. How long does it take the production cycle to be completed?
   b. How many of each type of machine does Farm-4-Less produce in a shift?

## Value Stream Mapping

4. Figure 6.12 provides a new current state value stream map for the family of retainers at the Jensen Bearings, Inc., firm described in Example 6.1. This map depicts the value stream after Kline Steel agrees to accept daily orders for steel sheets and Jensen Bearings continues to deliver the finished goods on a daily basis.

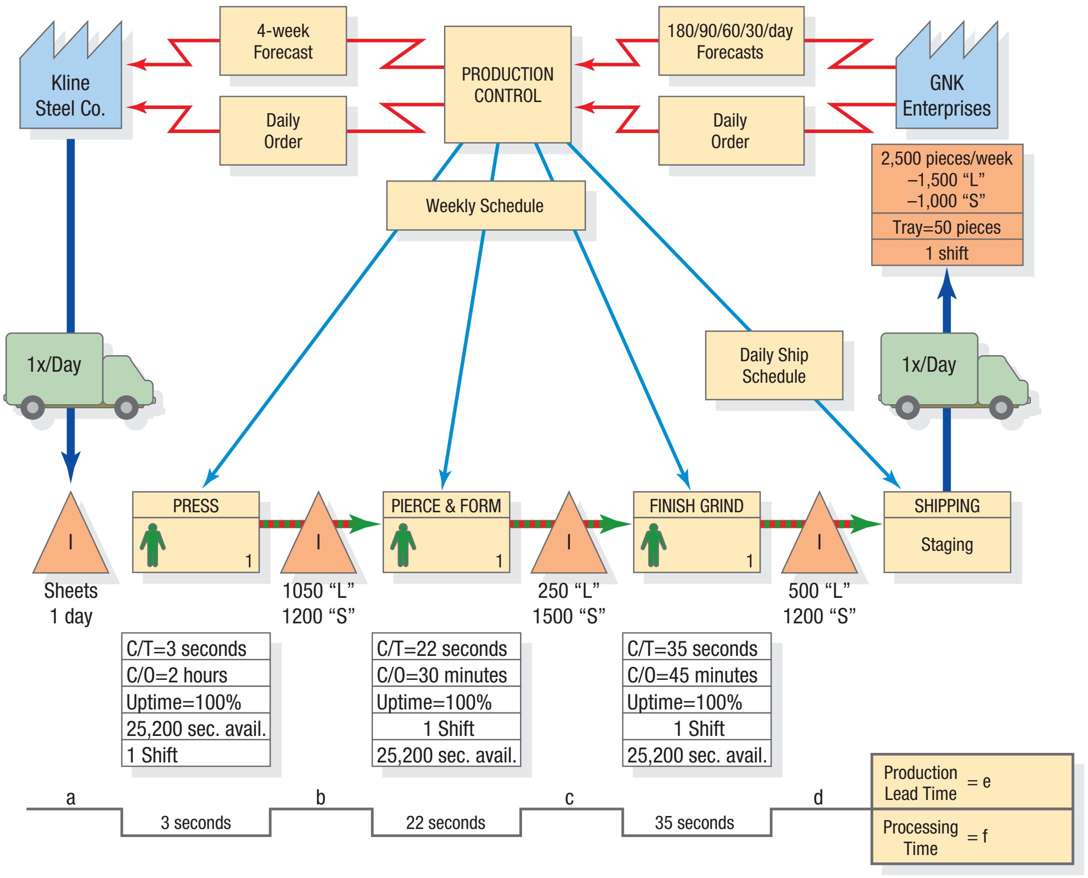



**FIGURE 6.12** ▶
New Current State Value Stream Map at Jensen Bearings, Inc.

Calculate each component of the new value stream's reduced lead time.

**a.** How many days of raw material does the Bearing's plant now hold?

**b.** How many days of work in process inventory is held between Press and Pierce & Form?

**c.** How many days of work in process inventory is held between Pierce & Form and Finish Grind?

**d.** How many days of work in process inventory is held between Finish Grind and Shipping?

**e.** What is the new value steam's production lead time?

**f.** What is the new value stream's processing time?

**5.** Anguilla Manufacturing is interested in using the data collected during Value Stream Mapping to evaluate the current state performance of the capacity of its manual assembly line process under different batch size assumptions. The availability of processing per shift, after accounting for breaks and a mid-shift employee meeting, is 436 minutes. The current operating characteristics of each processing step are found in the table below. Note that each step can only process one part at a time and all steps must process the same sized batches.

| | Saw | Sand | Drill | Assemble | Mark |
|---|---|---|---|---|---|
| Cycle time per part | 20 seconds | 15 seconds | 30 seconds | 25 seconds | 10 seconds |
| Setup time per batch | 3 minutes | 4 minutes | 0 minutes | 3 minutes | 8 minutes |

**a.** Calculate the average processing time per unit and the capacity at each step assuming batch sizes of:

**i.** 10 units

**ii.** 20 units

**iii.** 30 units

**iv.** 40 units

**b.** Identify the bottleneck operation and the line's processing capacity for each batch size listed in part a.

**c.** Explain why batch sizes beyond 40 units will not increase the line's processing capacity further.

**6.** The manager at Ormonde, Inc., collected the value stream mapping data from the plant's most problematic manufacturing cell that fabricates parts for washing machines. This data is shown in Table 6.5. Using this data, calculate the current state performance of the cell and answer the following questions.

**a.** What is the cell's current inventory level?

**b.** What is the takt time for this manufacturing cell?

**c.** What is the production lead time at each process in the manufacturing cell?

**d.** What is the total processing time of this manufacturing cell?

**e.** What is the capacity of this manufacturing cell?

**TABLE 6.5** | **OPERATIONS DATA FOR ORMONDE, INC.**

| | | |
|---|---|---|
| **Overall Process Attributes** | **Average demand: 550/day**<br>**Batch size: 20**<br>**Number of shifts per day: 3**<br>**Availability: 8 hours per shift with a 45-minute lunch break** | |
| **Process Step 1** | Cutting | Cycle time = 120 seconds<br>Setup time = 3 minutes<br>Up time = 100%<br>Operators = 1<br>WIP = 400 units (Before Cutting) |
| **Process Step 2** | Bending | Cycle time = 100 seconds<br>Setup time = 5 minutes<br>Up time = 100%<br>Operators = 1<br>WIP = 500 units (Before Bending) |
| **Process Step 3** | Punching | Cycle time = 140 seconds<br>Setup time = none<br>Up time = 100%<br>Operators = 1<br>WIP = 200 units (Before Punching)<br>WIP = 1,000 units (After Punching) |
| **Customer Shipments** | One shipment of 2,750 units each week | |
| **Information Flow** | All communications with customer are electronic<br>There is a weekly order release to Cutting<br>All material is pushed | |

## The *Kanban* System

**7.** A fabrication cell at Spradley's Sprockets uses the pull method to supply gears to an assembly line. George Jitson is in charge of the assembly line, which requires 500 gears per day. Containers typically wait 0.20 day in the fabrication cell. Each container holds 20 gears, and one container requires 1.8 days in machine time. Setup times are negligible. If the policy variable for unforeseen contingencies is set at 5 percent, how many containers should Jitson authorize for the gear replenishment system?

**8.** You are asked to analyze the *kanban* system of LeWin, a French manufacturer of gaming devices. One of the workstations feeding the assembly line produces part M670N. The daily demand for M670N is 1,800 units. The average processing time per unit is 0.003 day. LeWin's records show that the average container spends 1.05 days waiting at the feeder workstation. The container for M670N can hold 300 units. Twelve containers are authorized for the part. Recall that $\rho$ is the average processing time per container, not per individual part.

**a.** Find the value of the policy variable, $\alpha$, that expresses the amount of implied safety stock in this system.

**b.** Use the implied value of $\alpha$ from part (a) to determine the required reduction in waiting time if one container was removed. Assume that all other parameters remain constant.

**9.** An assembly line requires two components: gadjits and widjits. Gadjits are produced by center 1 and widjits by center 2. Each unit of the end item, called a jit-together, requires three gadjits and two widjits, as shown in Figure 6.13. The daily production quota on the assembly line is 800 jit-togethers.

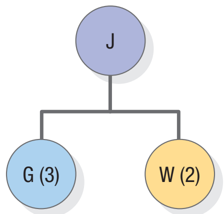



**FIGURE 6.13**
Components for End Item J

The container for gadjits holds 80 units. The policy variable for center 1 is set at 0.09. The average waiting time for a container of gadjits is 0.09 day, and 0.06 day is needed to produce a container. The container for widjits holds 50 units, and the policy variable for center 2 is 0.08. The average waiting time per container of widjits is 0.14 day, and the time required to process a container is 0.20 day.

**a.** How many containers are needed for gadjits?

**b.** How many containers are needed for widjits?

**10.** Gestalt, Inc. uses a *kanban* system in its automobile production facility in Germany. This facility operates 8 hours per day to produce the Jitterbug, a replacement for the obsolete but immensely popular Jitney Beetle. Suppose that a certain part requires 150 seconds of processing at machine cell 33B and a container of parts average 1.6 hours of waiting time there. Management allows a 10 percent buffer for unexpected occurrences. Each container holds 30 parts, and 8 containers are authorized. How much daily demand can be satisfied with this system? (Hint: Recall that $\rho$ is the average processing time per container, not per individual part.)

**11.** A U.S. Postal Service supervisor is looking for ways to reduce stress in the sorting department. With the existing arrangement, stamped letters are machine-canceled and loaded into tubs with 375 letters per tub. The tubs are then pushed to postal clerks, who read and key zip codes into an automated sorting machine at the rate of 1 tub per 375 seconds. To overcome the stress caused when the stamp canceling machine outpaces the sorting clerks, a pull system is proposed. When the clerks are ready to process another tub of mail, they will pull the tub from the canceling machine area. How many tubs should circulate between the sorting clerks and the canceling machine if 90,000 letters are to be sorted during an 8-hour shift, the safety stock policy variable, $\alpha$, is 0.18, and the average waiting time plus materials handling time is 25 minutes per tub?

**12.** The production schedule at Mazda calls for 1,200 Mazdas to be produced during each of 22 production days in January and 900 Mazdas to be produced during each of 20 production days in February. Mazda uses a *kanban* system to communicate with Gesundheit, a nearby supplier of tires. Mazda purchases four tires per vehicle from Gesundheit. The safety stock policy variable, $\alpha$, is 0.15. The container (a delivery truck) size is 200 tires. The average waiting time plus materials handling time is 0.16 day per container. Assembly lines are rebalanced at the beginning of each month. The average processing time per container in January is 0.10 day. February processing time will average 0.125 day per container. How many containers should be authorized for January? How many for February?

**13.** Jitsmart is a retailer of plastic action-figure toys. The action figures are purchased from Tacky Toys, Inc., and arrive in boxes of 48. Full boxes are stored on high shelves out of reach of customers. A small inventory is maintained on child-level shelves. Depletion of the lower-shelf inventory signals the need to take down a box of action figures to replenish the inventory. A reorder card is then removed from the box and sent to Tacky Toys to authorize replenishment of a container of action figures. The average demand rate for a popular action figure, Agent 99, is 36 units per day. The total lead time (waiting plus processing) is 11 days. Jitsmart's safety stocky policy variable, $\alpha$, is 0.25. What is the authorized stock level for Jitsmart?

**14.** Markland First National Bank of Rolla utilizes *kanban* techniques in its check processing facility. The following information is known about the process. Each *kanban* container can hold 50 checks and spends 24 minutes a day in processing and 2 hours a day in materials handling and waiting. Finally, the facility operates 24 hours per day and utilizes a policy variable for unforeseen contingencies of 0.25.

**a.** If there are 20 *kanban* containers in use, what is the current daily demand of the check processing facility?

**b.** If the muda or the waste in the system were eliminated completely, how many containers would then be needed?

## VIDEO CASE Lean Systems at Autoliv

Autoliv is a world-class example of lean manufacturing. This Fortune 500 company makes automotive safety components such as seat belts, airbags, and steering wheels, and has over 80 plants in more than 32 countries. Revenues in 2007 topped $6.7 billion. Autoliv's lean manufacturing environment is called the Autoliv Production System (APS) and is based on the principles of lean manufacturing pioneered by Toyota, one of the world's largest automobile manufacturers, and embodied in its Toyota Production System (TPS).

At the heart of Autoliv is a system that focuses on continuous improvement. Based on the "House of Toyota," Autoliv's Ogden, Utah, airbag module plant puts the concepts embodied in the house to work every day. The only difference between the Toyota house and the one at Autoliv is that the company has added a third pillar to its house to represent employee involvement in all processes because a culture of involvement, while the norm in Japan, is not always found in the United States.

Autoliv started its lean journey back in 1995. At that time, the Ogden plant was at manufacturing capacity with 22 work cells. Company managers acknowledge that, back then, Autoliv was "broken" and in need of significant and immediate change if it was to survive. This meant that everyone—from senior management to employees and suppliers—needed to be on-board with rebuilding the company. It was not that the company could not fulfill the needs of its automaker customers; however, with increasing demand for both reliable and cost-effective component supplies, pressure to change became obvious. Recognizing the value of Toyota's approach, senior management made the commitment to embark on its own journey to bring the transformative culture of lean manufacturing to Autoliv.

Pearson

Autoliv employee folds an air bag in a Toyota-inspired production cell.

In 1998, *sensei* Takashi Harada arrived from Japan to spend three years teaching top company managers the principles, techniques, and culture of the lean system. This helped managers create an environment in which continuous improvement could be fostered and revered as an essential activity for long-term success. Because the environment was changing, it made it difficult at first for suppliers to meet Autoliv's constantly changing and unstable processes. It also made problems visible and forced the company to address and resolve the problems instead of finding ways to work around them as had been done in the past. Daily audits, monthly training, and more in-depth education programs were created to help focus attention on where changes needed to be made. Workers and management were organized into teams that were held accountable for common goals and tasked with working toward common success.

By 2004, the lean culture was integrated into the company, and it now hosts regular visits by other corporations who want to learn from Autoliv's journey and experiences. Compared to 1995, the space required for a typical work cell has been reduced by 88.5 percent, while the number of cells has grown over 400 percent. This has allowed Autoliv to dramatically increase its production capacity with minimal investment.

Lean concepts play out every day in the each plant. For example, everyone gathers at the start of the workday for pre-shift stretching and a brief meeting—this is part of the employee involvement pillar in the APS House. Then, workers head to one of 104 work cells on the plant floor. Heijunka Room team members deliver heijunka cards to each cell to communicate the work to be done in that cell. Lot sizes may vary with each card delivered to the cell. Everything the workers need to make the lot is in the cell and regularly replenished through the *kanban* card system. Every 24 minutes, another heijunka card comes to the cell to signal workers what they will build next. This is part of the JIT pillar in the house.

Since a culture of continuous improvement requires employees at every level to be responsible for quality, a worker may identify an "abnormal condition" during work execution that slows down the work of the cell, or stops it altogether. This is embodied in the right pillar of the Toyota house—jidoka, which Autoliv interprets as "stop and fix." This is a rare occurrence, however, since both Autoliv and its suppliers are expected to deliver defect-free products. When a supplier is new or has experienced quality issues, the supplier pays for inspection in Autoliv's receiving dock area until Autoliv is certain the supplier can meet quality expectations for all future deliveries. In this manner, workers in the cells know they can trust the integrity of the raw materials arriving through the *kanban* system into their cells for assembly. Jidoka may also come into play when a machine does not operate properly or an employee notices a process that has deviated from the standard. When workers "stop and fix" a problem at the point of its creation, they save the company from added cost as well as lost confidence in the eyes of the customer.

To help focus worker efforts daily, Autoliv has a blue "communication wall" that everyone sees as they head to their work site. The wall contains the company's "policy deployment," which consists of company-wide goals for customer satisfaction, shareholder/financial performance, and safety and quality. The policy deployment begins with the company-wide goals, which then flow down to the plant level through the plant manager's goals, strategies, and actions for the facility. These linked activities assure that Autoliv achieves its goals. By communicating this information—and more—in a visual manner, the central pillar of the APS House is supported. Other visual communication and management methods are in place as well. For example, each cell has an overhead banner that states how that cell is doing each month in the areas of safety, quality, employee involvement, cost, and delivery. These all tie into the policy deployment shown on the communication wall.

Another visual communication method is to use a "rail" for the management of the heijunka cards in each cell. The rail has color-coded sections. As each card is delivered, it slides down a color-coded railing to the team. At the end nearest the cell, the rail is green, indicating that any cards that fall into this area can be completed within normal working hours. The middle of the rail is yellow, indicating overtime for the cell that day. The end is red, meaning weekend overtime is required to bring work processes back into harmony with customer demand. As a heijunka card slides down the rail, it stops when it hits the end or stacks up behind another card. If the cell is not performing at the required pace to meet customer demand, the cards will stack up on the rail and provide a very visual cue that the cell is not meeting expectations. This provides an opportunity for cell team members as well as management to implement immediate countermeasures to prevent required overtime if the situation is not remedied.

All aisles and walkways surrounding cells are to be clear of materials, debris, or other items. If anything appears in those areas, everyone can quickly see the abnormality. As team members work together to complete their day's work, the results of their efforts are displayed boldly on each cell's "communi-cube." This four-sided rotating display visually tells the story of the cell's productivity, quality, and 5S performance. The cube also contains a special section for the management of *kaizen* suggestions for the team itself. These *kaizens* enable the team to continuously improve the work environment as well as drive the achievement of team results.

Autoliv's lean journey embodied in the Autoliv Production System has led to numerous awards and achievement of its policy deployment goals. Product defects have been dramatically reduced, inventory levels are lower, and inventory turnover is approaching world-class levels of 50. Employee turnover is close to 5 percent and remains well below that of other manufacturers in the industry. Yet the destination has not been reached. The company continues its emphasis on driving systemic improvement to avoid complacency and loss of competitive advantage. Best practices from sources beyond each immediate area of the organization are studied and integrated. And finding ways to engage and reward Autoliv's workforce in a maturing market is critical. Kaizen suggestions in the most recent year at the Ogden plant totaled 74,000, or nearly 60 per employee, indicating the culture of continuous improvement in Autoliv's APS House is alive and well.

## QUESTIONS

1. Why is a visual management approach such an integral part of Autoliv's lean system?
2. Describe the JIT considerations presented in the chapter as they relate to Autoliv's manufacturing environment.
3. Which method of work flow is embodied in Autoliv's system? Why is this approach most suitable to its lean environment?
4. When Autoliv started its lean journey, a number of operational benefits and implementation issues had to be addressed. What were they, and how were they addressed?

# CASE Duraweld Ltd.

## Background

Duraweld is a British plastic binding manufacturer established in 1959 and the result of a merger between two local small and medium enterprises (SMEs) in 1970. This company has sailed through the recent economic downturn and has reinvented itself thanks to following lean principles. Duraweld produces customized plastic elements, such as stationery, and decided to move away from standardization to resist the growing competition from Asia on higher volume items resulting in low volume/high variety production profile. Their website is customer-oriented and orders can be processed online. Businesses can order personalized promotional products, such as tax discs and travel document holders. The responsiveness of the sales team and its customer support are praised by many users. Also, the company is part of the Prince's Mayday Network, an association of British companies annually reporting their environmental impact, with the aim to gradually reduce their carbon footprint.

## Lean Implementation

To sustain its growth, but most importantly to give agility to the operation side of the business, the Managing Director in 2006, hired John McEvans, a lean specialist with a proven track of success in the automotive industry, to replace the outgoing production manager. Before the lean implementation, the company had a 50 percent machine utilization rate to quickly produce to order, and a turnaround of 10 days. But a low utilization rate is a synonym of waste. As in any lean implementation, the changes are gradual; it is an evolution rather than a revolution. One of the first steps was the effort to reduce distances traveled by parts and goods within the factory. Duraweld quickly implemented a visual management of *kanban* cards to reduce overproduction. *Kanban* is a card system signaling depletion of the next stock. It is the foundation of the "pull" system, opposed to "push." These cards indicate, what to produce, when to produce and how much to produce. It allows a better regulation of intermediate stocks in the production cycle as less intermediate stock is needed, thus enhancing flexibility and driving costs down. A shadow board was used to properly store tools. Too often workers walk from a station to another to find the tools they need, and sometimes they do not even find them. Showing results is a key element in the spread of the lean philosophy across the company. A model of excellence was set to maximize the impact on other workers. Floors under the machines were painted white to detect early wear, prevent corrective maintenance, and favor preventive maintenance. Labels were used to ensure tools were stored in the proper place. At Duraweld, John McEvans also made sure the relevant machines and tools were aggregated in cells. This minimizes workers' travel as all the machines, tools, and information related to their tasks is set within a defined area. Among the employees, a champion was designated for every cell to promote and sustain lean efforts over time. Naturally, Duraweld discovered its "hidden factory" of unused equipment and mess, even though it prided itself as a fairly clean factory.

## Spreading Good Practice

The company also ensured that not only the employees from the shop floor, but also senior management would be committed to the lean programme success. Surprisingly, the higher resistance to change was met from the latter, believing it would be another lost opportunity to manage the plant more efficiently. However, over time, the lean production manager succeeded in reducing resistance and even to welcome earlier nonadopters. An important element of Duraweld's successful lean implementation was communication. Changes have to be seen and heard; people have to talk about the benefits these changes have brought them. Eventually, everyone becomes part of the system and ensures that waste is reduced, at every level.

## Lean Sustainability

Once these efforts made and shared across the entire company, the ultimate challenge was to sustain them over time. Duraweld understood this concept and invested in an enterprise resource planning (ERP) system to micromanage stock variations and seasonality (See Chapter 16: "Planning Sufficient Resources" for more discussion on ERP). These systems link operations across organizations. They are costly to implement as processes have sometimes to be formatted to fit the system. However eventually, materials movements, stocks and production schedules can all be managed from the monitor of a computer. The removal of the "hidden factory" meant that waste from plastic cuts would be recycled and reinserted in the manufacturing cycle. The lean implementation supported Duraweld's strategy of entering niche markets with higher margins. The company sustained its margins through the recent economic crisis and also ensured the production would stay in Great Britain rather than shifting to China, as it happened for other competitors. The company, thanks to productivity gains, reduced its shopfloor level staffing.

## Recognition

Duraweld gained countrywide recognition from its successful lean implementation. It acquired the ISO14001 certification and pioneered the polypropylene waste recycling into print-grade material. In an event organized by the UK Manufacturing Advisory Service, Duraweld organized a presentation of its lean processes and organized tours of its factory. This company shows that the lean system is not only for large manufacturers, but can also be implemented successfully by SMEs. The bottom line quickly improves as well as employee morale, the latter being proud to overachieve.

## QUESTIONS

1. List the 5S and compare to the lean implementation at Duraweld. If there are differences, explain them.
2. Describe which kind of waste was eliminated for each lean implementation at Duraweld. Can you think of other types of waste that could be eliminated?
3. Considering Duraweld's situation, explain which elements of the lean system you would further implement and what would be their positive consequences on the company.

*Source:* This case was prepared by Xavier Pierron, Coventry Business School, UK as basis for classroom discussion. Applying lean manufacturing to binding at Duraweld UK (2012) The Binding Edge, www.thebindingedge.com/article.asp?ID=95, accessed November 6, 2011.

Sean Dempsey/PA Wire/AP Images


Building on the success of Xbox 360, Xbox One was launched in 2013. Here, a gamer tries the Xbox One console at the Violin Factory in south London, ahead of its release in November.

# 7

# MANAGING EFFECTIVE PROJECTS

## XBOX 360

Anyone who has tried video gaming knows how entertaining and challenging it can be. What might not be known is that the total video game market is projected to be $111 billion for 2015. It is no wonder why companies such as Microsoft channel a lot of energy into the design and manufacture of video gaming consoles to satisfy that market. Microsoft's first offering was the Xbox in 2001 followed by the Xbox 360 in 2005, which has been touted to be the most influential product in the market because of its emphasis on digital media and online and multiplayer gaming. How did this trail-blazing product come into being?

Four years after the introduction of Xbox, Microsoft needed to quickly design, develop, and produce a new product. Sony's PlayStation 2 was dominating the video game market, and Microsoft needed a new product to compete with the impending release of PlayStation 3. Developing such a product is a project of massive proportions. The project consisted of four phases: (1) design, (2) analysis, (3) development, and (4) launch. The result was Xbox 360.

### Design

The design of the Xbox 360 was a collaborative effort between Microsoft and many other firms, including Astro Studios in San Francisco, which designed the overall console and controller; IBM, which designed the processor chip; ATI, which designed the graphics chip; and a host of game design firms to develop games for the new product. A key element of the new product was the built-in Internet access that allowed gamers to access online games, buy game add-ons, and access multiplayer games developed exclusively for Xbox 360. Microsoft also included its primary manufacturers, Flextronics and Wistron, in the design process to optimize the production and assembly of the more than 1,000 parts contained in an Xbox 360.

### Analysis

Getting an estimate of future sales for a new product is always difficult; however, in this case, the historic patterns for PlayStation 1, PlayStation 2, and Xbox were useful. Analysts found that the peak year for a PlayStation product was 4 years after its introduction and that the life cycle for those products is about 11 years. This information provided a basis for estimating the sales potential of Xbox 360, although actual sales may be limited due to supply constraints. Nonetheless, Microsoft realized that the potential was there to open a new generation of game consoles well ahead of the market.

### Development

Microsoft worked closely with Flextronics, Wistron, and the various design firms to iron out manufacturing problems in the early phases of Xbox 360 production. Once initial production was underway, Microsoft brought on Celestica to add production capacity. The decision was made to focus manufacturing operations in China. All told, 10,000 workers in China would be involved in Xbox 360 production.

### Launch

Microsoft's Xbox 360 gained an early lead in terms of market share due, in part, to its early launch date, which was one year ahead of its rivals PlayStation 3 and Wii. All told, the product was released in 36 countries in the first year of production, a Herculean effort requiring extensive coordination and a high level of project management skill. Sales of the Xbox 360 exceeded expectations with more than 10 million units sold in the first year alone; as of 2013, 80 million units were sold worldwide. Nonetheless, Microsoft experienced difficulties in getting the supply chain to meet customer demands in a timely fashion in the early days of the launch. The lesson to be learned is that projects can be planned and executed properly; however, the underlying infrastructure that delivers the product is equally important in the ultimate success of the venture.

The jobs of product designers and project managers do not end with the launch of a new product. Feedback from the market provides insight into new features for existing products or entirely new products. Subsequently, there was the Xbox 360 S in 2010, the Xbox 360 E in 2013, and the new generation Xbox One in 2013.

*Source:* David Holt, Charles Holloway, and Hau Lee, "Evolution of the Xbox Supply Chain," Stanford Graduate School of Business, Case: GS-49, (April 14, 2006); "Xbox 360," Wikipedia, the free encyclopedia, **http://en.wikipedia.org/wiki/Xbox_360**; Rob van der Meulen and Janessa Rivera, "Gartner Says Worldwide Video Market to Total $93 Billion in 2013," **http://www.gartner.com**, (October 29, 2013); Rick Marshall, "The History of the Xbox," **http://www.digitaltrends.com**, (May 12, 2013).

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

1. Explain the major activities associated with defining and organizing a project.
2. Describe the procedure for constructing a project network.
3. Develop the schedule of a project.
4. Analyze cost–time trade-offs in a project network.
5. Assess the risk of missing a project deadline.
6. Identify the options available to monitor and control projects.

Companies such as Microsoft are experts at managing projects such as Xbox 360. They master the ability to schedule activities and monitor progress within strict time, cost, and performance guidelines. A **project** is an interrelated set of activities with a definite starting and ending point, which results in a unique outcome for a specific allocation of resources.

**project**
An interrelated set of activities with a definite starting and ending point, which results in a unique outcome for a specific allocation of resources.

Projects are common in everyday life as well as in business. Planning weddings, remodeling bathrooms, writing term papers, and organizing surprise parties are examples of small projects in everyday life. Conducting company audits, planning mergers, creating advertising campaigns, reengineering processes, developing new services or products, and establishing a strategic alliance are examples of large projects in business.

The three main goals of any project are (1) complete the project on time or earlier, (2) do not exceed the budget, and (3) meet the specifications to the satisfaction of the customer. When we must undertake projects with some uncertainty involved, it does not hurt to have flexibility with respect to resource availability, deadlines, and budgets. Consequently, projects can be complex and challenging to manage. **Project management**, which is a systemized, phased approach to defining, organizing, planning, monitoring, and controlling projects, is one way to overcome that challenge.

**project management**
A systemized, phased approach to defining, organizing, planning, monitoring, and controlling projects.

Projects often cut across organizational lines because they need the skills of multiple professions and organizations. Furthermore, each project is unique, even if it is routine, requiring new combinations of skills and resources in the project process. For example, projects for adding a new branch office, installing new computers in a department, or developing a sales promotion may be initiated several times a year. Each project may have been done many times before; however, differences arise with each replication. Uncertainties, such as the advent of new technologies or the activities of competitors, can change the character of projects and require responsive countermeasures. Finally, projects are temporary because personnel, materials, and facilities are organized to complete them within a specified time frame and then are disbanded.

Projects, and the application of project management, facilitate the implementation of strategy. However, the power of this approach goes beyond the focus on one project. Operations strategy initiatives often require the coordination of many interdependent projects. Such a collection of projects is called a **program**, which is an interdependent set of projects with a common strategic purpose. As new project proposals come forward, management must assess their fit to the current operations strategy and ongoing initiatives and have a means to prioritize them because funds for projects are often limited. Projects can be also used to implement changes to processes and supply chains. For example, projects involving the implementation of major information technologies may affect all of a firm's core processes and supporting processes as well as some of their suppliers' and customers' processes. As such, projects are a useful tool for improving processes and supply chains.

**program**
An interdependent set of projects that have a common strategic purpose.

# Defining and Organizing Projects

A clear understanding of a project's organization and how personnel are going to work together to complete the project are keys to success. In this section, we will address (1) defining the scope and objectives, (2) selecting the project manager and team, and (3) recognizing the organizational structure.

Using Operations to Create Value

**PROCESS MANAGEMENT**
Process Strategy and Analysis
Managing Quality
Planning Capacity
Managing Process Constraints
Designing Lean Systems
→ **Managing Effective Projects**

**CUSTOMER DEMAND MANAGEMENT**
Forecasting Demand
Managing Inventories
Planning and Scheduling Operations
Efficient Resource Planning

**SUPPLY CHAIN MANAGEMENT**
Designing Effective Supply Chains
Supply Chains and Logistics
Integrating the Supply Chain
Managing Supply Chain Sustainability

## Defining the Scope and Objectives of a Project

A thorough statement of a project's scope, time frame, and allocated resources is essential to managing the project. This statement is often referred to as the *project objective statement*. The scope provides a succinct statement of project objectives and captures the essence of the desired project outcomes in the form of major deliverables, which are concrete outcomes of the project. Changes to the scope of a project inevitably increase costs and delay completion. Collectively, changes to scope are called *scope creep* and, in sufficient quantity, are primary causes of failed projects. The time frame for a project should be as specific as possible, as in "the project should be completed by January 1, 2017." Finally, although specifying an allocation of resources to a project may be difficult during the early stages of planning, it is important for managing the project. The allocation should be expressed as a dollar figure or as full-time equivalents of personnel time. A specific statement of allocated resources makes it possible to make adjustments to the scope of the project as it proceeds.

## Selecting the Project Manager and Team

Once the project is selected, a project manager must be chosen. The qualities of a good project manager should be well aligned with the roles a project manager must play.

- *Facilitator.* The project manager often must resolve conflicts between individuals or departments to ensure that the project has the appropriate resources for the job to be completed. Successful project managers have good leadership skills and a *systems view*, which encompasses the interaction of the project, its resources, and its deliverables with the firm as a whole.
- *Communicator.* Project progress and requests for additional resources must be clearly communicated to senior management and other stakeholders in a project. The project manager must also frequently communicate with the project team to get the best performance.

- *Decision Maker.* Good project managers will be sensitive to the way the team performs best and be ready to make tough decisions, if necessary. The project manger must organize the team meetings, specify how the team will make decisions, and determine the nature and timing of reports to senior management.

Selecting the project team is just as important as the selection of the project manager. Several characteristics should be considered.

- *Technical Competence.* Team members should have the technical competence required for the tasks to which they will be assigned.
- *Sensitivity.* All team members should be sensitive to interpersonal conflicts that may arise. Senior team members should be politically sensitive to help mitigate problems with upper-level management.
- *Dedication.* Team members should feel comfortable solving project problems that may spill over into areas outside their immediate expertise. They should also be dedicated to getting the project done, as opposed to maintaining a comfortable work schedule.

## Recognizing Organizational Structure

The relationship of the project manager to the project team is determined by the firm's organizational structure. Each of the three types of organizational structure described below has its own implications for project management.

- *Functional.* The project is housed in a specific department or functional area, presumably the one with the most interest in the project. Assistance from personnel in other functional areas must be negotiated by the project manager. In such cases, the project manager has less control over project timing than if the entire scope of the project fell within the purview of the department.
- *Pure Project.* The team members work exclusively for the project manager on a particular project. This structure simplifies the lines of authority and is particularly effective for large projects that consist of enough work for each team member to work full time. For small projects, it could result in significant duplication of resources across functional areas.
- *Matrix.* The matrix structure is a compromise between the functional and pure project structures. The project managers of the firm's projects all report to a program manager who coordinates resource and technological needs across the functional boundaries. The matrix structure allows each functional area to maintain control over who works on a project and the technology that is used. However, team members, in effect, have two bosses: the project manager and the department manager. Resolving these line-of-authority conflicts requires a strong project manager.


JB-2078/Alamy

The palm Jumeirah is an artificial archipelago in the shape of a palm tree extending into the Persian Gulf. The island has been created using 94 million cubic meters of sand and 7 million tons of rock. The island features themed hotels, three types of villas, apartment buildings, beaches, marinas, restaurants, and a variety of retail outlets. Projects of this magnitude must be carefully planned and organized.

# Constructing Project Networks

After the project is defined and organized, the team must formulize the specific work to be accomplished and the relationships between the activities in the project. Constructing a project network involves two steps: (1) defining the work breakdown structure, and (2) diagramming the network.

## Defining the Work Breakdown Structure

The **work breakdown structure (WBS)** is a statement of all work that has to be completed. Perhaps the single most important contributor to delay is the omission of work that is germane to the successful completion of the project. The project manager must work closely with the team to identify all activities. An **activity** is the smallest unit of work effort consuming both time and resources that the project manager can schedule and control. Typically, in the process of accumulating activities, the team generates a hierarchy to the work breakdown. Major work components are broken down to smaller tasks that ultimately are broken down to activities that are assigned to individuals. Figure 7.1 shows a WBS for a major project involving the relocation of a hospital. In the interest of better serving the surrounding community, the board of St. John's Hospital has decided to move to a new location. The project involves constructing a new hospital and making it operational. The work components at level 1 in the WBS can be broken down into smaller units of work in level 2 that could be further divided at level 3, until the project manager gets to activities at a level of detail that can be scheduled and controlled. For example, "Organizing and Site Preparation" has been divided into six activities at level 2 in Figure 7.1. We have kept our example simple so that the concept of the WBS can be easily understood. If our activities in the example are divided into even smaller units of work, it is easy to see that the total WBS for a project of this size may include many more than 100 activities. Regardless of the project, care must be taken to include all important activities in the WBS to avoid project delays. Often overlooked are the activities required to plan the project, get management approval at various stages, run pilot tests of new services or products, and prepare final reports.

**work breakdown structure (WBS)**

A statement of all work that has to be completed.

**activity**

The smallest unit of work effort consuming both time and resources that the project manager can schedule and control.

Each activity in the WBS must have an "owner" who is responsible for doing the work. *Activity ownership* avoids confusion in the execution of activities and assigns responsibility for timely completion. The team should have a defined procedure for assigning activities to team members, which can be democratic (consensus of the team) or autocratic (assigned by the project manager).

## Diagramming the Network

Network planning methods can help managers monitor and control projects. These methods treat a project as a set of interrelated activities that can be visually displayed in a **network diagram**, which consists of nodes (circles) and arcs (arrows) that depict the relationships between activities. Two

**network diagram**

A network planning method, designed to depict the relationships between activities, that consists of nodes (circles) and arcs (arrows).

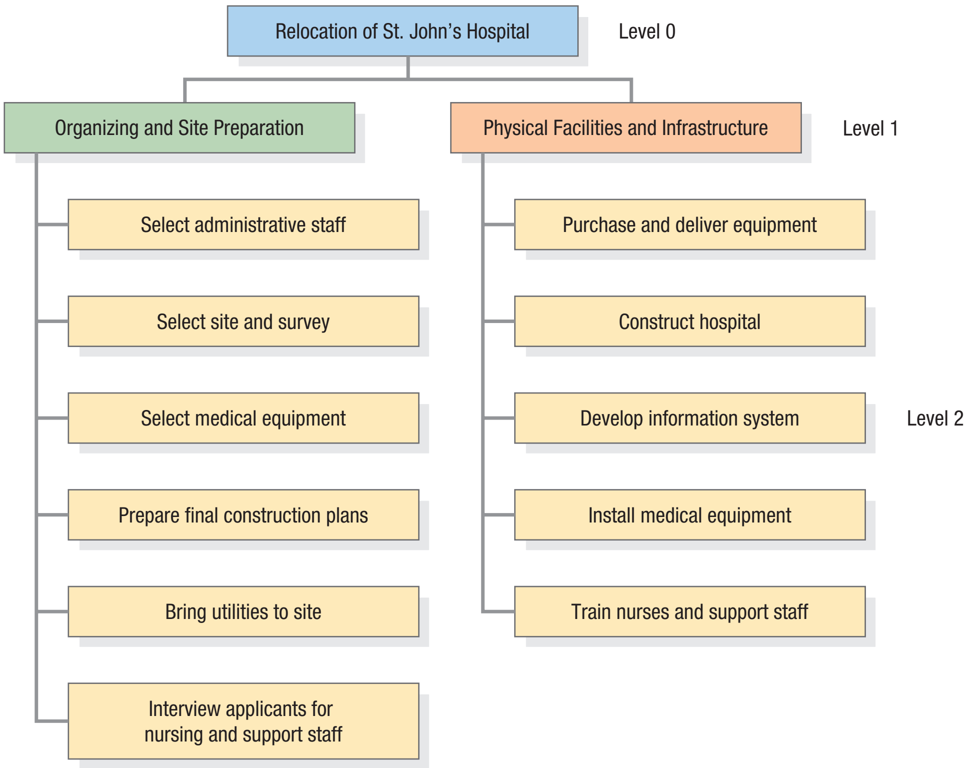



**FIGURE 7.1** Work Breakdown Structure for the St. John's Hospital Project

**program evaluation and review technique (PERT)**

A network planning method created for the U.S. Navy's Polaris missile project in the 1950s, which involved 3,000 separate contractors and suppliers.

**critical path method (CPM)**

A network planning method developed in the 1950s as a means of scheduling maintenance shutdowns at chemical-processing plants.

network planning methods were developed in the 1950s. The **program evaluation and review technique (PERT)** was created for the U.S. Navy's Polaris missile project, which involved 3,000 separate contractors and suppliers. The **critical path method (CPM)** was developed as a means of scheduling maintenance shutdowns at chemical-processing plants. Although early versions of PERT and CPM differed in their treatment of activity time estimates, today the differences are minor. For purposes of our discussion, we refer to them collectively as PERT/CPM. These methods offer several benefits to project managers, including the following:

1. Considering projects as networks forces project teams to identify and organize the data required and to identify the interrelationships between activities. This process also provides a forum for managers of different functional areas to discuss the nature of the various activities and their resource requirements.
2. Networks enable project managers to estimate the completion time of projects, an advantage that can be useful in planning other events and in conducting contractual negotiations with customers and suppliers.
3. Reports based on project networks highlight the activities that are crucial to completing projects on schedule. They also highlight the activities that may be delayed without affecting completion dates, thereby freeing up resources for other, more critical activities.
4. Network methods enable project managers to analyze the time and cost implications of resource trade-offs.

Diagramming the project network involves establishing precedence relationships and estimating activity times.

**precedence relationship**

A relationship that determines a sequence for undertaking activities; it specifies that one activity cannot start until a preceding activity has been completed.

**Establishing Precedence Relationships** A **precedence relationship** determines a sequence for undertaking activities; it specifies that one activity cannot start until a preceding activity has been completed. For example, brochures announcing a conference for executives must first be designed by the program committee (activity A) before they can be printed (activity B). In other words, activity A must *precede* activity B. For large projects, establishing precedence relationships is essential because incorrect or omitted precedence relationships will result in costly delays. The precedence relationships are represented by a network diagram, similar to what we used for analyzing line balancing problems (see Chapter 6, "Designing Lean Systems").

MyOMLab

**Estimating Activity Times** When the same type of activity has been done many times before, time estimates will have a relatively high degree of certainty. Several methods can be used to get time estimates in such an environment. First, statistical methods can be used if the project team has access to data on actual activity times experienced in the past (see MyOMLab Supplement H, "Measuring Output Rates,"). Second, if activity times improve with the number of replications, the times can be estimated using learning curve models (see Supplement I, "Learning Curve Analysis," in MyOMLab). Finally, the times for first-time activities are often estimated using managerial opinions based on similar prior experiences (see Chapter 8, "Forecasting Demand"). If the estimates involve a high degree of uncertainty, probability distributions for activity times can be used. We discuss how to incorporate uncertainty in project networks when we address risk assessment later in this chapter. For now, we assume that the activity times are known with certainty.

## EXAMPLE 7.1 Diagramming the St. John's Hospital Project

Judy Kramer, the project manager for the St. John's Hospital project, divided the project into two major modules. She assigned John Stewart the overall responsibility for the Organizing and Site Preparation module and Sarah Walker the responsibility for the Physical Facilities and Infrastructure module. Using the WBS shown in Figure 7.1, the project team developed the precedence relationships, activity time estimates, and activity responsibilities shown in the following table:

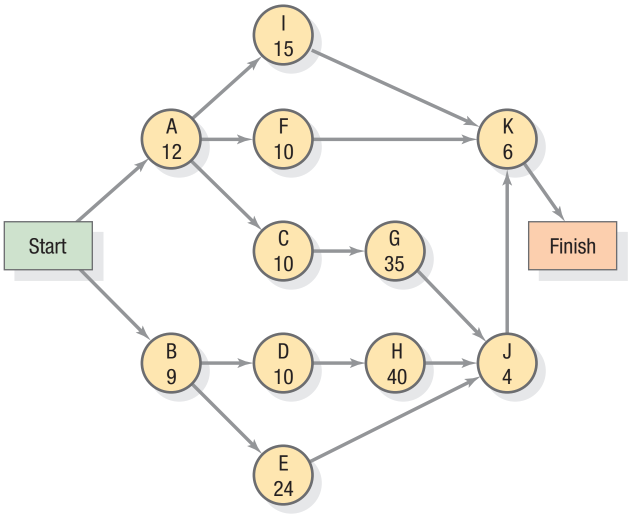
| Activity | Immediate Predecessors | Activity Times (wks) | Responsibility |
|---|---|---|---|
| **ST. JOHN'S HOSPITAL PROJECT** | | | Kramer |
| **START** | | 0 | |
| **ORGANIZING and SITE PREPARATION** | | | Stewart |
| A. Select administrative staff | Start | 12 | Johnson |

| Activity | Immediate Predecessors | Activity Times (wks) | Responsibility |
|---|---|---|---|
| B. Select site and survey | Start | 9 | Taylor |
| C. Select medical equipment | A | 10 | Adams |
| D. Prepare final construction plans | B | 10 | Taylor |
| E. Bring utilities to site | B | 24 | Burton |
| F. Interview applicants for nursing and support staff | A | 10 | Johnson |
| **PHYSICAL FACILITIES and INFRASTRUCTURE** | | | Walker |
| G. Purchase and deliver equipment | C | 35 | Sampson |
| H. Construct hospital | D | 40 | Casey |
| I. Develop information system | A | 15 | Murphy |
| J. Install medical equipment | E, G, H | 4 | Pike |
| K. Train nurses and support staff | F, I, J | 6 | Ashton |
| **FINISH** | K | 0 | |

For purposes of our example, we will assume a work week consists of five work days. Draw the network diagram for the hospital project.

**SOLUTION**

The network diagram, activities, and activity times for the hospital project are shown in Figure 7.2. The diagram depicts activities as circles, with arrows indicating the sequence in which they are to be performed. Activities A and B emanate from a *start* node because they have no immediate predecessors. The arrows connecting activity A to activities C, F, and I indicate that all three require completion of activity A before they can begin. Similarly, activity B must be completed before activities D and E can begin, and so on. Activity K connects to a *finish* node because no activities follow it. The start and finish nodes do not actually represent activities; they merely provide beginning and ending points for the network.




▲ **FIGURE 7.2**
Network Showing Activity Times for the St. John's Hospital Project

# Developing the Project Schedule

A key advantage of network planning methods is the creation of a schedule of project activities that will help managers achieve the objectives of the project. Given a project network, managers can (1) estimate the completion time of a project by finding the critical path, (2) identify the start and finish times for each activity for a project schedule, and (3) calculate the amount of slack time for each activity.

## Critical Path

A crucial aspect of project management is estimating the time of completion of a project. If each activity in relocating the hospital were done in sequence, with work proceeding on only one activity at a time, the time of completion would equal the sum of the times for all the activities, or 175 weeks. However, Figure 7.2 indicates that some activities can be carried on simultaneously, given adequate resources. We call each sequence of activities between the project's start and finish a **path**. The network describing the hospital relocation project has five paths: (1) A–I–K, (2) A–F–K, (3) A–C–G–J–K, (4) B–D–H–J–K, and (5) B–E–J–K. The **critical path** is the sequence of activities between a project's start and finish that takes the longest time

**path**

The sequence of activities between a project's start and finish.

**critical path**

The sequence of activities between a project's start and finish that takes the longest time to complete.

to complete. Thus, the activities along the critical path determine the completion time of the project; that is, if one of the activities on the critical path is delayed, the entire project will be delayed. The estimated times for the paths in the hospital project network are:

| Path | Estimated Time (weeks) |
|---|---|
| A–I–K | 33 |
| A–F–K | 28 |
| A–C–G–J–K | 67 |
| B–D–H–J–K | 69 |
| B–E–J–K | 43 |

**earliest finish time (EF)**
An activity's earliest start time plus its estimated duration, $t$, or $EF = ES + t$.

**earliest start time (ES)**
The earliest finish time of the immediately preceding activity.

**latest finish time (LF)**
The latest start time of the activity that immediately follows.

**latest start time (LS)**
The latest finish time minus its estimated duration, $t$, or $LS = LF - t$.

The activity string B–D–H–J–K is estimated to take 69 weeks to complete. As the longest, it constitutes the critical path. Because the critical path defines the completion time of the project, Judy Kramer and the project team should focus on these activities and any other path that is close in length to the critical path.

## Project Schedule

The typical objective is to finish the project as early as possible as determined by the critical path. The project schedule is specified by the start and finish times for each activity. For any activity, managers can use the earliest start and finish times, the latest start and finish times (and still finish the project on time), or times in between these extremes if the activity is not on the critical path.

George Hall/Corbis

Aircraft construction is an example of a large project that requires a sound project schedule because of the capital involved. Here several 747's are under construction at Boeing's plant in Everett, Washington.

- **Earliest Start and Earliest Finish Times** The earliest start and earliest finish times are obtained as follows:

  1. The **earliest finish time (EF)** of an activity equals its earliest start time plus its estimated duration, $t$, or $EF = ES + t$.
     The **earliest start time (ES)** for an activ ity is the earliest finish time of the immediately preceding activity. For activities with more than one preceding activity, ES is the latest of the earliest finish times of the preceding activities.
     To calculate the duration of the entire project, we determine the EF for the last activity on the critical path.

- **Latest Start and Latest Finish Times** To obtain the latest start and latest finish times, we must work backward from the finish node. We start by setting the latest finish time of the project equal to the earliest finish time of the last activity on the critical path.

  1. The **latest finish time (LF)** for an activity is the latest start time of the activity that immediately follows. For activities with more than one activity that immediately follow, LF is the earliest of the latest start times of those activities.
  2. The **latest start time (LS)** for an activity equals its latest finish time minus its estimated duration, $t$, or $LS = LF - t$.

### EXAMPLE 7.2 Calculating Start and Finish Times for the Activities

Calculate the ES, EF, LS, and LF times for each activity in the hospital project. Which activity should Kramer start immediately? Figure 7.2 contains the activity times.

**SOLUTION**

To compute the early start and early finish times, we begin at the start node at time zero. Because activities A and B have no predecessors, the earliest start times for these activities are also zero. The earliest finish times for these activities are

$$EF_A = 0 + 12 = 12 \text{ and } EF_B = 0 + 9 = 9$$

Because the earliest start time for activities I, F, and C is the earliest finish time of activity A,

$$ES_I = 12, ES_F = 12, \text{ and } ES_C = 12$$

Similarly,

$$ES_D = 9 \text{ and } ES_E = 9$$

After placing these ES values on the network diagram (see Figure 7.3), we determine the EF times for activities I, F, C, D, and E:

$$EF_I = 12 + 15 = 27, EF_F = 12 + 10 = 22, EF_C = 12 + 10 = 22,$$
$$EF_D = 9 + 10 = 19, \text{ and } EF_E = 9 + 24 = 33$$

The earliest start time for activity G is the latest EF time of all immediately preceding activities. Thus,

$$ES_G = EF_C = 22, ES_H = EF_D = 19$$
$$EF_G = ES_G + t = 22 + 35 = 57, EF_H = ES_H + t = 19 + 40 = 59$$

The project team can now determine the earliest time any activity can be started. Because activity J has several predecessors, the earliest time that activity J can begin is the latest of the EF times of any of its preceding activities: $EF_G, EF_H$, or $EF_E$. Thus, $EF_J = 59 + 4 = 63$. Similarly, $ES_K = 63$ and $EF_K = 63 + 6 = 69$. Because activity K is the last activity on the critical path, the earliest the project can be completed is week 69. The earliest start and finish times for all activities are shown in Figure 7.3.

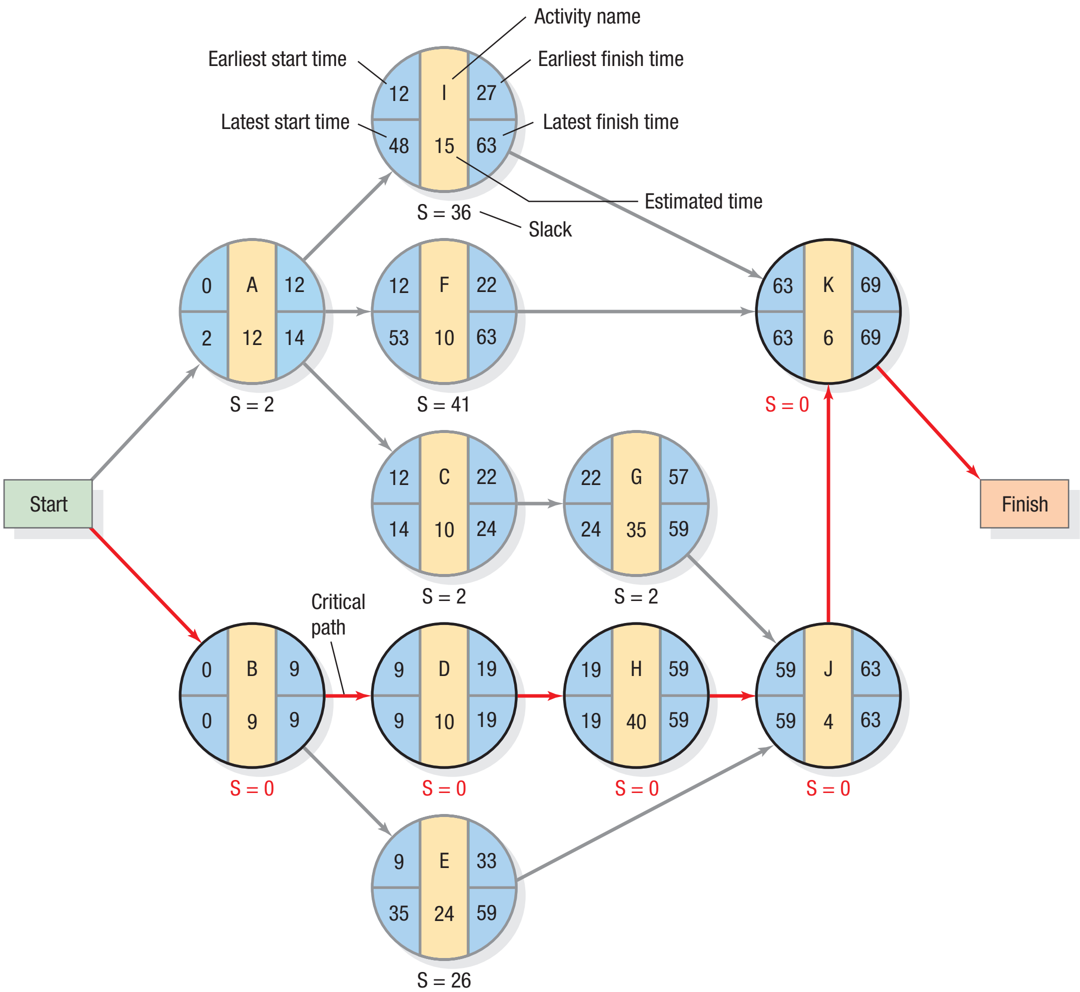



**FIGURE 7.3**
Network Diagram Showing Start and Finish Times and Activity Slack

MyOMLab Animation

To compute the latest start and latest finish times, we begin by setting the latest finish activity time of activity K at week 69, which is its earliest finish time as determined in Figure 7.3. Thus, the latest start time for activity K is

$$LS_K = LF_K - t = 69 - 6 = 63$$

If activity K is to start no later than week 63, all its predecessors must finish no later than that time. Consequently,

$$LF_I = 63, LF_F = 63, \text{ and } LF_J = 63$$

The latest start times for these activities are shown in Figure 7.3 as

$$LS_I = 63 - 15 = 48, LS_F = 63 - 10 = 53, \text{ and } LS_J = 63 - 4 = 59$$

After obtaining $LS_J$, we can calculate the latest start times for the immediate predecessors of activity J:

$$LS_G = 59 - 35 = 24, LS_H = 59 - 40 = 19, \text{ and } LS_E = 59 - 24 = 35$$

Similarly, we can now calculate the latest start times for activities C and D:

$$LS_C = 24 - 10 = 14 \text{ and } LS_D = 19 - 10 = 9$$

Activity A has more than one immediately following activity: I, F, and C. The earliest of the latest start times is 14 for activity C. Thus,

$$LS_A = 14 - 12 = 2$$

Similarly, activity B has two immediate followers: D and E. Because the earliest of the latest start times of these activities is 9,

$$LS_B = 9 - 9 = 0$$

**DECISION POINT**

The earliest or latest start times can be used for developing a project schedule. For example, Kramer should start activity B immediately because the latest start time is 0; otherwise, the project will not be completed by week 69. When the LS is greater than the ES for an activity, that activity could be scheduled for any date between ES and LS. Such is the case for activity E, which could be scheduled to start anytime between week 9 and week 35, depending on the availability of resources. The earliest start and earliest finish times and the latest start and latest finish times for all activities are shown in Figure 7.3.

**activity slack**

The maximum length of time that an activity can be delayed without delaying the entire project, calculated as S = LS − ES or S = LS − EF.

**MyOMLab**

Active Model 7.1 in MyOMLab provides additional insight on Gantt charts and their uses for the St. John's Hospital project.

**Gantt chart**

A project schedule, usually created by the project manager using computer software, that superimposes project activities, with their precedence relationships and estimated duration times, on a time line.

**normal time (NT)**

In the context of project management, the time necessary to complete an activity under normal conditions.

## Activity Slack

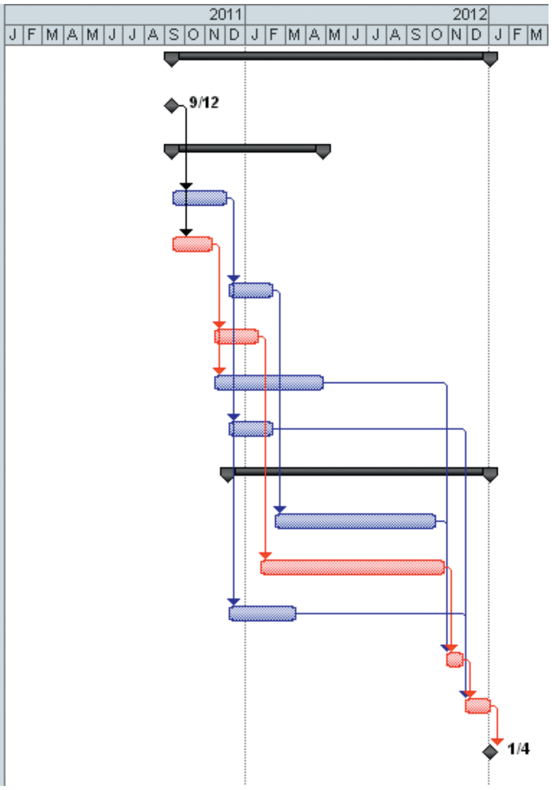
The maximum length of time that an activity can be delayed without delaying the entire project is called **activity slack**. Consequently, *activities on the critical path have zero slack.* Information on slack can be useful because it highlights activities that need close attention. In this regard, activity slack is the amount of schedule slippage that can be tolerated for an activity before the entire project will be delayed. Slack at an activity is reduced when the estimated time duration of an activity is exceeded or when the scheduled start time for the activity must be delayed because of resource considerations. Activity slack can be calculated in one of two ways for any activity:

$$S = LS - ES \quad \text{or} \quad S = LF - EF$$

Computers calculate activity slack and prepare periodic reports for large projects, enabling managers to monitor progress. Using these reports, managers can sometimes manipulate slack to overcome scheduling problems. When resources can be used on several different activities in a project, they can be taken from activities with slack and given to activities that are behind schedule until the slack is used up. The slack for each activity in the hospital project is shown in Figure 7.3.

**Gantt Chart** The project manager, often with the assistance of computer software, creates the project schedule by superimposing project activities, with their precedence relationships and estimated duration times, on a time line. The resulting diagram is called a **Gantt chart**. Figure 7.4 shows a Gantt chart for the hospital project created with Microsoft Project, a popular software package for project management. The critical path is shown in red. The chart clearly shows which activities can be undertaken simultaneously and when they should be started. Figure 7.4 also shows the earliest start schedule for the project. Microsoft Project can also be used to show the latest start schedule or to change the definition of the work week to declare Saturday and Sunday as work days, for example. Gantt charts are popular because they are intuitive and easy to construct.

| | Task Name | Duration | Start | Finish | Predecessors |
|---|---|---|---|---|---|
| 1 | **⊟ St John's Hospital Project** | **69 wks** | **Mon 9/12/11** | **Fri 1/4/13** | |
| 2 | Start | 0 wks | Mon 9/12/11 | Mon 9/12/11 | |
| 3 | **⊟ Organizing and Site Prep** | **33 wks** | **Mon 9/12/11** | **Fri 4/27/12** | |
| 4 | A. Select Staff | 12 wks | Mon 9/12/11 | Fri 12/2/11 | 2 |
| 5 | B. Select Site | 9 wks | Mon 9/12/11 | Fri 11/11/11 | 2 |
| 6 | C. Select Equipment | 10 wks | Mon 12/5/11 | Fri 2/10/12 | 4 |
| 7 | D. Construction Plans | 10 wks | Mon 11/14/11 | Fri 1/20/12 | 5 |
| 8 | E. Utilities | 24 wks | Mon 11/14/11 | Fri 4/27/12 | 5 |
| 9 | F. Interviews | 10 wks | Mon 12/5/11 | Fri 2/10/12 | 4 |
| 10 | **⊟ Facilities and Infrastructure** | **57 wks** | **Mon 12/5/11** | **Fri 1/4/13** | |
| 11 | G. Purchase Equipment | 35 wks | Mon 2/13/12 | Fri 10/12/12 | 6 |
| 12 | H. Construct Hospital | 40 wks | Mon 1/23/12 | Fri 10/26/12 | 7 |
| 13 | I. Information System | 15 wks | Mon 12/5/11 | Fri 3/16/12 | 4 |
| 14 | J. Install Equipment | 4 wks | Mon 10/29/12 | Fri 11/23/12 | 8,11,12 |
| 15 | K. Train Staff | 6 wks | Mon 11/26/12 | Fri 1/4/13 | 9,13,14 |
| 16 | Finish | 0 wks | Fri 1/4/13 | Fri 1/4/13 | 15 |




▲ **FIGURE 7.4**
MS Project Gantt Chart for the St. John's Hospital Project Schedule

## Analyzing Cost–Time Trade-Offs

Keeping costs at acceptable levels is almost always as important as meeting schedule dates. In this section, we discuss the use of PERT/CPM methods to obtain minimum-cost schedules.

The reality of project management is that there are always cost–time trade-offs. For example, a project can often be completed earlier than scheduled by hiring more workers or running extra shifts. Such actions could be advantageous if savings or additional revenues accrue from completing the project early. *Total project costs* are the sum of direct costs, indirect costs, and penalty costs. These costs are dependent either on activity times or on project completion time. *Direct costs* include labor, materials, and any other costs directly related to project activities. *Indirect costs* include administration, depreciation, financial, and other variable overhead costs that can be avoided by reducing total project time: The shorter the duration of the project, the lower the indirect costs will be. Finally, a project may incur *penalty costs* if it extends beyond some specific date, whereas *an incentive* may be provided for early completion. Managers can shorten individual activity times by using additional direct resources, such as overtime, personnel, or equipment. Thus, a project manager may consider *crashing*, or expediting, some activities to reduce overall project completion time and total project costs.


Mark Eveleigh/Alamy

Excavators work on the new Panama Canal project, which has international implications and massive costs.

### Cost to Crash

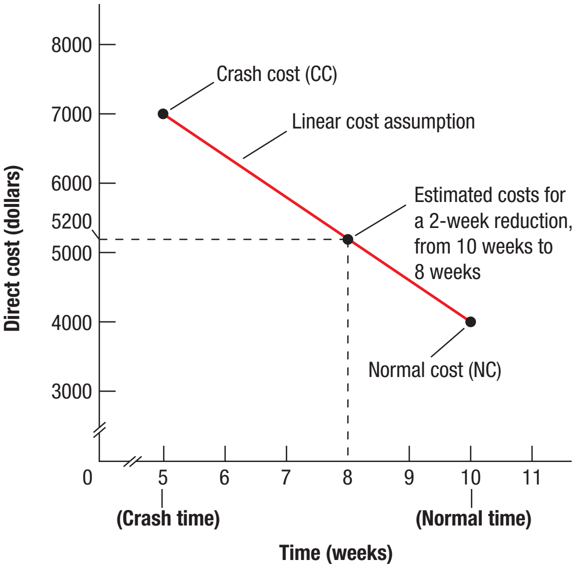
To assess the benefit of crashing certain activities—from either a cost or a schedule perspective—the project manager needs to know the following times and costs:

1. The **normal time (NT)** is the time necessary to complete an activity under normal conditions.
2. The **normal cost (NC)** is the activity cost associated with the normal time.
3. The **crash time (CT)** is the shortest possible time to complete an activity.
4. The **crash cost (CC)** is the activity cost associated with the crash time.

**normal cost (NC)**
The activity cost associated with the normal time.

**crash time (CT)**
The shortest possible time to complete an activity.

**crash cost (CC)**
The activity cost associated with the crash time.




▲ **FIGURE 7.5**
Cost–Time Relationships in Cost Analysis

Our cost analysis is based on the assumption that direct costs increase linearly as activity time is reduced from its normal time. This assumption implies that for every week the activity time is reduced, direct costs increase by a proportional amount. For example, suppose that the normal time for activity C in the hospital project is 10 weeks and is associated with a direct cost of \$4,000. Also, suppose that we can crash its time to only 5 weeks at a total cost of \$7,000; the net time reduction is 5 weeks at a net cost increase of \$3,000. We assume that crashing activity C costs $\$3{,}000/5 = \$600$ per week—an assumption of linear marginal costs that is illustrated in Figure 7.5. Thus, if activity C were expedited by 2 weeks (i.e., its time reduced from 10 weeks to 8 weeks), the estimated direct costs would be $\$4{,}000 + 2(\$600) = \$5{,}200$. For any activity, the cost to crash an activity by one week is

$$\text{Cost to crash per period} = \frac{\text{CC} - \text{NC}}{\text{NT} - \text{CT}}$$

Table 7.1 contains direct cost and time data, as well as the costs of crashing per week for the activities in the hospital project.

**TABLE 7.1** | **DIRECT COST AND TIME DATA FOR THE ST. JOHN'S HOSPITAL PROJECT**

| Activity | Normal Time (NT) (weeks) | Normal Cost (NC) (\$) | Crash Time (CT) (weeks) | Crash Cost (CC) (\$) | Maximum Time Reduction (week) | Cost of Crashing per Week (\$) |
|---|---|---|---|---|---|---|
| A | 12 | \$12,000 | 11 | 13,000 | 1 | 1,000 |
| B | 9 | 50,000 | 7 | 64,000 | 2 | 7,000 |
| C | 10 | 4,000 | 5 | 7,000 | 5 | 600 |
| D | 10 | 16,000 | 8 | 20,000 | 2 | 2,000 |
| E | 24 | 120,000 | 14 | 200,000 | 10 | 8,000 |
| F | 10 | 10,000 | 6 | 16,000 | 4 | 1,500 |
| G | 35 | 500,000 | 25 | 530,000 | 10 | 3,000 |
| H | 40 | 1,200,000 | 35 | 1,260,000 | 5 | 12,000 |
| I | 15 | 40,000 | 10 | 52,500 | 5 | 2,500 |
| J | 4 | 10,000 | 1 | 13,000 | 3 | 1,000 |
| K | 6 | 30,000 | 5 | 34,000 | 1 | 4,000 |
| | Totals | \$1,992,000 | | \$2,209,500 | | |

## Minimizing Costs

The objective of cost analysis is to determine the project schedule that minimizes total project costs. Suppose that project indirect costs are \$8,000 per week. Suppose also that, after week 65, the Regional Hospital Board imposes on St. John's a penalty cost of \$20,000 per week if the hospital is not fully operational. With a critical path completion time of 69 weeks, the hospital faces potentially large penalty costs unless the schedule is changed. For every week that the project is shortened—to week 65—the hospital saves one week of penalty *and* indirect costs, or \$28,000. For reductions beyond week 65, the savings are only the weekly indirect costs of \$8,000.

The minimum possible project duration can be found by using the crash times of each activity for scheduling purposes. However, the cost of that schedule could be prohibitive. Project managers are most interested in minimizing the costs of their projects so that budgets are not exceeded. In determining the **minimum-cost schedule**, we start with the normal time schedule and crash activities along the critical path, whose length equals the length of the project. We want to determine how much we can add in crash costs without exceeding the savings in indirect and penalty costs. The procedure involves the following steps:

**minimum-cost schedule**

A schedule determined by starting with the normal time schedule and crashing activities along the critical path, in such a way that the costs of crashing do not exceed the savings in indirect and penalty costs.

***Step 1.*** Determine the project's critical path(s).

***Step 2.*** Find the activity or activities on the critical path(s) with the lowest cost of crashing per week.

***Step 3.*** Reduce the time for this activity until (a) it cannot be further reduced, (b) another path becomes critical, or (c) the increase in direct costs exceeds the indirect and penalty cost savings that result from shortening the project. If more than one path is critical, the time for an activity on each path may have to be reduced simultaneously.

***Step 4.*** Repeat this procedure until the increase in direct costs is larger than the savings generated by shortening the project.

## EXAMPLE 7.3 Find a Minimum-Cost Schedule

Determine the minimum-cost schedule for the St. John's Hospital project. Use the information provided in Table 7.1 and Figure 7.3.

MyOMLab

Active Model 7.2 in MyOMLab provides additional insight on cost analysis for the St. John's Hospital project.

### SOLUTION

The projected completion time of the project is 69 weeks. The project costs for that schedule are \$1,992,000 in direct costs, 69(\$8,000) = \$552,000 in indirect costs, and (69 − 65)(\$20,000) = \$80,000 in penalty costs, for total project costs of \$2,624,000. The five paths in the network have the following normal times:

| | |
|---|---|
| A–I–K: | 33 weeks |
| A–F–K: | 28 weeks |
| A–C–G–J–K: | 67 weeks |
| B–D–H–J–K: | 69 weeks |
| B–E–J–K: | 43 weeks |

It will simplify our analysis if we can eliminate some paths from further consideration. If all activities on A–C–G–J–K were crashed, the path duration would be 47 weeks. Crashing all activities on B–D–H–J–K results in a project duration of 56 weeks. Because the *normal* times of A–I–K, A–F–K, and B–E–J–K are less than the minimum times of the other two paths, we can disregard those three paths; they will never become critical regardless of the crashing we may do.

### STAGE 1

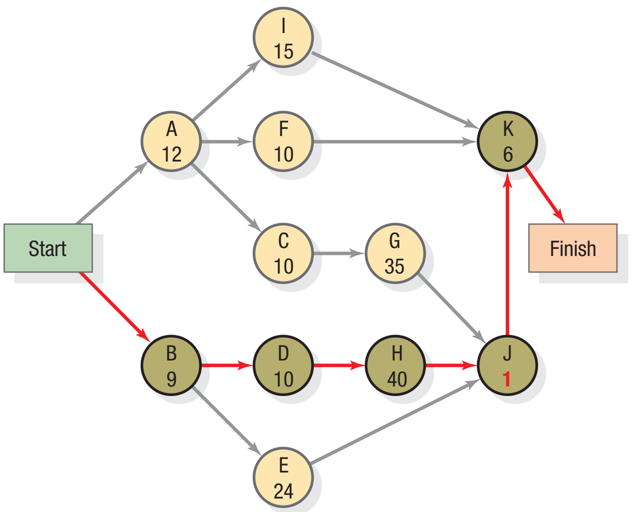
**Step 1.** The critical path is B–D–H–J–K.

**Step 2.** The cheapest activity to crash per week is J at \$1,000, which is much less than the savings in indirect and penalty costs of \$28,000 per week.

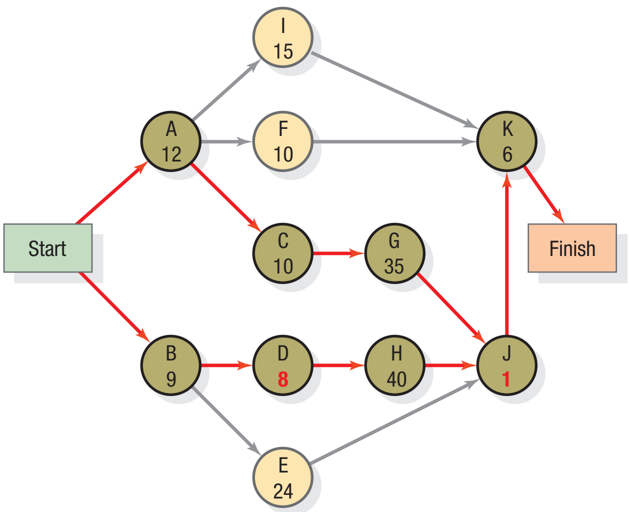
**Step 3.** Crash activity J by its limit of three weeks because the critical path remains unchanged. The new expected path times are

A–C–G–J–K: 64 weeks and B–D–H–J–K: 66 weeks

The net savings are 3 (\$28,000) − 3(\$1,000) = \$81,000. The total project costs are now \$2,624,000 − \$81,000 = \$2,543,000.




STAGE 1




STAGE 2

### STAGE 2

**Step 1.** The critical path is still B–D–H–J–K.

**Step 2.** The cheapest activity to crash per week is now D at $2,000.

**Step 3.** Crash D by two weeks. The first week of reduction in activity D saves $28,000 because it eliminates a week of penalty costs, as well as indirect costs. Crashing D by a second week saves only $8,000 in indirect costs because, after week 65, no more penalty costs are incurred. These savings still exceed the cost of crashing D for a second week. Updated path times are

A–C–G–J–K: 64 weeks and B–D–H–J–K: 64 weeks

The net savings are $28,000 + $8,000 − 2($2,000) = $32,000. Total project costs are now $2,543,000 − $32,000 = $2,511,000.

### STAGE 3

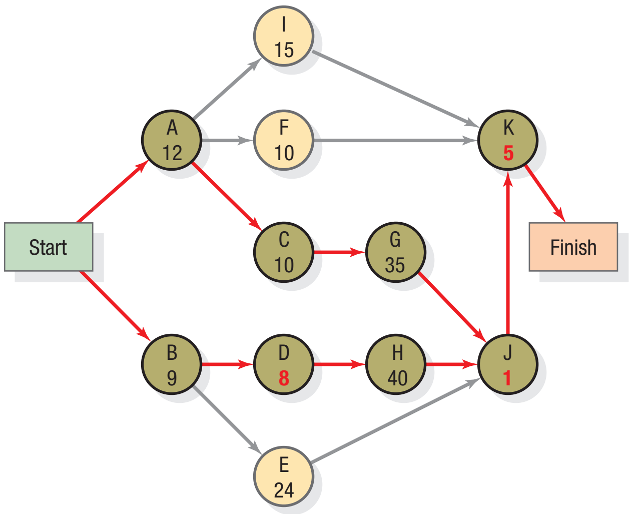
**Step 1.** After crashing D, we now have two critical paths. *Both* critical paths must now be shortened to realize any savings in indirect project costs. If one is shortened and the other is not, the length of the project remains unchanged.

**Step 2.** Our alternatives are to crash one of the following combinations of activities—(A, B), (A, H), (C, B), (C, H), (G, B), (G, H)—or to crash activity K, which is on both critical paths (J has already been crashed). We consider only those alternatives for which the cost of crashing is less than the potential savings of $8,000 per week. The only viable alternatives are (C, B) at a cost of $7,600 per week and K at $4,000 per week. We choose activity K to crash.

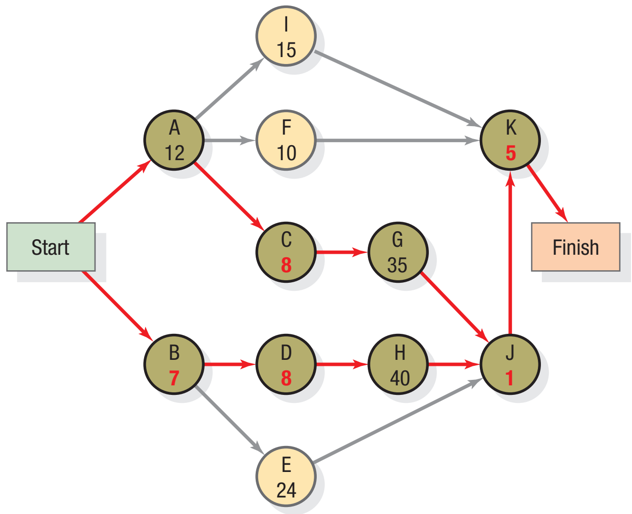
**Step 3.** We crash activity K to the greatest extent possible—a reduction of one week—because it is on both critical paths. Updated path times are

A–C–G–J–K: 63 weeks and B–D–H–J–K: 63 weeks

The net savings are $8,000 − $4,000 = $4,000. Total project costs are $2,511,000 − $4,000 = $2,507,000.




STAGE 3




STAGE 4

### STAGE 4

**Step 1.** The critical paths are B–D–H–J–K and A–C–G–J–K.

**Step 2.** The only viable alternative at this stage is to crash activities B and C simultaneously at a cost of $7,600 per week. This amount is still less than the savings of $8,000 per week.

**Step 3.** Crash activities B and C by two weeks, the limit for activity B. Updated path times are

A–C–G–J–K: 61 weeks and B–D–H–J–K: 61 weeks

Net savings are 2($8,000) − 2($7,600) = $800. Total project costs are $2,507,000 − $800 = $2,506,200.

The following table summarizes the analysis:

| Stage | Crash Activity | Time Reduction (weeks) | Resulting Critical Path(s) | Project Duration (weeks) | Project Direct Costs, Last Trial ($000) | Crash Cost Added ($000) | Total Indirect Costs ($000) | Total Penalty Costs ($000) | Total Project Costs ($000) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | — | — | B–D–H–J–K | 69 | 1,992.0 | — | 552.0 | 80.0 | 2,624.0 |
| 1 | J | 3 | B–D–H–J–K | 66 | 1,992.0 | 3.0 | 528.0 | 20.0 | 2,543.0 |
| 2 | D | 2 | B–D–H–J–K<br>A–C–G–J–K | 64 | 1,995.0 | 4.0 | 512.0 | 0.0 | 2,511.0 |
| 3 | K | 1 | B–D–H–J–K<br>A–C–G–J–K | 63 | 1,999.0 | 4.0 | 504.0 | 0.0 | 2,507.0 |
| 4 | B,C | 2 | B–D–H–J–K<br>A–C–G–J–K | 61 | 2,003.0 | 15.2 | 488.0 | 0.0 | 2,506.2 |

**DECISION POINT**

Because the crash costs exceed weekly indirect costs, any other combination of activities will result in a net increase in total project costs. The minimum-cost schedule is 61 weeks, with a total cost of $2,506,200. To obtain this schedule, the project team must crash activities B, D, J, and K to their limits and activity C to eight weeks. The other activities remain at their normal times. This schedule costs $117,800 less than the normal-time schedule.

# Assessing and Analyzing Risks

*Risk* is a measure of the probability and consequence of not reaching a defined project goal. Risk involves the notion of uncertainty as it relates to project timing and costs. Often, project teams must deal with uncertainty caused by labor shortages, weather, supply delays, or the outcomes of critical tests. In this section, we discuss risk management plans and the tools managers can use to analyze the risks, such as simulation and statistical analysis, which enable managers to estimate the probability of completing a project on time and the potential for near-critical paths to affect the project completion time.

## Risk-Management Plans

A major responsibility of the project manager at the start of a project is to develop a **risk-management plan**, which identifies the key risks to a project's success and prescribes ways to circumvent them. A good risk-management plan will quantify the risks, predict their impact on the project, and provide contingency plans. Project risk can be assessed by examining four categories:

**risk-management plan**

A plan that identifies the key risks to a project's success and prescribes ways to circumvent them.

- **Strategic Fit** The project may not be a good strategic fit in that it may not be clearly linked to the strategic goals of the firm.
- **Service/Product Attributes** If the project involves the development of a new service or product, there may be market, technological, or legal risks. There is a chance that competitors may offer a superior product or a technological discovery may render the service or product obsolete before it even hits the market. There may also be a legal risk of potential lawsuits or liability that could force a design change after product development has begun.
- **Project Team Capability** The project team may not have the capability to complete the project successfully because of the size and complexity of the project or the technology involved.
- **Operations** There may be an operations risk because of poor information accuracy, lack of communication, missing precedence relationships, or bad estimates for activity times.

These risks should be identified and the significant ones should have contingency plans in case something goes wrong. The riskier a project is, the more likely the project will experience difficulties as Managerial Practice 7.1 shows.

**Simulation** PERT/CPM networks can be used to quantify risks associated with project timing. Often, the uncertainty associated with an activity can be reflected in the activity's time duration.

For example, an activity in a new product development project might be developing the enabling technology to manufacture it, an activity that may take from eight months to a year. To incorporate uncertainty into the network model, probability distributions of activity times can be calculated using two approaches: (1) computer simulation and (2) statistical analysis. With simulation, the time for each activity is randomly chosen from its probability distribution (see MyOMLab Supplement E, "Simulation"). The critical path of the network is determined, and the completion date of the project computed. The procedure is repeated many times, which results in a probability distribution for the completion date. We will have more to say about simulation when we discuss near critical paths later in this chapter.

MyOMLab

## MANAGERIAL PRACTICE 7.1 San Francisco—Oakland Bay Bridge

**San Francisco, California,** has many noteworthy attractions: gardens, museums, Golden Gate Park, barking seals and seafood at Fisherman's Wharf, and the San Francisco Giants baseball team. The team was preparing to play in game 3 of the 1989 World Series against the Oakland Athletics when a 7.1 magnitude earthquake struck the Bay Area, minutes before the start of the game, resulting in the loss of many lives and billions of dollars in damage. Included in the damage was a 50-foot section of the upper deck of the Bay Bridge, which was closed until November 18, 1989, while the section was replaced. However, the Bay Bridge replacement project, which was needed to protect against future earthquakes, was not completed until September 12, 2013, at a cost of $6.4 billion, one of the most costly projects in the history of California. Are you wondering how that can happen? The answer lies at the heart of engaging in what we refer to as a risky project.

Karin Hildebrand Lau/Shutterstock

The eastern span replacement of the San Francisco–Oakland Bay Bridge was built between 2002 and 2013. It is the largest public works project in California history. The construction project was complex; the span is engineered to withstand the largest earthquake expected over a 1,500 year period, and it is expected to last at least 150 years with proper maintenance. Projects such as this pose many risks for project managers.

The two major indicators of project performance are time and cost. Let's explore these two factors for the Bay Bridge replacement project.

**Time.** Shortly after the initial repair of the bridge, engineers determined that the eastern span of the bridge had to be made more earthquake resistant. Several design proposals were submitted. One proposal was to retrofit the existing bridge by replacing or supplementing the existing supports, doing little to change the appearance of the existing structure. However, the design was called into question for lack of robustness in an earthquake. The second type of design would replace the entire eastern span of the bridge. Debate arose as two designs emerged, one lacking esthetics but meeting the structural requirements and having a lower price tag, called the *freeway on stilts*, and the other the result of a contest having a more innovative and dramatic appearance but costing more. It was referred to as the *signature span*. Meanwhile, in 1997, there was political bickering about whether the bridge should be built to the north or the south of the existing bridge. One of the complaints was that with the existing placement and design the bridge would cast a shadow over prime development sites on Yerba Buena Island, which is within the province of San Francisco. Consequently, San Francisco restricted soil engineers' access to the proposed site for two years while a bridge design compromise was worked out. Finally the revised signature span proposal was accepted, and on January 29, 2002, construction began with an estimated completion date in 2007. However, in 2004, the governor of the State of California announced that insufficient funds were available for the signature span design and that the "freeway on stilts" should be constructed instead. After six months of delay, in 2005, additional funding was found and the original signature span design was reapproved. Once the project was in full swing, additional unforeseen hurdles such as technical challenges, permitting, weather, and design revisions caused long delays that added years to the original project deadlines. Consequently, because the project was extremely complex and involved an esthetically pleasing but seldom built design, securing accurate time estimates for the activities was nearly impossible.

**Cost.** As project delays mounted, costs increased. In 1997, the cost for the signature span design was estimated to be $1.5 billion. By 2002, when approval for the start of the project was obtained, the cost for steel rose dramatically, primarily because of a building boom in China. The entire project required 100,000 tons of structural steel; the total project cost was reestimated to be about $6.2 billion. Contractors were now considering uncertainties in construction costs due to the innovative design as well as the increase in steel costs in their cost estimates. Further, the delay in 2004 over the funding of the signature span design added an estimated $83 million to the cost of the project. Additional problems, including defective rods anchoring the roadway to earthquake safety structures, broken bolts connecting portions of the bridge deck to concrete columns, and water leaks due to a problem with the caulking between the steel guardrails and the roadway, added cost as well. All told, the project was estimated to cost $6.4 billion.

Projects of this size and complexity are inherently risky; contingency plans should cover the most likely disruptions. Schedule and budget problems are not unusual; however, the job of project managers is to manage the risks and minimize the deviations.

*Sources:* **http://en.wikipedia.org/wiki/Eastern_span_replacement_of_the_San Francisco_Oakland Bay Bridge** (2013); Rick Weinberg, "26: World Series halted by Bay Area earthquake," **http://sports.espn.go.com/espn25** (2013); Jason Dearen, "After 24 years, $6.4 Billion S.F. Bay Bridge Project Draws to Close," **http://cnsnews.com/news/article** (2013); Jaxon Van Derbeken, "Bay Bridge's new problem: leaks," **http://www.sfgate.com/bayarea/article** (2014).

## Statistical Analysis

The statistical analysis approach requires that activity times be stated in terms of three reasonable time estimates:

1. The **optimistic time ($a$)** is the shortest time in which an activity can be completed, if all goes exceptionally well.
2. The **most likely time ($m$)** is the probable time required to perform an activity.
3. The **pessimistic time ($b$)** is the longest estimated time required to perform an activity.

**optimistic time ($a$)**
The shortest time in which an activity can be completed, if all goes exceptionally well.

**most likely time ($m$)**
The probable time required to perform an activity.

**pessimistic time ($b$)**
The longest estimated time required to perform an activity.

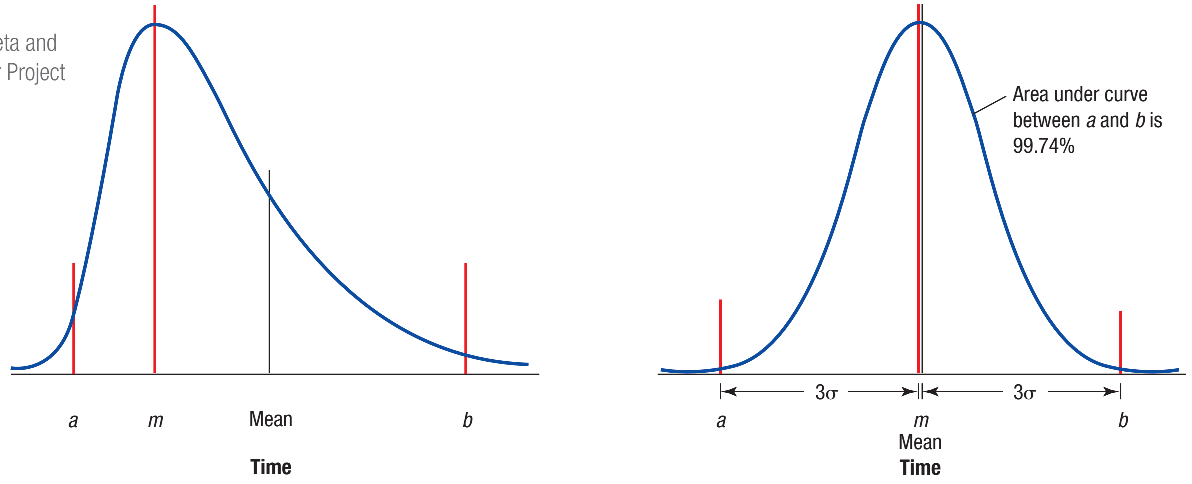
With three time estimates—the optimistic, the most likely, and the pessimistic—the project manager has enough information to estimate the probability that an activity will be completed on schedule. To do so, the project manager must first calculate the mean and variance of a probability distribution for each activity. In PERT/CPM, each activity time is treated as though it were a random variable derived from a beta probability distribution. This distribution can have various shapes, allowing the most likely time estimate ($m$) to fall anywhere between the pessimistic ($b$) and optimistic ($a$) time estimates. The most likely time estimate is the *mode* of the beta distribution, or the time with the highest probability of occurrence. This condition is not possible with the normal distribution, which is symmetrical, because the normal distribution requires the mode to be equidistant from the end points of the distribution. Figure 7.6 shows the difference between the two distributions.

Two key assumptions are required. First, we assume that $a$, $m$, and $b$ can be estimated accurately. The estimates might best be considered values that define a reasonable time range for the activity duration negotiated between the project manager and the team members responsible for the activities. Second, we assume that the standard deviation, $\sigma$, of the activity time is one-sixth the range $b - a$. Thus, the chance that actual activity times will fall between $a$ and $b$ is high. Why does this assumption make sense? If the activity time followed the normal distribution, six standard deviations would span approximately 99.74 percent of the distribution.

Even with these assumptions, derivation of the mean and variance of each activity's probability distribution is complex. These derivations show that the mean of the beta distribution can be estimated by using the following weighted average of the three time estimates:

$$t_e = \frac{a + 4m + b}{6}$$

**FIGURE 7.6** ▶
Differences Between Beta and Normal Distributions for Project Risk Analysis




(a) **Beta distribution:** The most likely time (*m*) has the highest probability and can be placed anywhere between the optimistic (*a*) and pessimistic (*b*) times.

(b) **Normal distribution:** The mean and most likely times must be the same. If *a* and *b* are chosen to be 6σ apart, there is a 99.74% chance that the actual activity time will fall between them.

Note that the most likely time has four times the weight of the pessimistic and optimistic estimates.

The variance of the beta distribution for each activity is

$$\sigma^2 = \left(\frac{b - a}{6}\right)^2$$

The variance, which is the standard deviation squared, increases as the difference between $b$ and $a$ increases. This result implies that the less certain a person is in estimating the actual time for an activity, the greater will be the variance.

## EXAMPLE 7.4 Calculating Means and Variances

Suppose that the project team has arrived at the following time estimates for activity B (Select site and survey) of the St. John's Hospital project:

$$a = 7 \text{ weeks}, m = 8 \text{ weeks, and } b = 15 \text{ weeks}$$

**a.** Calculate the expected time and variance for activity B.

**b.** Calculate the expected time and variance for the other activities in the project.

### SOLUTION

**a.** The expected time for activity B is

$$t_e = \frac{7 + 4(8) + 15}{6} = \frac{54}{6} = 9 \text{ weeks}$$

Note that the expected time (9 weeks) does not equal the most likely time (8 weeks) for this activity. These times will be the same only when the most likely time is equidistant from the optimistic and pessimistic times. We calculate the variance for activity B as

$$\sigma^2 = \left(\frac{15 - 7}{6}\right)^2 = \left(\frac{8}{6}\right)^2 = 1.78$$

**b.** The following table shows expected activity times and variances for the activities listed in the project description.

| | TIME ESTIMATES (WEEKS) | | | ACTIVITY STATISTICS | |
|---|---|---|---|---|---|
| Activity | Optimistic (*a*) | Most Likely (*m*) | Pessimistic (*b*) | Expected Time ($t_e$) | Variance ($\sigma^2$) |
| A | 11 | 12 | 13 | 12 | 0.11 |
| B | 7 | 8 | 15 | 9 | 1.78 |
| C | 5 | 10 | 15 | 10 | 2.78 |
| D | 8 | 9 | 16 | 10 | 1.78 |
| E | 14 | 25 | 30 | 24 | 7.11 |
| F | 6 | 9 | 18 | 10 | 4.00 |
| G | 25 | 36 | 41 | 35 | 7.11 |
| H | 35 | 40 | 45 | 40 | 2.78 |
| I | 10 | 13 | 28 | 15 | 9.00 |
| J | 1 | 2 | 15 | 4 | 5.44 |
| K | 5 | 6 | 7 | 6 | 0.11 |

**DECISION POINT**

The project team should notice that the greatest uncertainty lies in the time estimate for activity I, followed by the estimates for activities E and G. These activities should be analyzed for the source of the uncertainties, and actions should be taken to reduce the variance in the time estimates.

## Analyzing Probabilities

Because time estimates for activities involve uncertainty, project managers are interested in determining the probability of meeting project completion deadlines. To develop the probability distribution for project completion time, we assume that the duration time of one activity does not depend on that of any other activity. This assumption enables us to estimate the mean and variance of the probability distribution of the time duration of the entire project by summing the duration times and variances of the activities along the critical path. However, if one work crew is assigned two activities that can be done at the same time, the activity times will be interdependent and the assumption is not valid. In addition, if other paths in the network have small amounts of slack, one of them might become the critical path before the project is completed; we should calculate a probability distribution for those paths as well.

Because of the assumption that the activity duration times are independent random variables, we can make use of the central limit theorem, which states that the sum of a group of independent, identically distributed random variables approaches a normal distribution as the number of random variables increases. The mean of the normal distribution is the sum of the expected activity times on the path. In the case of the critical path, it is the earliest expected finish time for the project:

$$T_E = \sum(\text{Expected activity times on the critical path}) = \text{Mean of normal distribution}$$

Similarly, because of the assumption of activity time independence, we use the sum of the variances of the activities along the path as the variance of the time distribution for that path. That is, for the critical path,

$$\sigma_P^2 = \sum(\text{Variances of activities on the critical path})$$

To analyze probabilities of completing a project by a certain date using the normal distribution, we focus on the *critical path* and use the *z*-transformation formula:

$$z = \frac{T - T_E}{\sigma_P}$$

where

$$T = \text{due date for the project}$$

Given the value of $z$, we use the Normal Distribution appendix to find the probability that the project will be completed by time $T$, or sooner. An implicit assumption in this approach is that no other path will become critical during the time span of the project. Example 7.5, part (a), demonstrates this calculation for the St. John's Hospital project.

The procedure for assessing the probability of completing any activity in a project by a specific date is similar to the one just discussed. However, instead of the critical path, we would use the longest time path of activities from the start node to the activity node in question.

## Near-Critical Paths

A project's duration is a function of its critical path. However, paths that are close to the same duration as the critical path may ultimately become the critical path over the life of the project. In practice, at the start of the project, managers typically do not know the activity times with certainty and may never know which path was the critical path until the actual activity times are known at the end of the project. Nonetheless, this uncertainty does not reduce the usefulness of identifying the probability of one path or another causing a project to exceed its target completion time; it helps to identify the activities that need close management attention. To assess the chances of near-critical paths delaying the project completion, we can focus on the longest paths in the project network keeping in mind that both duration and variance along the path must be considered. Shorter paths with high variances could have just as much a chance to delay the project as longer paths with smaller variances. We can then estimate the probability that a given path will exceed the project target completion time. We demonstrate that approach using statistical analysis in Example 7.5, part (b).

Alternatively, simulation can be used to estimate the probabilities. The advantage of simulation is that you are not restricted to the use of the beta distribution for activity times. Also, activity or path dependencies, such as decision points that could involve different groups of activities to be undertaken, can be incorporated in a simulation model much more easily than with the statistical analysis approach. Fortunately, regardless of the approach used, it is rarely necessary to evaluate every path in the network. In large networks, many paths will have both short durations and low variances, making them unlikely to affect the project duration.

### EXAMPLE 7.5 Calculating the Probability of Completing a Project by a Given Date

MyOMLab

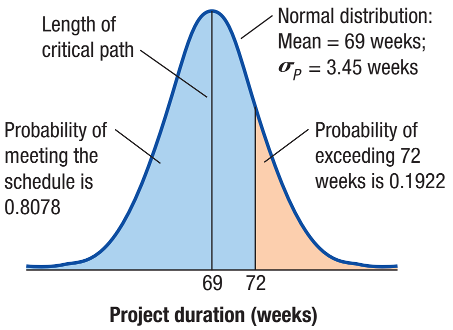
Active Model 7.3 in MyOMLab provides additional insight on probability analysis for the St. John's Hospital project.

Calculate the probability that St. John's Hospital will become operational in 72 weeks, using (a) the critical path and (b) near-critical path A–C–G–J–K.

**SOLUTION**

**a.** The critical path B–D–H–J–K has a length of 69 weeks. From the table in Example 7.4, we obtain the variance of path B–D–H–J–K: $\sigma_P^2 = 1.78 + 1.78 + 2.78 + 5.44 + 0.11 = 11.89$. Next, we calculate the $z$-value:

$$z = \frac{72 - 69}{\sqrt{11.89}} = \frac{3}{3.45} = 0.87$$




▲ **FIGURE 7.7**
Probability of Completing the St. John's Hospital Project on Schedule

Using the Normal Distribution appendix, we go down the left-hand column until we arrive at the value 0.8 and then across until we arrive at the 0.07 column, which shows a tabular value of 0.8078. Consequently, we find that the probability is about 0.81 that the length of path B–D–H–J–K will be no greater than 72 weeks. Because this path is the critical path, there is a 19 percent probability that the project will take longer than 72 weeks. This probability is shown graphically in Figure 7.7.

**b.** From the table in Example 7.4, we determine that the sum of the expected activity times on path A–C–G–J–K is 67 weeks and that $\sigma_P^2 = 0.11 + 2.78 + 7.11 + 5.44 + 0.11 = 15.55$. The $z$-value is

$$z = \frac{72 - 67}{\sqrt{15.55}} = \frac{5}{3.94} = 1.27$$

The probability is about 0.90 that the length of path A–C–G–J–K will be no greater than 72 weeks.

**DECISION POINT**

The project team should be aware of the 10 percent chance that path A–C–G–J–K will exceed the target completion date of week 72. Although the probability is not high for that path, activities A, C, and G bear watching during the first 57 weeks of the project to make sure no more than 2 weeks of slippage occurs in their schedules. This attention is especially important for activity G, which has a high time variance.

# Monitoring and Controlling Projects

Once project planning is over, the challenge becomes keeping the project on schedule within the budget of allocated resources. In this section, we discuss how to monitor project status and resource usage. In addition, we identify the features of project management software useful for monitoring and controlling projects.

Visual & Written/SuperStock

Monitoring and controlling shipbuilding projects is critical to keeping these complex projects on schedule. Here a propeller is attached to an ocean-going vessel.

## Monitoring Project Status

A good tracking system will help the project team accomplish its project goals. Effective tracking systems collect information on three topics: (1) open issues, (2) risks, and (3) schedule status.

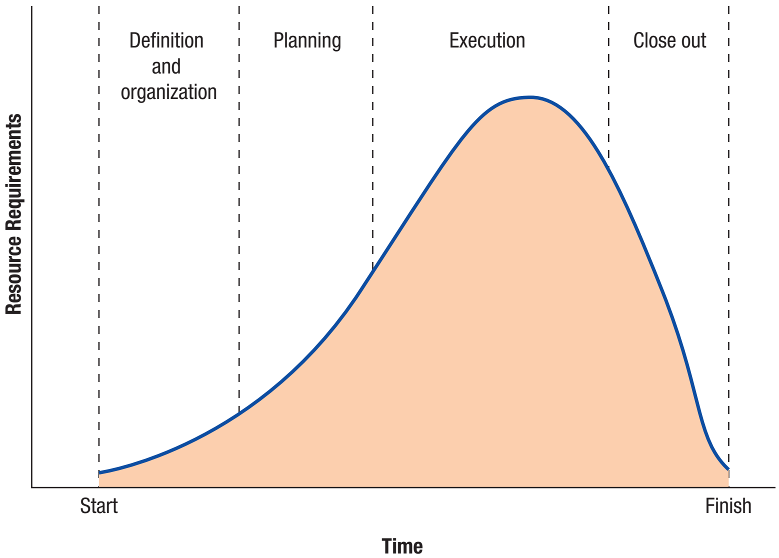
**Open Issues and Risks** One of the duties of the project manager is to make sure that issues that have been raised during the project actually get resolved in a timely fashion. The tracking system should remind the project manager of due dates for open issues and who was responsible for seeing that they are resolved. Likewise, it should provide the status of each risk to project delays specified in the risk management plan so that the team can review them at each meeting. To be effective, the tracking system requires team members to update information periodically regarding their respective responsibilities.

**Schedule Status** Even the best laid project plans can go awry. A tracking system that provides periodic monitoring of slack time in the project schedule can help the project manager control activities along the critical path. Periodic updating of the status of ongoing activities in the project allows the tracking system to recalculate activity slacks and indicate those activities that are behind schedule or are in danger of using up all of their slack. Managers can then focus on those activities and reallocate resources as needed.

## Monitoring Project Resources

Experience has shown that the resources allocated to a project are consumed at an uneven rate that is a function of the timing of the schedules for the project's activities. Projects have a *life cycle* that consists of four major phases: (1) definition and organization, (2) planning, (3) execution, and (4) close out. Figure 7.8 shows that each of the four phases requires different resource commitments.

We have already discussed the activities associated with the project definition and organization and project planning phases. The phase that takes the most resources is the *execution phase*, during which manager's focus on activities pertaining to deliverables. The project schedule becomes very important because it shows when each resource devoted to a given activity will be required. Monitoring the progress of activities throughout the project is important to avoid potential overloading of resources. Problems arise when a specific resource, such as a construction crew or staff specialist, is required on several activities with overlapping schedules. Project managers have several options to alleviate resource problems, including the following:




▲ **FIGURE 7.8**
Project Life Cycle

- *Resource Leveling.* The attempt to reduce the peaks and valleys in resource needs by shifting the schedules of conflicting activities within their earliest and latest start dates. Software packages such as MS Project have algorithms that move activities to avoid violating resource constraints.
- *Resource Allocation.* The assignment of resources to the most important activities. Most popular project management software packages have a few priority rules that can be used to decide which activity a critical resource should be scheduled to perform when conflicts arise. For example, for all the activities requiring a given resource, assign the resource to the one with the earliest start time. An activity slack report identifies potential candidates for resource shifting—shift resources from high slack activities to those behind schedule.
- *Resource Acquisition.* The addition of more of an overloaded resource to maintain the schedule of an activity. Obviously, this tactic is constrained by the project budget.

## Controlling Projects

Project managers have the responsibilities of accounting for the effective use of the firm's resources as well as managing the activities to achieve the time and quality goals of the project. The firm's assets include the physical assets, human resources, and financial resources. Physical assets are controlled by the timely maintenance of machines and equipment so that their failure does not delay the project. Inventories must be received, stored for future use, and replenished. Project managers are also responsible for human resource development. Projects provide a rich environment to develop future leaders; project managers can take advantage of the situation by assigning team members important activities to aid in their managerial development. Last, but not least, project managers must control the expenditures of the firm's financial resources. Most project management software packages contain accounting reports, budget reports, capital investment controls, and cash flow reports. Deviations from the project plan, often referred to as variances, must be periodically reported and analyzed for their causes.

**close out**

An activity that includes writing final reports, completing remaining deliverables, and compiling the team's recommendations for improving the project process.

Monitoring and controlling projects are ongoing activities throughout the execution phase of the project life cycle. The project **close out**, however, is an activity that many project managers forget to include in their consideration of resource usage. The purpose of this final phase in the project life cycle is to write final reports and complete remaining deliverables. An important aspect of this phase, however, is compiling the team's recommendations for improving the project process of which they were a part. Many team members will be assigned to other projects where they can apply what they learned.

## LEARNING GOALS IN REVIEW

| Learning Goal | Guidelines for Review | MyOMLab Resources |
|---|---|---|
| 1 Explain the major activities associated with defining and organizing a project. | Read the opener to the chapter, which shows the four major phases of the project to introduce the new XBOX 360 product, the introduction to the chapter, and the section "Defining and Organizing Projects," pp. 259–260. | **Video:** Project Management at the Phoenician |
| 2 Describe the procedure for constructing a project network. | Focus on the section "Constructing Project Networks," pp. 261–263, paying close attention to Example 7.1. | **SmartDraw** – free trial |
| 3 Develop the schedule of a project. | Review the section "Developing the Project Schedule," pp. 263–267. The schedule is determined when activity slacks and the critical path are computed. Focus on Example 7.2 and Figure 7.3. | **Active Model Exercise:** 7.1: Gantt Chart<br>**OME Solver:** Single Time Estimates<br>**POM for Windows:** Single Time Estimates<br>**MS Project** – free trial<br>**Supplement H:** Measuring Output Rates<br>**Supplement I:** Learning Curve Analysis |
| 4 Analyze cost–time trade-offs in a project network. | The section "Analyzing Cost–Time Trade-offs," pp. 267–271, and Example 7.3 demonstrate how the relevant costs must be considered to minimize costs. Figure 7.5 explains a key assumption in the analysis. Solved Problem 1 contains a detailed solution. | **Active Model Exercise:** 7.2: Cost Analysis<br>**POM for Windows:** Crashing |
| 5 Assess the risk of missing a project deadline. | See the section "Assessing and Analyzing Risks," pp. 271–276, which explains the risks faced by project managers and how to compute the probabilities. Be sure to understand Examples 7.4 and 7.5 and Solved Problem 2. | **Active Model Exercise:** 7.3: Probability Analysis<br>**OME Solver:** Three Time Estimates<br>**POM for Windows:** Triple Time Estimates; Mean/Standard Deviation Given<br>**Simquick Simulation Exercise:** Software Development Company<br>**Supplement E:** Simulation |
| 6 Identify the options available to monitor and control projects. | See the section "Monitoring and Controlling Projects," pp. 277–278. | **OME Solver:** Project Budgeting<br>**POM for Windows:** Cost Budgeting |

# Key Equations

## Developing the Project Schedule

**1.** Start and finish times:

$$t = \text{estimated time duration of the activity}$$
$$\text{ES} = \text{latest of the EF times of all activities immediately preceding activity}$$
$$\text{EF} = \text{ES} + t$$
$$\text{LF} = \text{earliest of the LS times of all activities immediately following activity}$$
$$\text{LS} = \text{LF} - t$$

**2.** Activity slack:

$$\text{S} = \text{LS} - \text{ES} \text{ or } \text{S} = \text{LF} - \text{EF}$$

## Analyzing Cost–Time Trade-offs

**3.** Project costs:

$$\text{Crash cost per period} = \frac{\text{Crash cost} - \text{Normal cost}}{\text{Normal time} - \text{Crash time}} = \frac{\text{CC} - \text{NC}}{\text{NT} - \text{CT}}$$

## Assessing and Analyzing Risks

**4.** Activity time statistics:

$$t_e = \text{mean of an activity's beta distribution}$$
$$t_e = \frac{a + 4m + b}{6}$$
$$\sigma^2 = \text{variance of the activity time}$$
$$\sigma^2 = \left(\frac{b - a}{6}\right)^2$$

**5.** $z$-transformation formula:

$$z = \frac{T - T_E}{\sigma_P}$$

where

$$T = \text{due date for the project}$$
$$T_E = \sum(\text{expected activity times on the critical path})$$
$$= \text{mean of normal distribution of critical path time}$$
$$\sigma_P = \text{standard deviation of critical path time distribution}$$

# Key Terms

activity 261
activity slack 266
close out 278
crash cost (CC) 267
crash time (CT) 267
critical path 263
critical path method (CPM) 262
earliest finish time (EF) 264
earliest start time (ES) 264
Gantt chart 266
latest finish time (LF) 264
latest start time (LS) 264
minimum-cost schedule 268
most likely time ($m$) 273
network diagram 261
normal cost (NC) 267
normal time (NT) 266
optimistic time ($a$) 273
path 263
pessimistic time ($b$) 273
precedence relationship 262
program 259
program evaluation and review technique (PERT) 262
project 259
project management 259
risk-management plan 271
work breakdown structure (WBS) 261

# Solved Problem 1

MyOMLab Video

Your company has just received an order from a good customer for a specially designed electric motor. The contract states that, starting on the 13th day from now, your firm will experience a penalty of $100 per day until the job is completed. Indirect project costs amount to $200 per day. The data on direct costs and activity precedence relationships are given in Table 7.2.

**TABLE 7.2 | ELECTRIC MOTOR PROJECT DATA**

| Activity | Normal Time (days) | Normal Cost ($) | Crash Time (days) | Crash Cost ($) | Immediate Predecessor(s) |
|---|---|---|---|---|---|
| A | 4 | 1,000 | 3 | 1,300 | None |
| B | 7 | 1,400 | 4 | 2,000 | None |
| C | 5 | 2,000 | 4 | 2,700 | None |
| D | 6 | 1,200 | 5 | 1,400 | A |
| E | 3 | 900 | 2 | 1,100 | B |
| F | 11 | 2,500 | 6 | 3,750 | C |
| G | 4 | 800 | 3 | 1,450 | D, E |
| H | 3 | 300 | 1 | 500 | F, G |

**a.** Draw the project network diagram.

**b.** What completion date would you recommend?

### SOLUTION

**a.** The network diagram, including normal activity times, for this procedure is shown in Figure 7.9. Keep the following points in mind while constructing a network diagram.

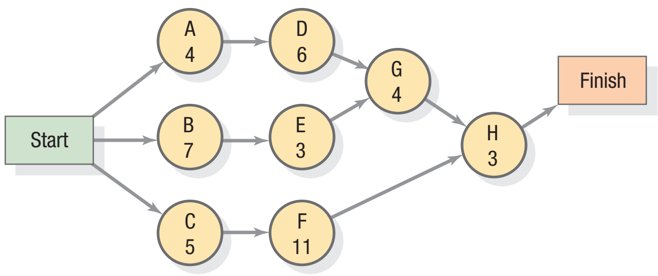
1. Always have start and finish nodes.
2. Try to avoid crossing paths to keep the diagram simple.
3. Use only one arrow to directly connect any two nodes.
4. Put the activities with no predecessors at the left and point the arrows from left to right.
5. Be prepared to revise the diagram several times before you come up with a correct and uncluttered diagram.

**b.** With these activity durations, the project will be completed in 19 days and incur a $700 penalty. Determining a good completion date requires the use of the minimum-cost schedule procedure. Using the data provided in Table 7.2, you can determine the maximum crash-time reduction and crash cost per day for each activity. For example, for activity A

$$\begin{aligned}\text{Maximum crash time} &= \text{Normal time} - \text{Crash time}\\ &= 4 \text{ days} - 3 \text{ days} = 1 \text{ day}\end{aligned}$$

$$\begin{aligned}\text{Crash cost per day} &= \frac{\text{Crash cost} - \text{Normal cost}}{\text{Normal time} - \text{Crash time}}\\ &= \frac{CC - NC}{NT - CT}\\ &= \frac{\$1{,}300 - \$1{,}000}{4 \text{ days} - 3 \text{ days}} = \$300\end{aligned}$$

**FIGURE 7.9 ▶**
Network Diagram for the Electric Motor Project



| Activity | Crash Cost per Day ($) | Maximum Time Reduction (days) |
|---|---|---|
| A | 300 | 1 |
| B | 200 | 3 |
| C | 700 | 1 |
| D | 200 | 1 |
| E | 200 | 1 |
| F | 250 | 5 |
| G | 650 | 1 |
| H | 100 | 2 |

Table 7.3 summarizes the analysis and the resultant project duration and total cost. The critical path is C–F–H at 19 days, which is the longest path in the network. The cheapest of these activities to crash is H, which costs only an extra $100 per day to crash. Doing so saves $200 + $100 = $300 per day in indirect and penalty costs. If you crash this activity for two days (the maximum), the lengths of the paths are now

A–D–G–H: 15 days, B–E–G–H: 15 days, and C–F–H: 17 days

The critical path is still C–F–H. The next cheapest critical activity to crash is F at $250 per day. You can crash F only two days because at that point you will have three critical paths. Further reductions in project duration will require simultaneous crashing of more than one activity (D, E, and F). The cost to do so, $650, exceeds the savings, $300. Consequently, you should stop. Note that every activity is critical. The project costs are minimized when the completion date is day 15. However, some goodwill costs may be associated with disappointing a customer who wants delivery in 12 days.

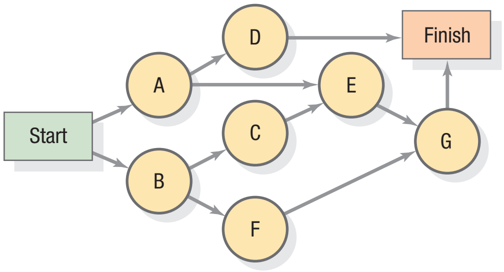
**TABLE 7.3** | **PROJECT COST ANALYSIS**

| Stage | Crash Activity | Time Reduction (days) | Resulting Critical Path(s) | Project Duration (days) | Project Direct Costs, Last Trial ($) | Crash Cost Added ($) | Total Indirect Costs ($) | Total Penalty Costs ($) | Total Project Costs ($) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | — | — | C–F–H | 19 | 10,100 | — | 3,800 | 700 | 14,600 |
| 1 | H | 2 | C–F–H | 17 | 10,100 | 200 | 3,400 | 500 | 14,200 |
| 2 | F | 2 | A–D–G–H<br>B–E–G–H<br>C–F–H | 15 | 10,300 | 500 | 3,000 | 300 | 14,100 |

## Solved Problem 2

An advertising project manager developed the network diagram shown in Figure 7.10 for a new advertising campaign. In addition, the manager gathered the time information for each activity, as shown in the accompanying table.

| | TIME ESTIMATES (WEEKS) | | | |
|---|---|---|---|---|
| Activity | Optimistic | Most Likely | Pessimistic | Immediate Predecessor(s) |
| A | 1 | 4 | 7 | — |
| B | 2 | 6 | 7 | — |
| C | 3 | 3 | 6 | B |
| D | 6 | 13 | 14 | A |
| E | 3 | 6 | 12 | A, C |
| F | 6 | 8 | 16 | B |
| G | 1 | 5 | 6 | E, F |




▲ **FIGURE 7.10**
Network Diagram for the Advertising Project

**a.** Calculate the expected time and variance for each activity.

**b.** Calculate the activity slacks and determine the critical path, using the expected activity times.

**c.** What is the probability of completing the project within 23 weeks?

## SOLUTION

**a.** The expected time and variance for each activity are calculated as follows:

$$t_e = \frac{a + 4m + b}{6}$$

| Activity | Expected Time (weeks) | Variance ($\sigma^2$) |
|---|---|---|
| A | 4.0 | 1.00 |
| B | 5.5 | 0.69 |
| C | 3.5 | 0.25 |
| D | 12.0 | 1.78 |
| E | 6.5 | 2.25 |
| F | 9.0 | 2.78 |
| G | 4.5 | 0.69 |

**b.** We need to calculate the earliest start, latest start, earliest finish, and latest finish times for each activity. Starting with activities A and B, we proceed from the beginning of the network and move to the end, calculating the earliest start and finish times:

| Activity | Earliest Start (weeks) | Earliest Finish (weeks) |
|---|---|---|
| A | 0 | 0 + 4.0 = 4.0 |
| B | 0 | 0 + 5.5 = 5.5 |
| C | 5.5 | 5.5 + 3.5 = 9.0 |
| D | 4.0 | 4.0 + 12.0 = 16.0 |
| E | 9.0 | 9.0 + 6.5 = 15.5 |
| F | 5.5 | 5.5 + 9.0 = 14.5 |
| G | 15.5 | 15.5 + 4.5 = 20.0 |

Based on expected times, the earliest finish for the project is week 20, when activity G has been completed. Using that as a target date, we can work backward through the network, calculating the latest start and finish times (shown graphically in Figure 7.11):

| Activity | Latest Start (weeks) | Latest Finish (weeks) |
|---|---|---|
| G | 15.5 | 20.0 |
| F | 6.5 | 15.5 |
| E | 9.0 | 15.5 |
| D | 8.0 | 20.0 |
| C | 5.5 | 9.0 |
| B | 0.0 | 5.5 |
| A | 4.0 | 8.0 |

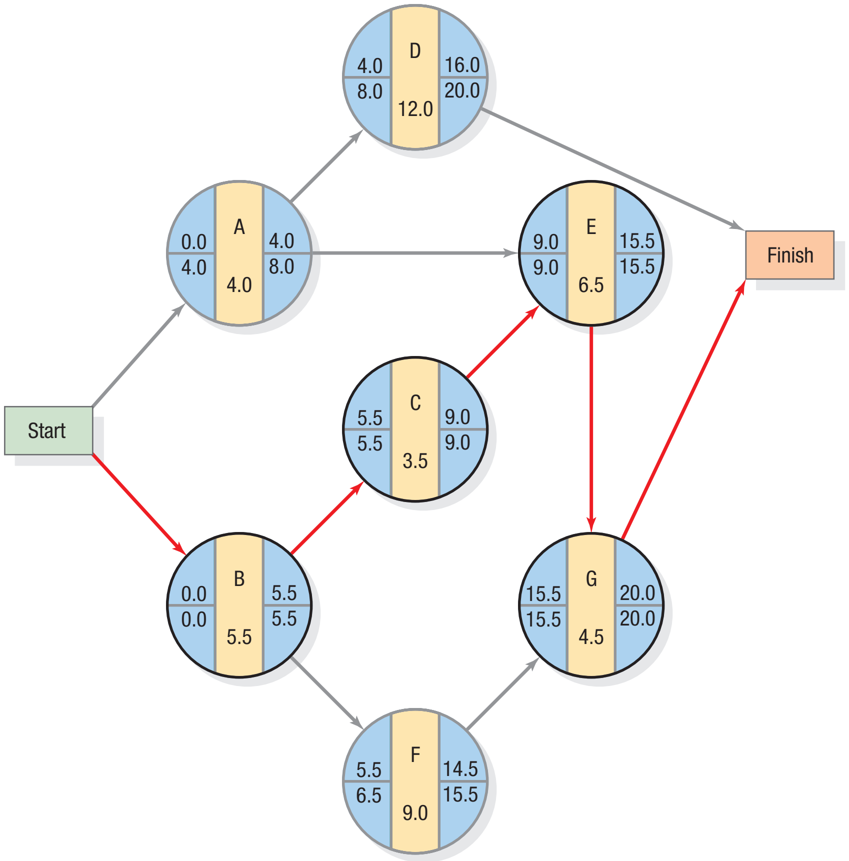



**FIGURE 7.11**
Network Diagram with All Time Estimates Needed to Compute Slack

We now calculate the activity slacks and determine which activities are on the critical path:

| | START (WEEKS) | | FINISH (WEEKS) | | | |
|---|---|---|---|---|---|---|
| **Activity** | **Earliest** | **Latest** | **Earliest** | **Latest** | **Slack** | **Critical Activity** |
| A | 0.0 | 4.0 | 4.0 | 8.0 | 4.0 | No |
| B | 0.0 | 0.0 | 5.5 | 5.5 | 0.0 | Yes |
| C | 5.5 | 5.5 | 9.0 | 9.0 | 0.0 | Yes |
| D | 4.0 | 8.0 | 16.0 | 20.0 | 4.0 | No |
| E | 9.0 | 9.0 | 15.5 | 15.5 | 0.0 | Yes |
| F | 5.5 | 6.5 | 14.5 | 15.5 | 1.0 | No |
| G | 15.5 | 15.5 | 20.0 | 20.0 | 0.0 | Yes |

The paths, and their total expected times and variances, are

| Path | Total Expected Time (weeks) | Total Variance ($\sigma_P^2$) |
|---|---|---|
| A–D | $4 + 12 = 16$ | $1.00 + 1.78 = 2.78$ |
| A–E–G | $4 + 6.5 + 4.5 = 15$ | $1.00 + 2.25 + 0.69 = 3.94$ |
| B–C–E–G | $5.5 + 3.5 + 6.5 + 4.5 = 20$ | $0.69 + 0.25 + 2.25 + 0.69 = 3.88$ |
| B–F–G | $5.5 + 9 + 4.5 = 19$ | $0.69 + 2.78 + 0.69 = 4.16$ |

The critical path is B–C–E–G, with a total expected time of 20 weeks. However, path B–F–G is 19 weeks and has a large variance.

**c.** We first calculate the $z$-value:

$$z = \frac{T - T_E}{\sigma_P} = \frac{23 - 20}{\sqrt{3.88}} = 1.52$$

Using the Normal Distribution appendix, we find that the probability of completing the project in 23 weeks or fewer is 0.9357. Because the length of path B–F–G is close to that of the critical path and has a large variance, it might well become the critical path during the project.

# Discussion Questions

1. What is the work breakdown structure (WBS), and why is it so essential for project management? When providing your answer, make sure to discuss the concept of "activity ownership."
2. Explain how to determine the slack for each activity in a project. Why is it important for managers to know where the slack is in their projects?
3. What is critical path analysis? How is it implemented in project management?

# Problems

The OM Explorer and POM for Windows software is available to all students using the 11th edition of this textbook. Go to **http://www.pearsonglobaleditions.com/krajewski** to download these computer packages. If you purchased MyOMLab, you also have access to Active Models software and significant help in doing the following problems. Check with your instructor on how best to use these resources. In many cases, the instructor wants you to understand how to do the calculations by hand. At the least, the software provides a check on your calculations. When calculations are particularly complex and the goal is interpreting the results in making decisions, the software replaces entirely the manual calculations.

## Developing the Project Schedule

1. Consider the following data for a project to install a new server at a local high school:

| Activity | Activity Time (days) | Immediate Predecessor(s) |
|---|---|---|
| A | 4 | — |
| B | 5 | A |
| C | 4 | A |
| D | 4 | B |
| E | 1 | B |
| F | 6 | B, C |
| G | 3 | D, E |
| H | 2 | F |
| I | 5 | F |
| J | 7 | G, H, I |

   **a.** Draw a network diagram.

   **b.** Calculate the critical path for this project.

   **c.** How much slack is in each of the activities G, H, and I?

2. The following information is known about a project to upgrade a point-of-sale system at Kids and Tots Apparel.

| Activity | Activity Time (days) | Immediate Predecessor(s) |
|---|---|---|
| A | 8 | — |
| B | 4 | A |
| C | 3 | A |
| D | 5 | B, C |
| E | 4 | D |
| F | 2 | E |
| G | 8 | E |

   **a.** Draw a network diagram for this project.

   **b.** Determine the critical path and project duration.

   **c.** Calculate the slack for each activity.

3. A project for improving a billing process has the following precedence relationships and activity times:

| Activity | Activity Time (days) | Immediate Predecessor(s) |
|---|---|---|
| A | 2 | — |
| B | 7 | — |
| C | 7 | A |
| D | 11 | B, C |
| E | 9 | B |
| F | 4 | D |
| G | 7 | E |
| H | 9 | F, G |

a. Draw the network diagram.

b. Calculate the slack for each activity. Which activities are on the critical path?

4. The following information is available about a project to organize an event at a High School in your country:

| Activity | Activity Time (days) | Immediate Predecessor(s) |
|---|---|---|
| A | 2 | — |
| B | 3 | — |
| C | 6 | — |
| D | 4 | — |
| E | 8 | A |
| F | 1 | B, C, D |
| G | 3 | E, F |
| H | 6 | F |
| I | 5 | G |
| J | 3 | G |
| K | 3 | H |

a. Draw the network diagram.

b. Find the critical path.

5. The following information has been gathered for a project to install a new machine lathe at Emerald Manufacturing, Inc:

| Activity | Activity Time (weeks) | Immediate Predecessor(s) |
|---|---|---|
| A | 5 | — |
| B | 7 | A |
| C | 10 | B |
| D | 4 | B |
| E | 17 | D |
| F | 12 | C, D |
| G | 13 | F, E |

a. Draw the network diagram.

b. Calculate the slack for each activity and determine the critical path. How long will the project take?

6. Consider the following information for a project to add a drive-through window at Crestview Bank.

| Activity | Activity Time (weeks) | Immediate Predecessor(s) |
|---|---|---|
| A | 7 | — |
| B | 3 | — |
| C | 6 | — |
| D | 3 | A, B |
| E | 4 | B |
| F | 4 | D, C |
| G | 4 | E, C |
| H | 10 | F, G |

a. Draw the network diagram for this project.

b. Specify the critical path.

c. Calculate the slack for activities A and D.

7. Consider the following data for a project to reorganize the office space at Platinum Financial Advisors:

| Activity | Expected Time $t_e$ (weeks) | Immediate Predecessor(s) |
|---|---|---|
| A | 5 | — |
| B | 3 | — |
| C | 2 | A |
| D | 5 | B |
| E | 4 | C, D |
| F | 7 | D |

a. Draw the network diagram for this project.

b. Identify the critical path and estimate the project's duration.

c. Calculate the slack for each activity.

8. Paul Silver, owner of Sculptures International, just initiated a new art project. The following data are available for the project:

| Activity | Activity Time (days) | Immediate Predecessor(s) |
|---|---|---|
| A | 4 | — |
| B | 1 | — |
| C | 3 | A |
| D | 2 | B |
| E | 3 | C, D |

a. Draw the network diagram for the project.

b. Determine the project's critical path and duration.

c. What is the slack for each activity?

9. Reliable Garage is completing production of the J2000 kit car. The following data are available for the project:

| Activity | Activity Time (days) | Immediate Predecessor(s) |
|---|---|---|
| A | 2 | — |
| B | 6 | A |
| C | 4 | B |
| D | 5 | C |
| E | 7 | C |
| F | 5 | C |
| G | 5 | F |
| H | 3 | D, E, G |

a. Draw the network diagram for the project.

b. Determine the project's critical path and duration.

c. What is the slack for each activity?

**10.** The following information concerns a project to raise money for the Kids Against Crime Foundation:

| Activity | Activity Time (days) | Immediate Predecessor(s) |
|---|---|---|
| A | 10 | — |
| B | 11 | — |
| C | 9 | A, B |
| D | 5 | A, B |
| E | 8 | A, B |
| F | 13 | C, E |
| G | 5 | C, D |
| H | 10 | G |
| I | 6 | F, G |
| J | 9 | E, H |
| K | 11 | I, J |

**a.** Draw the network diagram for this project.

**b.** Determine the critical path and project completion time.

**11.** D Consider a project to produce custom door moldings for GMC Acadia cross-over vehicles, described in Table 7.4.

**a.** If you start the project immediately, when will it be finished?

**b.** You are interested in completing your project as soon as possible. You have only one option. Suppose you could assign Employee A, currently assigned to activity G, to help Employee B, currently assigned to activity F. Each week that Employee A helps Employee B will result in activity G increasing its time by one week and activity F reducing its time by one week. How many weeks should Employee A work on activity F?

**TABLE 7.4** | **PROJECT DATA FOR GMC ACADIA**

| Activity | Activity Time (weeks) | Immediate Predecessor(s) |
|---|---|---|
| START | 0 | — |
| A | 3 | START |
| B | 4 | START |
| C | 4 | B |
| D | 4 | A |
| E | 5 | A, B |
| F | 6 | D, E |
| G | 2 | C, E |
| FINISH | 0 | F, G |

## Analyzing Cost–Time Trade-offs

**12.** Table 7.5 contains information about an environmental clean-up project in the township of Hiles. Shorten the project three weeks by finding the minimum-cost schedule. Assume that project indirect costs and penalty costs are negligible. Identify activities to crash while minimizing the additional crash costs.

**TABLE 7.5** | **ENVIRONMENTAL PROJECT DATA**

| Activity | Normal Time (weeks) | Crash Time (weeks) | Cost to Crash ($ per week) | Immediate Predecessor(s) |
|---|---|---|---|---|
| A | 7 | 6 | 200 | None |
| B | 12 | 9 | 250 | None |
| C | 7 | 6 | 250 | A |
| D | 6 | 5 | 300 | A |
| E | 1 | 1 | — | B |
| F | 1 | 1 | — | C, D |
| G | 3 | 1 | 200 | D, E |
| H | 3 | 2 | 350 | F |
| I | 2 | 2 | — | G |

**13.** The Advanced Tech Company has a project to design an integrated information database for a major bank. Data for the project are given in Table 7.6. Indirect project costs amount to $300 per day. The company will incur a $150 per day penalty for each day the project lasts beyond day 14.

**a.** What is the project's duration if only normal times are used?

**b.** What is the minimum-cost schedule?

**c.** What is the critical path for the minimum-cost schedule?

**TABLE 7.6** | **DATABASE DESIGN PROJECT DATA**

| Activity | Normal Time (days) | Normal Cost ($) | Crash Time (days) | Crash Cost ($) | Immediate Predecessor(s) |
|---|---|---|---|---|---|
| A | 6 | 1,000 | 5 | 1,200 | — |
| B | 4 | 800 | 2 | 2,000 | — |
| C | 3 | 600 | 2 | 900 | A, B |
| D | 2 | 1,500 | 1 | 2,000 | B |
| E | 6 | 900 | 4 | 1,200 | C, D |
| F | 2 | 1,300 | 1 | 1,400 | E |
| G | 4 | 900 | 4 | 900 | E |
| H | 4 | 500 | 2 | 900 | G |

**14.** You are the manager of a project to improve a billing process at your firm. Table 7.7 contains the data you will need to conduct a cost analysis of the project. Indirect costs are $1,600 per week, and penalty costs are $1,200 per week after week 12.

**a.** What is the minimum-cost schedule for this project?

**b.** What is the difference in total project costs between the earliest completion time of the project using "normal" times and the minimum-cost schedule you derived in part (a)?

D = Difficult Problem

**TABLE 7.7** DATA FOR THE BILLING PROCESS PROJECT

| Activity | Immediate Predecessor(s) | Normal Time (weeks) | Crash Time (weeks) | Normal Cost ($) | Crash Cost ($) |
|---|---|---|---|---|---|
| A | — | 4 | 1 | 5,000 | 8,000 |
| B | — | 5 | 3 | 8,000 | 10,000 |
| C | A | 1 | 1 | 4,000 | 4,000 |
| D | B | 6 | 3 | 6,000 | 12,000 |
| E | B, C | 7 | 6 | 4,000 | 7,000 |
| F | D | 7 | 6 | 4,000 | 7,000 |

**15.** Table 7.8 contains data for the installation of new equipment in a manufacturing process at Excello Corporation. Your company is responsible for the installation project. Indirect costs are $15,000 per week, and a penalty cost of $9,000 per week will be incurred by your company for every week the project is delayed beyond week 9.

**a.** What is the shortest time duration for this project regardless of cost?

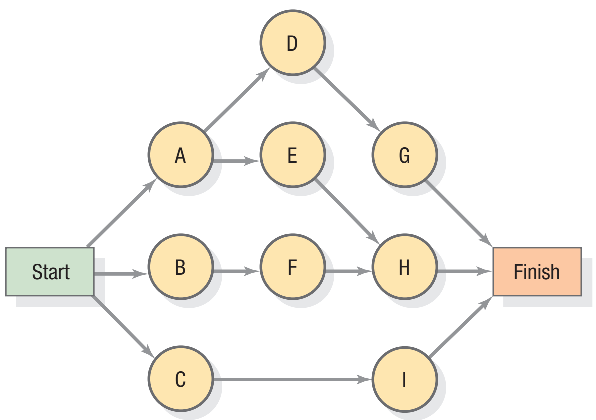
**b.** What is the minimum total cost associated with completing the project in 9 weeks?

**c.** What is the total time of the minimum-cost schedule?

**TABLE 7.8** DATA FOR THE EQUIPMENT INSTALLATION PROJECT

| Activity | Immediate Predecessor(s) | Normal Time (weeks) | Crash Time (weeks) | Normal Cost ($) | Crash Cost ($) |
|---|---|---|---|---|---|
| A | — | 2 | 1 | 7,000 | 10,000 |
| B | — | 2 | 2 | 3,000 | 3,000 |
| C | A | 3 | 1 | 12,000 | 40,000 |
| D | B | 3 | 2 | 12,000 | 28,000 |
| E | C | 1 | 1 | 8,000 | 8,000 |
| F | D, E | 5 | 3 | 5,000 | 15,000 |
| G | E | 3 | 2 | 9,000 | 18,000 |

**16.** The diagram in Figure 7.12 was developed for the project launch of Kitty Condo, a new product in the luxury cat cage market. Suppose that you, as project manager, are interested in finding ways to speed up the project at minimal additional cost. Determine the schedule for completing the project in 25 days at minimum cost. Penalty and project-overhead costs are negligible. Time and cost data for each activity are shown in Table 7.9.




▲ **FIGURE 7.12**
Network Diagram for Kitty Condo

**TABLE 7.9** PROJECT ACTIVITY AND COST DATA

| | NORMAL | | CRASH | |
|---|---|---|---|---|
| Activity | Time (days) | Cost ($) | Time (days) | Cost ($) |
| A | 12 | 1,300 | 11 | 1,900 |
| B | 13 | 1,050 | 9 | 1,500 |
| C | 18 | 3,000 | 16 | 4,500 |
| D | 9 | 2,000 | 5 | 3,000 |
| E | 12 | 650 | 10 | 1,100 |
| F | 8 | 700 | 7 | 1,050 |
| G | 8 | 1,550 | 6 | 1,950 |
| H | 2 | 600 | 1 | 800 |
| I | 4 | 2,200 | 2 | 4,000 |

**17.** D You are in charge of a project at the local community center. The center needs to remodel one of the rooms in time for the start of a new program. Delays in the project mean that the center must rent other space at a nearby church at additional cost. Time and cost data for your project are contained in Table 7.10. Your interest is in minimizing the cost of the project to the community center.

**a.** Using the *normal times* for each activity, what is the earliest date you can complete the project?

**b.** Suppose the variable overhead costs are $50 per day for your project. Also, suppose that the center must pay $40 per day for a temporary room on day 15 or beyond. Find the minimum-cost project schedule.

**TABLE 7.10** DATA FOR THE COMMUNITY CENTER PROJECT

| Activity | Normal Time (days) | Normal Cost ($) | Crash Time (days) | Crash Cost ($) | Immediate Predecessor(s) |
|---|---|---|---|---|---|
| START | 0 | 0 | 0 | 0 | — |
| A | 10 | 50 | 8 | 150 | START |
| B | 4 | 40 | 2 | 200 | START |
| C | 7 | 70 | 6 | 160 | B |
| D | 2 | 20 | 1 | 50 | A, C |
| E | 3 | 30 | 3 | 30 | A, C |
| F | 8 | 80 | 5 | 290 | B |
| G | 5 | 50 | 4 | 180 | D |
| H | 6 | 60 | 3 | 180 | E, F |
| FINISH | 0 | 0 | 0 | 0 | G, H |

**18.** D The information in Table 7.11 is available for a large fund-raising project.

**a.** Determine the critical path and the expected completion time of the project.

**b.** Plot the total project cost, starting from day 1 to the expected completion date of the project, assuming the earliest start times for each activity. Compare that result to a similar plot for the latest start times. What implication does the time differential have for cash flows and project scheduling?

**TABLE 7.11** FUND-RAISING PROJECT DATA

| Activity | Activity Time (days) | Activity Cost ($) | Immediate Predecessor(s) |
|---|---|---|---|
| A | 3 | 100 | — |
| B | 4 | 150 | — |
| C | 2 | 125 | A |
| D | 5 | 175 | B |
| E | 3 | 150 | B |
| F | 4 | 200 | C, D |
| G | 6 | 75 | C |
| H | 2 | 50 | C, D, E |
| I | 1 | 100 | E |
| J | 4 | 75 | D, E |
| K | 3 | 150 | F, G |
| L | 3 | 150 | G, H, I |
| M | 2 | 100 | I, J |
| N | 4 | 175 | K, M |
| O | 1 | 200 | H, M |
| P | 5 | 150 | N, L, O |

**19.** D You are the project manager of the software installation project in Table 7.12. You would like to find the minimum-cost schedule for your project. There is a $1,000-per-week penalty for each week the project is delayed beyond week 25. In addition, your project team determined that indirect project costs are $2,500 per week.

**a.** What would be your target completion week?

**b.** How much would you save in total project costs with your schedule?

**TABLE 7.12** DATA FOR SOFTWARE INSTALLATION PROJECT

| Activity | Immediate Predecessors | Normal Time (weeks) | Normal Cost ($) | Crash Time (weeks) | Crash Cost ($) |
|---|---|---|---|---|---|
| A | — | 5 | 2,000 | 3 | 4,000 |
| B | — | 8 | 5,000 | 7 | 8,000 |
| C | A | 10 | 10,000 | 8 | 12,000 |
| D | A, B | 4 | 3,000 | 3 | 7,000 |
| E | B | 3 | 4,000 | 2 | 5,000 |
| F | D | 9 | 8,000 | 6 | 14,000 |
| G | E, F | 2 | 2,000 | 2 | 2,000 |
| H | G | 8 | 6,000 | 5 | 9,000 |
| I | C, F | 9 | 7,000 | 7 | 15,000 |

D = Difficult Problem

## Assessing and Analyzing Risks

**20.** Jordanne King, the project manager for Webjets International, Inc., compiled a table showing time estimates for each of the activities of a project to upgrade the company's Web page, including optimistic, most likely, and pessimistic.

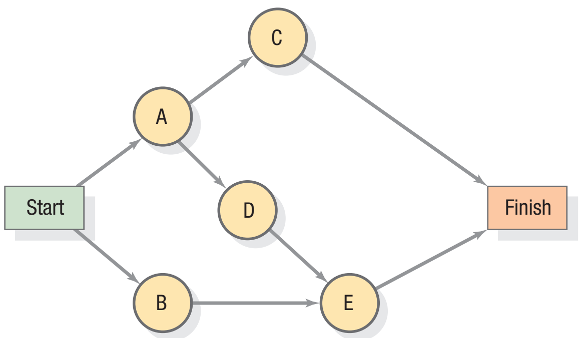
**a.** Calculate the expected time, $t_e$, for each activity.

**b.** Calculate the variance, $\sigma^2$, for each activity.

| Activity | Optimistic (days) | Most Likely (days) | Pessimistic (days) |
|---|---|---|---|
| A | 3 | 8 | 19 |
| B | 12 | 15 | 18 |
| C | 2 | 6 | 16 |
| D | 4 | 9 | 20 |
| E | 1 | 4 | 7 |

**21.** Recently, you were assigned to manage a project to remodel the seminar room for your company. You have constructed a network diagram depicting the various activities in the project (Figure 7.13). In addition, you have asked your team to estimate the amount of time that they would expect each of the activities to take. Their responses are shown in the following table:

| | TIME ESTIMATES (DAYS) | | |
|---|---|---|---|
| **Activity** | **Optimistic** | **Most Likely** | **Pessimistic** |
| A | 5 | 8 | 11 |
| B | 4 | 8 | 11 |
| C | 5 | 6 | 7 |
| D | 2 | 4 | 6 |
| E | 4 | 7 | 10 |




▲ **FIGURE 7.13**
Network Diagram for Problem 21

**a.** What is the expected completion time of the project?

**b.** What is the probability of completing the project in 21 days?

**c.** What is the probability of completing the project in 17 days?

**22.** In Solved Problem 2, estimate the probability that the noncritical path B–F–G will take more than 20 weeks. *Hint:* Subtract from 1.0 the probability that B–F–G will take 20 weeks or less.

**23.** The director of continuing education at Bluebird University just approved the planning for a sales training seminar. Her administrative ass istant identified the various activities that must be done and their relationships to each other, as shown in Table 7.13.

**TABLE 7.13** ACTIVITIES FOR THE SALES TRAINING SEMINAR

| Activity | Description | Immediate Predecessor(s) |
|---|---|---|
| A | Design brochure and course announcement | — |
| B | Identify prospective teachers | — |
| C | Prepare detailed outline of course | — |
| D | Send brochure and student applications | A |
| E | Send teacher applications | B |
| F | Select teacher for course | C, E |
| G | Accept students | D |
| H | Select text for course | F |
| I | Order and receive texts | G, H |
| J | Prepare room for class | G |

Because of the uncertainty in planning the new course, the assistant also has supplied the following time estimates for each activity:

| | TIME ESTIMATES (DAYS) | | |
|---|---|---|---|
| **Activity** | **Optimistic** | **Most Likely** | **Pessimistic** |
| A | 5 | 7 | 8 |
| B | 6 | 8 | 12 |
| C | 3 | 4 | 5 |
| D | 11 | 17 | 25 |
| E | 8 | 10 | 12 |
| F | 3 | 4 | 5 |
| G | 4 | 8 | 9 |
| H | 5 | 7 | 9 |
| I | 8 | 11 | 17 |
| J | 4 | 4 | 4 |

The director wants to conduct the seminar 47 working days from now. What is the probability that everything will be ready in time?

**24.** Gabrielle Kramer, owner of Pet Paradise, is opening a new store in Columbus, Ohio. Her major concern is the hiring of a manager and several associates who are animal lovers. She also has to coordinate the renovation of a building that was previously owned by a chic clothing store. Kramer has gathered the data shown in Table 7.14.

**a.** How long is the project expected to take?

**b.** Suppose that Kramer has a personal goal of completing the project in 14 weeks. What is the probability that it will happen this quickly?

**TABLE 7.14 | DATA FOR THE PET PARADISE PROJECT**

| | | | TIME (WEEKS) | | |
|---|---|---|---|---|---|
| **Activity** | **Description** | **Immediate Predecessor(s)** | ***A*** | ***m*** | ***b*** |
| A | Interview for new manager | — | 1 | 3 | 6 |
| B | Renovate building | — | 6 | 9 | 12 |
| C | Place ad for associates and interview applicants | — | 6 | 8 | 16 |
| D | Have new manager prospects visit | A | 2 | 3 | 4 |
| E | Purchase equipment for new store and install | B | 1 | 3 | 11 |
| F | Check employee applicant references and make final selection | C | 5 | 5 | 5 |
| G | Check references for new manager and make final selection | D | 1 | 1 | 1 |
| H | Hold orientation meetings and do payroll paperwork | E, F, G | 3 | 3 | 3 |

**25.** **D** The project manager of Good Public Relations gathered the data shown in Table 7.15 for a new advertising campaign.

**a.** How long is the project likely to take?

**b.** What is the probability that the project will take more than 38 weeks?

**c.** Consider the path A–E–G–H–J. What is the probability that this path will exceed 38 weeks?

**TABLE 7.15 | ACTIVITY DATA FOR ADVERTISING PROJECT**

| | TIME ESTIMATES (WEEKS) | | | |
|---|---|---|---|---|
| **Activity** | **Optimistic** | **Most Likely** | **Pessimistic** | **Immediate Predecessor(s)** |
| A | 8 | 10 | 12 | START |
| B | 5 | 8 | 17 | START |
| C | 7 | 8 | 9 | START |
| D | 1 | 2 | 3 | B |
| E | 8 | 10 | 12 | A, C |
| F | 5 | 6 | 7 | D, E |
| G | 1 | 3 | 5 | D, E |
| H | 2 | 5 | 8 | F, G |
| I | 2 | 4 | 6 | G |
| J | 4 | 5 | 8 | H |
| K | 2 | 2 | 2 | H |

**26.** **D** Consider the office renovation project data in Table 7.16. A "zero" time estimate means that the activity could take a very small amount of time and should be treated as a numeric zero in the analysis.

**a.** Based on the critical path, find the probability of completing the office renovation project by 39 days.

**b.** Find the date by which you would be 90 percent sure of completing the project.

**D** = **Difficult Problem**

**TABLE 7.16** DATA FOR THE OFFICE RENOVATION PROJECT

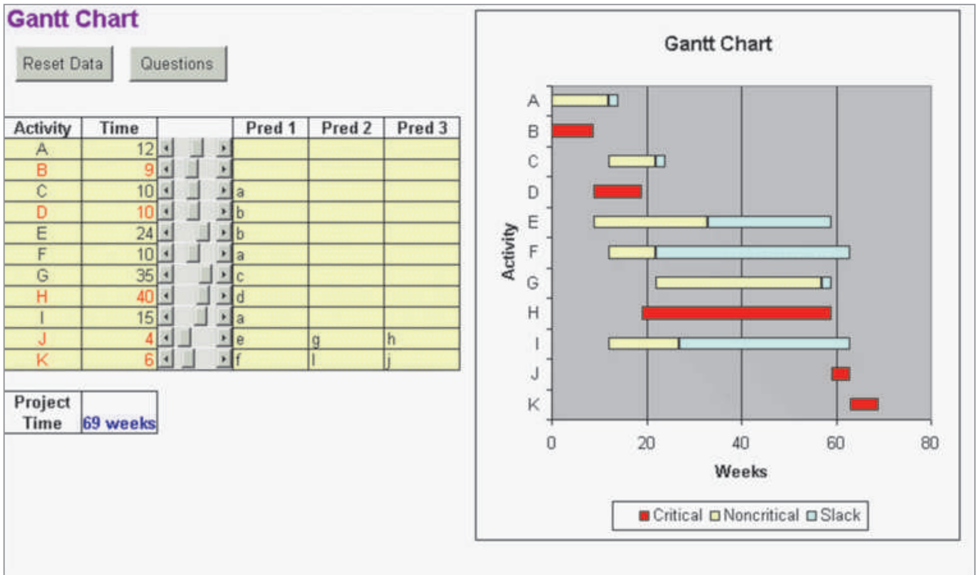
| | TIME ESTIMATES (DAYS) | | | |
|---|---|---|---|---|
| **Activity** | **Optimistic** | **Most Likely** | **Pessimistic** | **Immediate Predecessor(s)** |
| START | 0 | 0 | 0 | — |
| A | 6 | 10 | 14 | START |
| B | 0 | 1 | 2 | A |
| C | 16 | 20 | 30 | A |
| D | 3 | 5 | 7 | B |
| E | 2 | 3 | 4 | D |
| F | 7 | 10 | 13 | C |
| G | 1 | 2 | 3 | D |
| H | 0 | 2 | 4 | G |
| I | 2 | 2 | 2 | C, G |
| J | 2 | 3 | 4 | I |
| K | 0 | 1 | 2 | H |
| L | 1 | 2 | 3 | J, K |
| FINISH | 0 | 0 | 0 | E, F, L |

## Active Model Exercise

Active Model 7.1, Gantt Chart, appears in MyOMLab. It allows you to evaluate the sensitivity of the project time to changes in activity times and activity predecessors. In this exercise we use the data from Example 7.2 to develop a Gantt chart.

### QUESTIONS

1. Activity B and activity K are critical activities. Describe the difference that occurs on the graph when you increase activity B versus when you increase activity K.
2. Activity F is not critical. Use the scroll bar to determine how many weeks you can increase activity F until it becomes critical.
3. Activity A is not critical. How many weeks can you increase activity A until it becomes critical? What happens when activity A becomes critical?
4. What happens when you increase activity A by one week after it becomes critical?
5. Suppose that building codes may change and, as a result, activity C would have to be completed before activity D could be started. How would this affect the project?




Gantt Chart Using Data from Example 7.2

## VIDEO CASE Project Management at the Phoenician

The Phoenician in Phoenix, Arizona, is part of Starwood's Luxury Collection and its only AAA Five Diamond Award resort in the southwestern United States. Sophistication, elegance, and excellence only begin to describe the guest experience at the hotel. Guests can dine in one of nine restaurants, relax poolside, play tennis, take in 27 holes of golf on three 9-hole courses, or relax with a variety of soothing spa treatments at the 22,000-square-foot Centre for Well-Being.

The Phoenician recently embarked on an ambitious $38 million spa and golf renovation program. The resort's golf and spa programs historically earned high marks from surveys in their industries over the years, but the environment was changing. Evidence of this change was seen in the explosive growth of new golf courses and spas in the Southwest region. Phoenix alone has over 275 golf courses, and the Southwest boasts the largest concentration of new luxury spas anywhere. The Phoenician's facilities, while world-class and highly rated, were more than 15 years old. The hotel's recently awarded Five Diamond status renewed emphasis on bringing every process and service at the property up to Five Diamond level.

The decision to renovate the golf course and existing spa became not a question of *whether* to undertake the projects, but *to what degree* they needed to be pursued. Key considerations centered on (1) whether to build basic facilities or commit to the grandiose luxury level, (2) having a domestic versus international reputation, and (3) developing creative packaging of the new facilities to attract loyal guests, such as a spa and golf "country club-like" membership program. Such a program would be limited to about 600 spa/golf memberships, with a one-time fee of $65,000 each.

The company's senior management considered three options for the Centre for Well-Being spa. First, the existing space in the heart of the resort could be renovated. This option would require relocating the spa to another part of the resort and offering limited treatments during this time, thereby reducing spa revenues significantly. With option 2, hilly terrain directly behind the resort could be carved out to create a new mountainside facility with sweeping vistas. This option meant the closure of one of the hotel's buildings housing 60 guest rooms and suites during the construction period. The existing spa could remain open, however. Under option 3, a parking structure on existing hotel property could be used, having the least impact on revenues. The first option was seen as a short-term fix, while the remaining two were viewed as having longer-term potential.

Additional discussion centered on the type of spa to be built. Recent acquisition of the Bliss spa brand for Starwood's W Hotels was an option, offering day spa amenities and an indulgence atmosphere. The second option was to remain a holistic resort spa with an emphasis on health and restoration. The third option was to become a destination spa with dedicated guest stays and week-long programs. Day spas are the fastest-growing category, with few destination spas.

The Phoenician management team, with assistance from Starwood Field Operations and Corporate offices, prepared an extensive analysis of strengths, weaknesses, opportunities, and threats to better understand the environment. The result of this analysis was used by the team to identify the set of activities necessary for each option. The Corporate Design and Construction group developed architectural and engineering plans, as well as the work breakdown structure and diagrams showing

| Work Breakdown Structure | Activity Time (days) | Activity Precedence Relationships |
|---|---|---|
| **Project Conception** | | |
| A. Kick-off meeting | 2 | |
| B. Creation of spa specifications | 30 | A |
| **Geotechnical Investigation** | | |
| C. Preliminary site characterizations | 10 | B |
| D. Subsurface investigation | 10 | C |
| E. Laboratory testing | 5 | D |
| F. Geologic hazard assessments | 10 | E |
| **Design Development** | | |
| G. Initial designs | 70 | B |
| H. Preliminary zoning compliance plan | 15 | C, G |
| I. Final designs | 18 | H |
| J. Owner approval of designs | 5 | I |
| **Documentation and Cost Estimation** | | |
| K. Construction documentation and landscape package | 80 | F, I |
| L. Acquisition of contractor estimates and bids | 90 | J, K |
| **Decision** | | |
| M. Owner approval of one of the three projects | 60 | L |

the critical path for the possible project options. The work breakdown structure, activity times, and activity precedence relationships are shown in the table on the previous page.

## QUESTIONS

1. Coordinating departments in a major project is always a challenge. Which departments within the Starwood organization likely played a role in each of the following project related activities?
   - **a.** Defining and organizing the project
   - **b.** Planning the project
   - **c.** Monitoring and controlling the project
2. Many times, project decision makers do not rely solely on financial hurdles, such as return on investment or internal rates of return, but place a lot of emphasis on intangible factors. Which are the salient intangible factors associated with selecting one of the three options for the spa?
3. Timing is always a challenge in managing projects. Construct a network diagram for the spa selection process. How soon can the Phoenician management make a decision on the spa?

Pearson

When the Phoenician, a luxury hotel in Phoenix, Arizona, sought to redesign its Center for Well-Being, its management team created a work breakdown structure in order to compare different project options and choose the best one.

# CASE The Pert Mustang

Roberts Auto Sales and Service (RASAS) consists of three car dealerships that sell and service several makes of American and Japanese cars, two auto parts stores, a large body shop and car painting business, and an auto salvage yard. Vicky Roberts, owner of RASAS, went into the car business when she inherited a Ford dealership from her father. She was able to capitalize on her knowledge and experience to build her business into the diversified and successful mini-empire it is today. Her motto, "Sell 'em today, repair 'em tomorrow!" reflects a strategy that she refers to in private as "Get 'em coming and going."

Roberts has always retained a soft spot in her heart for high-performance Mustangs and just acquired a 1965 Shelby Mustang GT 350 that needs a lot of restoration. She also notes the public's growing interest in the restoration of vintage automobiles. Roberts is thinking of expanding into the vintage car restoration business and needs help in assessing the feasibility of such a move. She wants to restore her 1965 Shelby Mustang to mint condition, or as close to mint condition as possible. If she decides to go into the car restoring business, she can use the Mustang as an exhibit in sales and advertising and take it to auto shows to attract business for the new shop.

Roberts believes that many people want the thrill of restoring an old car themselves, but they do not have the time to run down all the old parts. Still, others just want to own a vintage auto because it is different and many of them have plenty of money to pay someone to restore an auto for them.

Roberts wants the new business to appeal to both types of people. For the first group, she envisions serving as a parts broker for NOS ("new old stock"), new parts that were manufactured many years ago and are still packaged in their original cartons. It can be a time-consuming process to find the right part. RASAS could also machine new parts to replicate those that are hard to find or that no longer exist.

In addition, RASAS could assemble a library of parts and body manuals for old cars to serve as an information resource for do-it-yourself restorers. The do-it-yourselfers could come to RASAS for help in compiling parts lists, and RASAS could acquire the parts for them. For others, RASAS would take charge of the entire restoration.

Roberts asked the director of service operations to take a good look at her Mustang and determine what needs to be done to restore it to the condition it was in when it came from the factory more than 40 years ago. She wants to restore this car in time to exhibit it at the Detroit Auto Show. If the car gets a lot of press, it will be a real public relations coup for RASAS—especially if Roberts decides to enter this new venture. Even if she does not, the car will be a showpiece for the rest of the business.

Roberts asked the director of service operations to prepare a report about what is involved in restoring the car and whether it can be done in time for the Detroit show in 45 working days using PERT/CPM. The parts manager, the body shop manager, and the chief mechanic have provided the following estimates of times and activities that need to be done, as well as cost estimates:

- **a.** Order all needed material and parts (upholstery, windshield, carburetor, and oil pump). Time: 2 days. Cost (telephone calls and labor): $100.
- **b.** Receive upholstery material for seat covers. Cannot be done until order is placed. Time: 30 days. Cost: $2,100.
- **c.** Receive windshield. Cannot be done until order is placed. Time: 10 days. Cost: $800.
- **d.** Receive carburetor and oil pump. Cannot be done until order is placed. Time: 7 days. Cost: $1,750.
- **e.** Remove chrome from body. Can be done immediately. Time: 1 day. Cost: $200.
- **f.** Remove body (doors, hood, trunk, and fenders) from frame. Cannot be done until chrome is removed. Time: 1 day. Cost: $300.
- **g.** Have fenders repaired by body shop. Cannot be done until body is removed from frame. Time: 4 days. Cost: $1,000.
- **h.** Repair doors, trunk, and hood. Cannot be done until body is removed from frame. Time: 6 days. Cost: $1,500.
- **i.** Pull engine from chassis. Do after body is removed from frame. Time: 1 day. Cost: $200.

**j.** Remove rust from frame. Do after the engine has been pulled from the chassis. Time: 3 days. Cost $900.

**k.** Regrind engine valves. Do after the engine has been pulled from the chassis. Time: 5 days. Cost: $1,000.

**l.** Replace carburetor and oil pump. Do after engine has been pulled from chassis and after carburetor and oil pump have been received. Time: 1 day. Cost: $200.

**m.** Rechrome the chrome parts. Chrome must have been removed from the body first. Time: 3 days. Cost: $210.

**n.** Reinstall engine. Do after valves are reground and carburetor and oil pump have been installed. Time: 1 day. Cost: $200.

**o.** Put doors, hood, and trunk back on frame. The doors, hood, and trunk must have been repaired first. The frame must have had its rust removed first. Time: 1 day. Cost: $240.

**p.** Rebuild transmission and replace brakes. Do so after the engine has been reinstalled and the doors, hood, and trunk are back on the frame. Time: 4 days. Cost: $2,000.

**q.** Replace windshield. Windshield must have been received. Time: 1 day. Cost: $100.

**r.** Put fenders back on. The fenders must have been repaired first, the transmission rebuilt, and the brakes replaced. Time: 1 day. Cost: $100.

**s.** Paint car. Cannot be done until the fenders are back on and windshield replaced. Time: 4 days. Cost: $1,700.

**t.** Reupholster interior of car. Must have received upholstery material first. Car must have been painted first. Time: 7 days. Cost: $2,400.

**u.** Put chrome parts back on. Car must have been painted and chrome parts rechromed first. Time: 1 day. Cost: $100.

**v.** Pull car to the Detroit Auto Show. Must have completed reupholstery of interior and have put the chrome parts back on. Time: 2 days. Cost: $1,000.

Roberts wants to limit expenditures on this project to what could be recovered by selling the restored car. She has already spent $50,000 to acquire the car. In addition, she wants a brief report on some of the aspects of the proposed business, such as how it fits in with RASAS's other businesses and what RASAS's operations task should be with regard to cost, quality, customer service, and flexibility.

In the restoration business there are various categories of restoration. A basic restoration gets the car looking great and running, but a mint-condition restoration puts the car back in original condition—as it was "when it rolled off the line." When restored cars are resold, a car in mint condition commands a much higher price than one that is just a basic restoration. As cars are restored, they can also be customized. That is, something is put on the car that could not have been on the original. Roberts wants a mint-condition restoration for her Mustang without customization. (The proposed new business would accept any kind of restoration a customer wanted.)

The total budget cannot exceed $70,000 including the $50,000 Roberts has already spent. In addition, Roberts cannot spend more than $3,600 in any week given her present financial position. Even though much of the work will be done by Roberts's own employees, labor and materials costs must be considered. All relevant costs have been included in the cost estimates.

## QUESTIONS

1. Using the information provided, prepare the report that Vicky Roberts requested, assuming that the project will begin immediately. Assume 45 working days are available to complete the project, including transporting the car to Detroit before the auto show begins. Your report should briefly discuss the aspects of the proposed new business, such as the competitive priorities that Roberts asked about.
2. Construct a table containing the project activities using the letter assigned to each activity, the time estimates, and the precedence relationships from which you will assemble the network diagram.
3. Draw a network diagram of the project similar to Figure 7.3. Determine the activities on the critical path and the estimated slack for each activity.
4. Prepare a project budget showing the cost of each activity and the total for the project. Can the project be completed within the budget? Will the project require more than $3,600 in any week? To answer this question, assume that activities B, C, and D must be paid for when the item is received (the earliest finish time for the activity). Assume that the costs of all other activities that span more than one week can be prorated. Each week contains five work days. If problems exist, how might Roberts overcome them?

*Source:* This case was prepared by and is used by permission of Dr. Sue P. Siferd, Professor Emerita, Arizona State University (Updated September, 2007).

Annette M. Drowlette/Agusta Chronicle/ZUMAPRESS.com/Newscom

Accurate forecasting is crucial to maintaining the proper amount of product in the supply chain. Kimberly-Clark recently incorporated demand-signal data—information on actual consumer sales—into its forecasting system and greatly increased the accuracy of the forecasts. Here a worker moves pallets of paper products at a Kimberly-Clark warehouse in Beech Island, South Carolina.

# 8

# FORECASTING DEMAND

## Kimberly-Clark

What do Kleenex tissues, Huggies diapers, and Scott paper towels all have in common? They are all produced by Kimberly-Clark, a $21 billion multi-national company based in Irving, Texas. With 106 production and warehouse facilities worldwide one can only imagine the complexity of ensuring that retail customers located in 175 countries receive their orders on time. Any time the retailer's inventories are out of sync with production forecasts, it can have a dramatic effect on Kimberly-Clark's bottom line: empty shelves at the retail level force consumers to seek out competitors' products while too much inventory at Kimberly-Clark is very costly. For example, during the high-volume flu season a one-day reduction in safety stock inventories translates into a $10 million savings across the supply chain network. It is no wonder that forecast accuracy is a top priority at Kimberly-Clark. Forecast errors drive the need for safety stocks (greater forecast errors equate to greater uncertainty in demands) and result in inefficient operations and higher costs. Consequently, Kimberly-Clark undertook a major project to improve its forecasting performance.

Prior to the onset of the project, forecasts were based on historical shipment data. The shipments were geared to satisfy actual customer orders. Intuitively, those data should be good for making forecasts of future orders. However, actual shipments may be subject to all sorts of anomalies such as supply disruptions, factory or transportation capacity limits, or severe weather, all of which could delay the shipments and miss the dates the customer actually wanted the product. Perhaps the biggest problem with using past shipment data for making forecasts is that it is backward-looking; forecasts assume that what happened in the past will happen in the future. Such an approach will miss spikes in consumer demand. For example, Hurricane Sandy pummeled the east coast in 2012 and caused a drop in the sales of paper products in the northeast region. Estimating weekly sales on the basis of historical shipment data when there was no storm will be fraught with errors; even managerial judgment to temper the forecasts will not provide much relief. When would consumers in the northeast turn their attention from buying generators and portable lighting products to paper towels and diapers again?

The project to improve forecasting performance was a major part of a larger project to create a demand-driven supply chain. Kimberly-Clark reduced the number of production facilities and warehouses, opened new larger facilities, and repurposed others to handle a smaller set of customers or to ship only promotional items. All told, this design not only improved logistical efficiency but also simplified the forecasting effort. The key, however, to creating a demand-driven supply chain was to incorporate demand-signal data—information about actual consumer purchases—into its plans to resupply retailers with product. In close collaboration with Terra Technology, whose Multi-Enterprise Demand Sensing (MDS) system was chosen for the forecasting tool, Kimberly-Clark incorporated the point-of-sale data (POS) from three of its largest retail customers in North America. The software uses that data along with inventory in the distribution channel, shipments from warehouses, and the retailer's own forecasts to create a daily operational forecast. These inputs are re-evaluated weekly for their influence on the forecast. For example, POS might be the best predictor of a shipment forecast on a three-week horizon, but actual orders could be the best predictor for the current week. A new metric for evaluating forecast performance was created; it was defined as the absolute difference between shipments and forecast and reported as a percentage of shipments. Using that metric and the new forecasting system, Kimberly-Clark observed forecast error reductions as high as 35 percent in the first week of the horizon and 20 percent on a two-week horizon. These forecast error reductions can translate into one to three weeks reduction in safety stocks.

*Sources:* James A. Cooke, "Kimberly-Clark Connects Its Supply Chain to the Store Shelf," *DC Velocity*, April 10, 2013; Paul Taylor, "Demand Forecasting Pays Off for Kimberly-Clark," *Financial Times*, September 10, 2011; Heather Clancy, "Kimberly-Clark Makes Sense of Demand," *CGT,* **http://consumergoods.edgl.com**; Kimberly-Clark Annual Report, 2013, **http://www.Kimberly-Clark.com.**

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

1. Explain how managers can change demand patterns.
2. Describe the two key decisions on making forecasts.
3. Calculate the five basic measures of forecast errors.
4. Compare and contrast the four approaches to judgmental forecasting.
5. Use regression to make forecasts with one or more independent variables.
6. Make forecasts using the five most common statistical approaches for time-series analysis.
7. Describe the six steps in a typical forecasting process.

Balancing supply and demand begins with making accurate forecasts, and then reconciling them across the supply chain as shown by Kimberly-Clark. A **forecast** is a prediction of future events used for planning purposes. Planning, on the other hand, is the process of making management decisions on how to deploy resources to best respond to the demand forecasts. Forecasting methods may be based on mathematical models that use available historical data, or on qualitative methods that draw on managerial experience and judgments, or on a combination of both.

**forecast**

A prediction of future events used for planning purposes.

In this chapter our focus is on demand forecasts. We begin with different types of demand patterns. We examine forecasting methods in three basic categories: (1) judgment, (2) causal, and (3) time-series methods. Forecast errors are defined, providing important clues for making better forecasts. We next consider the forecasting techniques themselves, and then how they can be combined to bring together insights from several sources. We conclude with overall processes for making forecasts and designing the forecasting system.

Forecasts are useful for both managing processes and managing supply chains. At the supply chain level, a firm needs forecasts to coordinate with its customers and suppliers. At the process level, output forecasts are needed to design the various processes throughout the organization, including identifying and dealing with in-house bottlenecks.

As you might imagine, the organization-wide forecasting process cuts across functional areas. Forecasting overall demand typically originates with marketing, but internal customers throughout the organization depend on forecasts to formulate and execute their plans as well. Forecasts are critical inputs to business plans, annual plans, and budgets. Finance needs forecasts to project cash flows and capital requirements. Human resources uses forecasts to anticipate hiring and training needs. Marketing is an important source for sales forecast information because it is closest to external customers. Operations and supply chain managers need forecasts to plan output levels, purchases of services and materials, workforce and output schedules, inventories, and long-term capacities. Managers at all levels need estimates of future demands, so that they can plan activities that are consistent with the firm's competitive priorities.



# Managing Demand

Before we get into the tools and techniques for forecasting demands, it is important to understand that the timing and sizing of customer demand can often be manipulated. Accurately forecasting customer demand is a difficult task because the demand for services and goods can vary greatly. For example, demand for lawn fertilizer predictably increases in the spring and summer months; however, the particular weekends when demand is heaviest may depend on uncontrollable factors such as the weather. These demand swings are costly to satisfy for any process, even if they are predictable. However, managers can often do two things to alleviate the pains of demand swings. First, understand the demand pattern they are facing; second, employ one or more options to alleviate any avoidable swings.

## Demand Patterns

Forecasting demand requires uncovering the underlying patterns from available information. The repeated observations of demand for a service or product in their order of occurrence form a pattern known as a **time series**. There are five basic patterns of most demand time series:

**time series**

The repeated observations of demand for a service or product in their order of occurrence.

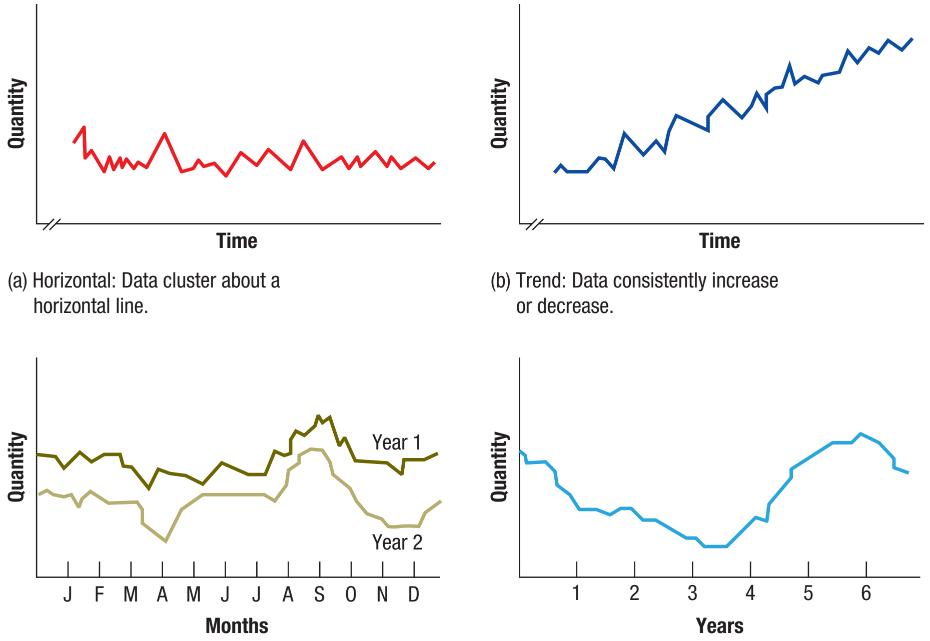
1. *Horizontal.* The fluctuation of data around a constant mean.
2. *Trend.* The systematic increase or decrease in the mean of the series over time.
3. *Seasonal.* A repeatable pattern of increases or decreases in demand, depending on the time of day, week, month, or season.
4. *Cyclical.* The less predictable gradual increases or decreases in demand over longer periods of time (years or decades).
5. *Random.* The unforecastable variation in demand.

Cyclical patterns arise from two influences. The first is the business cycle, which includes factors that cause the economy to go from recession to expansion over a number of years. The other influence is the service or product life cycle, which reflects the stages of demand from development through decline. Business cycle demand is difficult to predict because it is affected by national or international events.

The four patterns of demand—horizontal, trend, seasonal, and cyclical—combine in varying degrees to define the underlying time pattern of demand for a service or product. The fifth pattern,

**FIGURE 8.1 ▶**
Patterns of Demand

MyOMLab Animation




(a) Horizontal: Data cluster about a horizontal line.

(b) Trend: Data consistently increase or decrease.

(c) Seasonal: Data consistently show peaks and valleys.

(d) Cyclical: Data reveal gradual increases and decreases over extended periods of time.

random variation, results from chance causes and thus, cannot be predicted. Random variation is an aspect of demand that makes every forecast ultimately inaccurate. Figure 8.1 shows the first four patterns of a demand time series, all of which contain random variations.

## Demand Management Options

Matching supply with demand becomes a challenge when forecasts call for uneven demand patterns—and uneven demand is more the rule than the exception. Demand swings can be from one month to the next, one week to the next, or even one hour to the next. Peaks and valleys in demand are costly or can cause poor customer service. Air New Zealand can lose sales because capacity is exceeded for one of its flights, while another of its flights to the same destination at about the same time has many empty seats. If nothing is done to even out demand, sales are lost or greater capacity cushions might be needed. All come at an extra cost. Here we deal with **demand management**, the process of changing demand patterns using one or more demand options.

**demand management**
The process of changing demand patterns using one or more demand options.

Various options are available in managing demand, including complementary products, promotional pricing, prescheduled appointments, reservations, revenue management, backlogs, backorders, and stockouts. The manager may select one or more of them, as we illustrate below.

**Complementary Products** One demand option for a company to even out the load on resources is to produce **complementary products**, or services that have similar resource requirements but different demand cycles. For example, manufacturers of matzoh balls for the Jewish Passover holiday are in a seasonal business. The B. Manischewitz Company, a kosher foods manufacturer in Jersey City, New Jersey, previously experienced 40 percent of its annual sales for the 8-day Passover holiday alone. It expanded toward markets with year-round appeal such as low-carb, low-fat foods, including canned soups and crackers, borscht, cake mixes, dressing and spreads, juices, and condiments.

**complementary products**
Services or products that have similar resource requirements but different demand cycles.

For service providers, a city parks and recreation department can counterbalance seasonal staffing requirements for summer activities by offering ice skating, tobogganing, or indoor activities during the winter months. The key is to find services and products that can be produced with the existing resources and can level off the need for resources over the year.

**Promotional Pricing** Promotional campaigns are designed to increase sales with creative pricing. Examples include automobile rebate programs, price reductions for winter clothing in the late summer months, reduced prices for hotel rooms during off-peak periods, and “two-for-the-price-of-one” automobile tire sales. Lower prices can increase demand for the product or service from new and existing customers during traditional slack periods or encourage customers to move up future buying.

**Prescheduled Appointments** Service providers often can schedule customers for definite periods of order fulfillment. With this approach, demand is leveled to not exceed supply capacity. An appointment system assigns specific times for service to customers. The advantages of this method are timely customer service and the high utilization of service personnel.

Doctors, dentists, lawyers, and automobile repair shops are examples of service providers that use appointment systems. Doctors can use the system to schedule parts of their day to visit hospital patients, and lawyers can set aside time to prepare cases. Care must be taken to tailor the length of appointments to individual customer needs rather than merely scheduling customers at equal time intervals.

**Reservations** Reservation systems, although quite similar to appointment systems, are used when the customer actually occupies or uses facilities associated with the service. For example, customers reserve hotel rooms, automobiles, airline seats, and concert seats. The major advantage of reservation systems is the lead time they give service managers and the ability to level demand. Managers can deal with no-shows with a blend of overbooking, deposits, and cancellation penalties. Sometimes overbooking means that a customer with reservations cannot be served as promised. In such cases, bonuses can be offered for compensation. For example, an airline passenger might not only get on the next available flight, but also may be given a free ticket for a second flight sometime in the future.

**Revenue Management** A specialized combination of the pricing and reservation options for service providers is revenue management. **Revenue management** (sometimes called *yield management*) is the process of varying price at the right time for different customer segments to maximize revenues generated from existing supply capacity. It works best if customers can be segmented, prices can be varied by segment, fixed costs are high, variable costs are low, service duration is predictable, and capacity is lost if not used (sometimes called *perishable capacity*). Airlines, hotels, cruise lines, restaurants (early-bird specials), and rental cars are good examples. Computerized reservation systems can make hour-by-hour updates, using decision rules for opening or closing price classes depending on the difference between supply and continually updated demand forecasts. In the airlines industry, prices are lowered if a particular airline flight is not selling as fast as expected, until more seats are booked. Alternately, if larger than expected demand is developing, prices for the remaining seats may be increased. Last-minute business travelers pay the higher prices, whereas leisure travelers making reservations well in advance and staying over the weekend get the bargain prices. Southwest Airlines now segments its customers by creating a "Business Select" ticket class that rewards more perks to frequent fliers willing to pay higher prices.

**revenue management**
Varying price at the right time for different customer segments to maximize revenues yielded by existing supply capacity.

**Backlogs** Much like the appointments or reservations of service providers, a **backlog** is an accumulation of customer orders that a manufacturer has promised for delivery at some future date. Manufacturers in the supply chain that maintain a backlog of orders as a normal business practice can allow the backlog to grow during periods of high demand and then reduce it during periods of low demand. Airplane manufacturers do not promise instantaneous delivery, as do wholesalers or retailers farther forward in the supply chain. Instead, they impose a lead time between when the order is placed and when it is delivered. For example, an automotive parts manufacturer may agree to deliver to the repair department of a car dealership a batch of 100 door latches for a particular car model next Tuesday. The parts manufacturer uses that due date to plan its production of door latches within its capacity limits. Firms that are most likely to use backlogs—and increase the size of them during periods of heavy demand—make customized products and tend to have a make-to-order strategy. Backlogs reduce the uncertainty of future production requirements and also can be used to level demand. However, they become a competitive disadvantage if they get too big.

**backlog**
An accumulation of customer orders that a manufacturer has promised for delivery at some future date.

**Backorders and Stockouts** A last resort in demand management is to set lower standards for customer service, either in the form of backorders or stockouts. Not to be confused with a backlog, a **backorder** is a customer order that cannot be filled when promised or demanded but is filled later. Demand may be too unpredictable or the item may be too costly to hold it in inventory. Although the customer is not pleased with the delay, the customer order is not lost and it is filled at a later date. In contrast, a **stockout** is an order that cannot be satisfied, resulting in a loss of the sale. A backorder adds to the next period's demand requirement, whereas a stockout does not. Backorders and stockouts can lead dissatisfied customers to do their future business with another firm. Generally, backorders and stockouts are to be avoided.

**backorder**
A customer order that cannot be filled when promised or demanded but is filled later.

**stockout**
An order that cannot be satisfied, resulting in a loss of the sale.

**aggregation**

The act of clustering several similar services or products so that forecasts and plans can be made for whole families.

**judgment methods**

A forecasting method that translates the opinions of managers, expert opinions, consumer surveys, and salesforce estimates into quantitative estimates.

**causal methods**

A quantitative forecasting method that uses historical data on independent variables, such as promotional campaigns, economic conditions, and competitors' actions, to predict demand.

**time-series analysis**

A statistical approach that relies heavily on historical demand data to project the future size of demand and recognizes trends and seasonal patterns.

Combinations of demand options can also be used. For example, a manufacturer of lighting equipment had several products characterized as "slow movers with spikes," where only 2 or 3 units were sold for several weeks, and then suddenly there was a huge order for 10,000 units the next week. The reason is that their product was purchased by commercial property managers who might be upgrading the lighting in a large office building. The result was a forecasting nightmare and having to resort to high cost supply options to meet the demand spikes. The breakthrough in solving this problem was to combine the pricing and backlog options. Contractors are now offered a 3 percent discount (the pricing option) on any order in excess of 10,000 units that are placed five or more weeks before they are needed (the backlog option). The advanced warning allows the manufacturer to smooth out its production processes, saving millions of dollars annually.

# Key Decisions on Making Forecasts

Before using forecasting techniques, a manager must make two decisions: (1) what to forecast, and (2) what type of forecasting technique to select for different items.

## Deciding What to Forecast

Although some sort of demand estimate is needed for the individual services or goods produced by a company, forecasting total demand for groups or clusters and then deriving individual service or product forecasts may be easiest. Also, selecting the correct unit of measurement (e.g., units, customers, or machine-hours) for forecasting may be as important as choosing the best method.

**Level of Aggregation** Few companies err by more than 5 percent when forecasting the annual total demand for all their services or products. However, errors in forecasts for individual items and shorter time periods may be much higher. Recognizing this reality, many companies use a two-tier forecasting system. They first cluster (or "roll up") several similar services or products in a process called **aggregation**, making forecasts for families of services or goods that have similar demand requirements and common processing, labor, and materials requirements. Next, they derive forecasts for individual items, which are sometimes called stock-keeping units. A *stock-keeping unit (SKU)* is an individual item or product that has an identifying code and is held in inventory somewhere along the supply chain, such as in a distribution center.

Mark Lennihan/Associated Press

A Moto X phone manufactured by Motorola Mobility. Motorola considerably improved its demand forecasting process by closely collaborating with its major retailers, obtaining point-of-sale data from them.

**Units of Measurement** Rather than using dollars as the initial unit of measurement, forecasts often begin with service or product units, such as individual products, express packages to deliver, or customers needing maintenance service or repairs for their cars. Forecasted units can then be translated to dollars by multiplying them by the unit price. If accurately forecasting demand for a service or product is not possible in terms of number of units, forecast the standard labor or machine-hours required of each of the critical resources.

## Choosing the Type of Forecasting Technique

Forecasting systems offer a variety of techniques, and no one of them is best for all items and situations. The forecaster's objective is to develop a useful forecast from the information at hand with the technique that is appropriate for the different patterns of demand. Two general types of forecasting techniques are used: judgment methods and quantitative methods. **Judgment methods** translate the opinions of managers, expert opinions, consumer surveys, and salesforce estimates into quantitative estimates. Quantitative methods include causal methods, time-series analysis, and trend projection with regression. **Causal methods** use historical data on independent variables, such as promotional campaigns, economic conditions, and competitors' actions, to predict demand. **Time-series analysis** is a statistical approach that relies heavily on historical demand data to project the future size of demand and recognizes trends and seasonal patterns. **Trend projection with regression** is a hybrid between a time-series technique and the causal method.

# Forecast Error

For any forecasting technique, it is important to measure the accuracy of its forecasts. Forecasts almost always contain errors. Random error results from unpredictable factors that cause the forecast to deviate from the actual demand. Forecasting analysts try to minimize forecast errors by selecting appropriate forecasting models, but eliminating all forms of errors is impossible.

**Forecast error** for a given period $t$ is simply the difference found by subtracting the forecast from actual demand, or

$$E_t = D_t - F_t$$

where

$$E_t = \text{forecast error for period } t$$
$$D_t = \text{actual demand for period } t$$
$$F_t = \text{forecast for period } t$$

This equation (notice the alphabetical order with $D_t$ coming before $F_t$) is the starting point for creating several measures of forecast error that cover longer periods of time.

There are five basic measures of forecast error: CFE, MSE, $(\sigma)$, MAD, and MAPE. Figure 8.2 shows the output from the *Error Analysis* routine in Forecasting's dropdown menu of POM for Windows. Part (a) gives a big picture view of how well the forecast has been tracking the actual demand. Part (b) shows the detailed calculations needed to obtain the summary error terms. Finally, Part (c) gives the summary error measures summarized across all 10 time periods, as derived from Part (b).

**trend projection with regression**
A forecasting model that is a hybrid between a time-series technique and the causal method.

**forecast error**
The difference found by subtracting the forecast from actual demand for a given period.

## Cumulative Sum of Forecast Errors

The **cumulative sum of forecast errors (CFE)** measures the total forecast error:

$$\text{CFE} = \sum E_t$$

CFE is a cumulative sum. Figure 8.2(b) shows that it is the sum of the errors for all 10 periods. For any given period, it would be the sum of errors up through that period. For example, it would be $-8$ (or $-2-6$) for period 2. CFE is also called the *bias error* and results from consistent mistakes—the forecast is always too high or too low. This type of error typically causes the greatest disruption to planning efforts. For example, if a forecast is consistently lower than actual demand, the value of CFE will gradually get larger and larger. This increasingly large error indicates some systematic deficiency in the forecasting approach. The average forecast error, sometimes called the *mean bias*, is simply

$$\bar{E} = \frac{\text{CFE}}{n}$$

**cumulative sum of forecast errors (CFE)**
A measurement of the total forecast error that assesses the bias in a forecast.

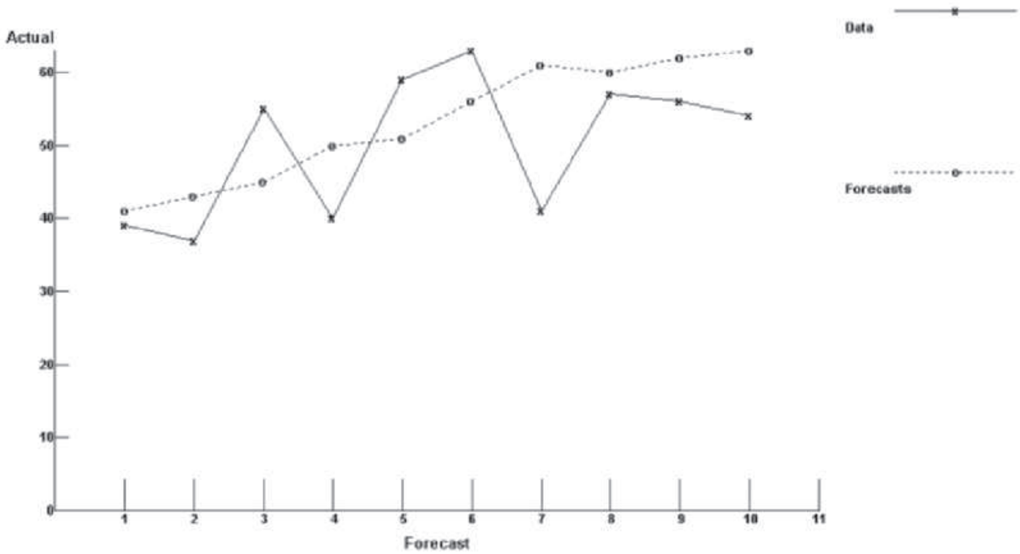



**FIGURE 8.2(a)**
Graph of Actual and Forecast Demand Using *Error Analysis* of Forecasting in POM for Windows

**FIGURE 8.2(b)** Detailed Calculations of Forecast Errors

| | | Forecast | Error | \|Error\| | Error^2 | \|Pct Error\| |
|---|---|---|---|---|---|---|
| Past period 1 | 39 | 41 | -2 | 2 | 4 | 5.128% |
| Past period 2 | 37 | 43 | -6 | 6 | 36 | 16.216% |
| Past period 3 | 55 | 45 | 10 | 10 | 100 | 18.182% |
| Past period 4 | 40 | 50 | -10 | 10 | 100 | 25% |
| Past period 5 | 59 | 51 | 8 | 8 | 64 | 13.559% |
| Past period 6 | 63 | 56 | 7 | 7 | 49 | 11.111% |
| Past period 7 | 41 | 61 | -20 | 20 | 400 | 48.78% |
| Past period 8 | 57 | 60 | -3 | 3 | 9 | 5.263% |
| Past period 9 | 56 | 62 | -6 | 6 | 36 | 10.714% |
| Past period 10 | 54 | 63 | -9 | 9 | 81 | 16.667% |
| TOTALS | 501 | | -31 | 81 | 879 | 170.621% |
| AVERAGE | 50.1 | | -3.1 | 8.1 | 87.9 | 17.062% |
| | | | (Bias) | (MAD) | (MSE) | (MAPE) |
| | | | | Std dev | 29.648 | |

## Dispersion of Forecast Errors

**mean squared error (MSE)**

A measurement of the dispersion of forecast errors.

**standard deviation of the errors ($\sigma$)**

A measurement of the dispersion of forecast errors.

**mean absolute deviation (MAD)**

A measurement of the dispersion of forecast errors.

The **mean squared error (MSE)**, **standard deviation of the errors** $(\sigma)$, and **mean absolute deviation (MAD)** measure the dispersion of forecast errors attributed to trend, seasonal, cyclical, or random effects:

$$\text{MSE} = \frac{\sum E_t^2}{n}$$

$$\sigma = \sqrt{\frac{\sum (E_t - \overline{E})^2}{n - 1}}$$

$$\text{MAD} = \frac{\sum |E_t|}{n}$$

Figure 8.2(b) shows the squared error in period 1 is 4, and MSE is 87.9 for the whole sample. The standard deviation of the errors, shown as 29.648 in Figure 8.2(b), is calculated using a separate function available in Excel. The absolute value of the error in period 2 is 6, and MAD is 8.1 across the whole sample.

The mathematical symbol | | is used to indicate the absolute value—that is, it tells you to disregard positive or negative signs. If MSE, $\sigma$, or MAD is small, the forecast is typically close to actual demand; by contrast, a large value indicates the possibility of large forecast errors. The measures do differ in the way they emphasize errors. Large errors get far more weight in MSE and $\sigma$ because the errors are squared. MAD is a widely used measure of forecast error and is easily understood; it is merely the mean of the absolute forecast errors over a series of time periods, without regard to whether the error was an overestimate or an underestimate.

**mean absolute percent error (MAPE)**

A measurement that relates the forecast error to the level of demand and is useful for putting forecast performance in the proper perspective.

## Mean Absolute Percent Error

The **mean absolute percent error (MAPE)** relates the forecast error to the level of demand and is useful for putting forecast performance in the proper perspective:

$$\text{MAPE} = \frac{(\sum |E_t|/D_t)(100)}{n} \text{ (expressed as a percentage)}$$

For example, an absolute forecast error of 100 results in a larger percentage error when the demand is 200 units than when the demand is 10,000 units. MAPE is the best error measure to use when making comparisons between time series for different SKUs. Looking again at Figure 8.2(b), the percent error in period 2 is 16.22 percent, and MAPE, the average over all 10 periods, is 17.062 percent.

Finally, Figure 8.2(c) summarizes the key error terms across all 10 time periods. They are actually found in selected portions of Figure 8.2(b). For example, CFE is −31, which is in the error column of Figure 8.2(b) in the TOTALS row. MAD is 8.1, found in the |Error| column and AVERAGE row. Finally, MAPE is 17.062%, which is in the |Pct Error| column and AVERAGE row.

**FIGURE 8.2(c)** Error Measures

| Measure | Value |
|---|---|
| Error Measures | |
| CFE (Cumulative Forecast Error) | -31 |
| MAD (Mean Absolute Deviation) | 8.1 |
| MSE (Mean Squared Error) | 87.9 |
| Standard Deviation of Errors | 29.648 |
| MAPE (Mean Absolute Percent | 17.062% |

**EXAMPLE 8.1**

## Calculating Forecast Error Measures

The following table shows the actual sales of upholstered chairs for a furniture manufacturer and the forecasts made for each of the last 8 months. Calculate CFE, MSE, $\sigma$, MAD, and MAPE for this product.

| Month, $t$ | Demand, $D_t$ | Forecast, $F_t$ | Error, $E_t$ | Error, Squared, $E_t^2$ | Absolute Error, $\lvert E_t \rvert$ | Absolute Percent Error, $(\lvert E_t \rvert / D_t)(100)$ |
|---|---|---|---|---|---|---|
| 1 | 200 | 225 | −25 | 625 | 25 | 12.5% |
| 2 | 240 | 220 | 20 | 400 | 20 | 8.3 |
| 3 | 300 | 285 | 15 | 225 | 15 | 5.0 |
| 4 | 270 | 290 | −20 | 400 | 20 | 7.4 |
| 5 | 230 | 250 | −20 | 400 | 20 | 8.7 |
| 6 | 260 | 240 | 20 | 400 | 20 | 7.7 |
| 7 | 210 | 250 | −40 | 1,600 | 40 | 19.0 |
| 8 | 275 | 240 | 35 | 1,225 | 35 | 12.7 |
| | | Total | −15 | 5,275 | 195 | 81.3% |

### SOLUTION

Using the formulas for the measures, we get

Cumulative forecast error (bias):

$$\text{CFE} = -15 \text{ (the bias, or the sum of the errors for all time periods in the time series)}$$

Average forecast error (mean bias):

$$\bar{E} = \frac{\text{CFE}}{n} = \frac{-15}{8} = -1.875$$

Mean squared error:

$$\text{MSE} = \frac{\Sigma E_t^2}{n} = \frac{5{,}275}{8} = 659.4$$

Standard deviation of the errors:

$$\sigma = \sqrt{\frac{\Sigma[E_t - (-1.875)]^2}{7}} = 27.4$$

Mean absolute deviation:

$$\text{MAD} = \frac{\Sigma \lvert E_t \rvert}{n} = \frac{195}{8} = 24.4$$

Mean absolute percent error:

$$\text{MAPE} = \frac{[\Sigma \lvert E_t \rvert / D_t]100}{n} = \frac{81.3\%}{8} = 10.2\%$$

A CFE of −15 indicates that the forecast has a slight bias to overestimate demand. The MSE, $\sigma$, and MAD statistics provide measures of forecast error variability. A MAD of 24.4 means that the average forecast error was 24.4 units in absolute value. The value of $\sigma$, 27.4, indicates that the sample distribution of forecast errors has a standard deviation of 27.4 units. A MAPE of 10.2 percent implies that, on average, the forecast error was within about 10 percent of actual demand. These measures become more reliable as the number of periods of data increases.

### DECISION POINT

Although reasonably satisfied with these forecast performance results, the analyst decided to test out a few more forecasting methods before reaching a final forecasting method to use for the future.

### Computer Support

Computer support, such as from OM Explorer or POM for Windows, makes error calculations easy when evaluating how well forecasting models fit with past data. Errors are measured across past data, often called the *history file* in practice. They show the various error measures across the entire history file for each forecasting method evaluated. They also make forecasts into the future, based on the method selected.

## Judgment Methods

Forecasts from quantitative methods are possible only when there is adequate historical data, (i.e., the *history file*). However, the history file may be nonexistent when a new product is introduced or when technology is expected to change. The history file might exist but be less useful when certain events (such as rollouts or special packages) are reflected in the past data, or when certain events are expected to occur in the future. In some cases, judgment methods are the only practical way to make a forecast. In other cases, judgment methods can also be used to modify forecasts that are generated by quantitative methods. They may recognize that one or two quantitative models have been performing particularly well in recent periods. Adjustments certainly would be called for if the forecaster has important contextual knowledge. *Contextual knowledge* is knowledge that practitioners gain through experience, such as cause-and-effect relationships, environmental cues, and organizational information that may have an effect on the variable being forecast. Adjustments also could account for unusual circumstances, such as a new sales promotion or unexpected international events. They could also have been used to remove the effect of special one-time events in the history file before quantitative methods are applied. Four of the more successful judgment methods are as follows: (1) salesforce estimates, (2) executive opinion, (3) market research, and (4) the Delphi method.

**salesforce estimates**

The forecasts that are compiled from estimates of future demands made periodically by members of a company's salesforce.

**executive opinion**

A forecasting method in which the opinions, experience, and technical knowledge of one or more managers are summarized to arrive at a single forecast.

**technological forecasting**

An application of executive opinion to keep abreast of the latest advances in technology.

**market research**

A systematic approach to determine external consumer interest in a service or product by creating and testing hypotheses through data-gathering surveys.

**Delphi method**

A process of gaining consensus from a group of experts while maintaining their anonymity.

**linear regression**

A causal method in which one variable (the dependent variable) is related to one or more independent variables by a linear equation.

**dependent variable**

The variable that one wants to forecast.

**Salesforce estimates** are forecasts compiled from estimates made periodically by members of a company's salesforce. The salesforce is the group most likely to know which services or products customers will be buying in the near future and in what quantities. Forecasts of individual salesforce members can be combined easily to get regional or national sales estimates. However, individual biases of the salespeople may taint the forecast. For example, some people are naturally optimistic, whereas others are more cautious. Adjustments in forecasts may need to be made to account for these individual biases.

**Executive opinion** is a forecasting method in which the opinions, experience, and technical knowledge of one or more managers or customers are summarized to arrive at a single forecast. All of the factors going into judgmental forecasts would fall into the category of executive opinion. Executive opinion can also be used for **technological forecasting**. The quick pace of technological change makes keeping abreast of the latest advances difficult.

**Market research** is a systematic approach to determine external consumer interest in a service or product by creating and testing hypotheses through data-gathering surveys. Conducting a market research study includes designing a questionnaire, deciding how to administer it, selecting a representative sample, and analyzing the information using judgment and statistical tools to interpret the responses. Although market research yields important information, it typically includes numerous qualifications and hedges in the findings.

The **Delphi method** is a process of gaining consensus from a group of experts while maintaining their anonymity. This form of forecasting is useful when no historical data are available from which to develop statistical models and when managers inside the firm have no experience on which to base informed projections. A coordinator sends questions to each member of the group of outside experts, who may not even know who else is participating. The coordinator prepares a statistical summary of the responses along with a summary of arguments for particular responses. The report is sent to the same group for another round, and the participants may choose to modify their previous responses. These rounds continue until consensus is obtained.

In the remainder of this chapter, we turn to the commonly used quantitative forecasting approaches.

## Causal Methods: Linear Regression

Causal methods are used when historical data are available and the relationship between the factor to be forecasted and other external or internal factors (e.g., government actions or advertising promotions) can be identified. These relationships are expressed in mathematical terms and can be complex. Causal methods are good for predicting turning points in demand and for preparing long-range forecasts. We focus on linear regression, one of the best known and most commonly used causal methods.

In **linear regression**, one variable, called a dependent variable, is related to one or more independent variables by a linear equation. The **dependent variable** (such as demand for door hinges) is the one the manager wants to forecast. The **independent variables** (such as advertising expenditures and new housing starts) are assumed to affect the dependent variable and thereby "cause" the results observed in the past. Figure 8.3 shows how a linear regression line relates to the data. In technical terms, the regression line minimizes the squared deviations from the actual data.

**independent variables**

Variables that are assumed to affect the dependent variable and thereby "cause" the results observed in the past.

In the simplest linear regression models, the dependent variable is a function of only one independent variable and, therefore, the theoretical relationship is a straight line:

$$Y = a + bX$$

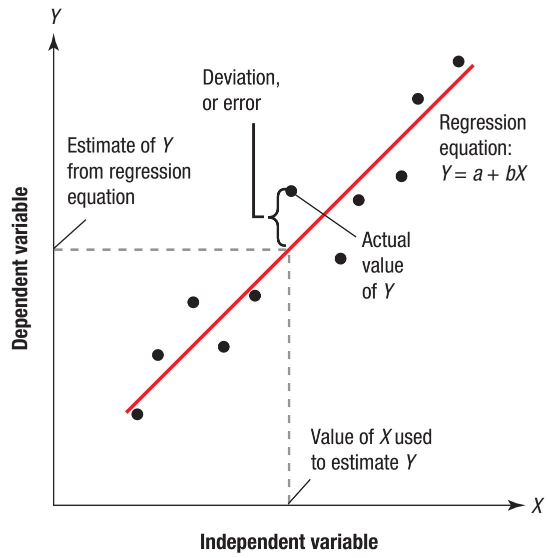
where

$Y =$ dependent variable

$X =$ independent variable

$a =$ $Y$-intercept of the line

$b =$ slope of the line




▲ **FIGURE 8.3**
Linear Regression Line Relative to Actual Demand

The objective of linear regression analysis is to find values of $a$ and $b$ that minimize the sum of the squared deviations of the actual data points from the graphed line. Computer programs are used for this purpose. For any set of matched observations for $Y$ and $X$, the program computes the values of $a$ and $b$ and provides measures of forecast accuracy. Three measures commonly reported are (1) the sample correlation coefficient, (2) the sample coefficient of determination, and (3) the standard error of the estimate.

The *sample correlation coefficient, r*, measures the direction and strength of the relationship between the independent variable and the dependent variable. The value of $r$ can range from $-1.00$ to $+1.00$. A correlation coefficient of $+1.00$ implies that period-by-period changes in direction (increases or decreases) of the independent variable are always accompanied by changes in the same direction by the dependent variable. An $r$ of $-1.00$ means that decreases in the independent variable are always accompanied by increases in the dependent variable, and vice versa. A zero value of $r$ means no linear relationship exists between the variables. The closer the value of $r$ is to $\pm 1.00$, the better the regression line fits the points.

The *sample coefficient of determination* measures the amount of variation in the dependent variable about its mean that is explained by the regression line. The coefficient of determination is the square of the correlation coefficient, or $r^2$. The value of $r^2$ ranges from 0.00 to 1.00. Regression equations with a value of $r^2$ close to 1.00 mean a close fit.

The *standard error of the estimate*, $s_{xy}$, measures how closely the data on the dependent variable cluster around the regression line. Although it is similar to the sample standard deviation, it measures the error from the dependent variable, $Y$, to the regression line, rather than to the mean. Thus, it is the standard deviation of the difference between the actual demand and the estimate provided by the regression equation.

## EXAMPLE 8.2 Using Linear Regression to Forecast Product Demand

The supply chain manager seeks a better way to forecast the demand for door hinges and believes that the demand is related to advertising expenditures. The following are sales and advertising data for the past 5 months:

**MyOMLab**

Active Model 8.1 in MyOMLab provides insight on varying the intercept and slope of the model.

| Month | Sales (Thousands of Units) | Advertising (Thousands of $) |
|---|---|---|
| 1 | 264 | 2.5 |
| 2 | 116 | 1.3 |
| 3 | 165 | 1.4 |
| 4 | 101 | 1.0 |
| 5 | 209 | 2.0 |

The company will spend $1,750 next month on advertising for the product. Use linear regression to develop an equation and a forecast for this product.

**SOLUTION**

We used POM for Windows to determine the best values of $a$, $b$, the correlation coefficient, the coefficient of determination, and the standard error of the estimate.

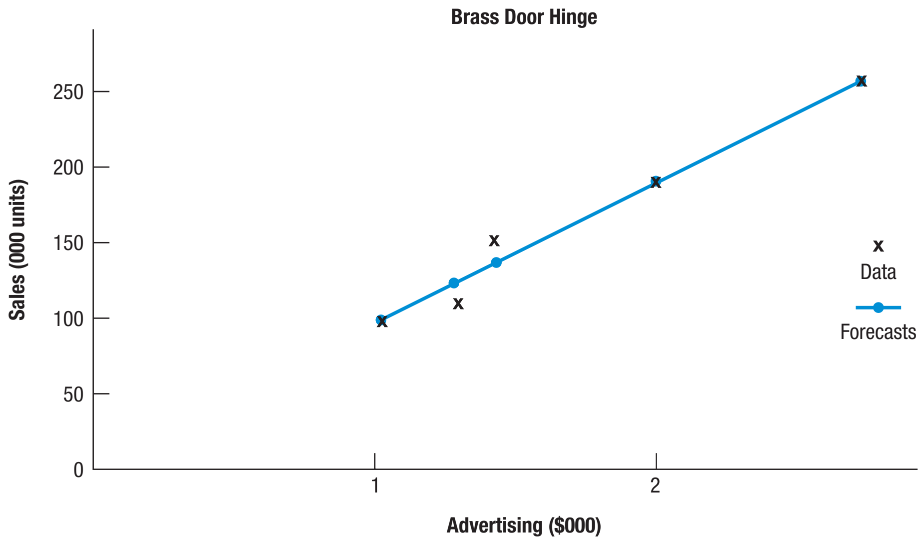
$$a = -8.135$$
$$b = 109.229X$$
$$r = 0.980$$
$$r^2 = 0.960$$
$$s_{yx} = 15.603$$

The regression equation is

$$Y = -8.135 + 109.229X$$

and the regression line is shown in Figure 8.4. The sample correlation coefficient, $r$, is 0.98, which is unusually close to 1.00 and suggests an unusually strong positive relationship exists between sales and advertising expenditures. The sample coefficient of determination, $r^2$, implies that 96 percent of the variation in sales is explained by advertising expenditures.

**FIGURE 8.4** ▶
Linear Regression Line for the Sales and Advertising Data Using POM for Windows




**DECISION POINT**

The supply chain manager decided to use the regression model as input to planning production levels for month 6. As the advertising expenditure will be $1,750, the forecast for month 6 is $Y = -8.135 + 109.229(1.75) = 183.016$, or 183,016 units.

Often several independent variables may affect the dependent variable. For example, advertising expenditures, new corporation start-ups, and residential building contracts all may be important for estimating the demand for door hinges. In such cases, *multiple regression analysis* is helpful in determining a forecasting equation for the dependent variable as a function of several independent variables. Such models can be analyzed with POM for Windows or OM Explorer and can be quite useful for predicting turning points and solving many planning problems.

## Time-Series Methods

Rather than using independent variables for the forecast as regression models do, time-series methods use historical information regarding only the dependent variable. These methods are based on the assumption that the dependent variable's past pattern will continue in the future. Time-series analysis identifies the underlying patterns of demand that combine to produce an observed historical pattern of the dependent variable and then develops a model to replicate it. In this section, we focus on five statistical time-series methods that address the horizontal, trend, and seasonal patterns of demand: simple moving averages, weighted moving averages, exponential smoothing, trend projection with regression, and multiplicative seasonal method. Before we discuss statistical methods, let us take a look at the simplest time-series method for addressing all patterns of demand—the naïve forecast.

## Naïve Forecast

A method often used in practice is the **naïve forecast**, whereby the forecast for the next period $(F_{t+1})$ equals the demand for the current period $(D_t)$. So if the actual demand for Wednesday is 35 customers, the forecasted demand for Thursday is 35 customers. Despite its name, the naïve forecast can perform well.

**naïve forecast**

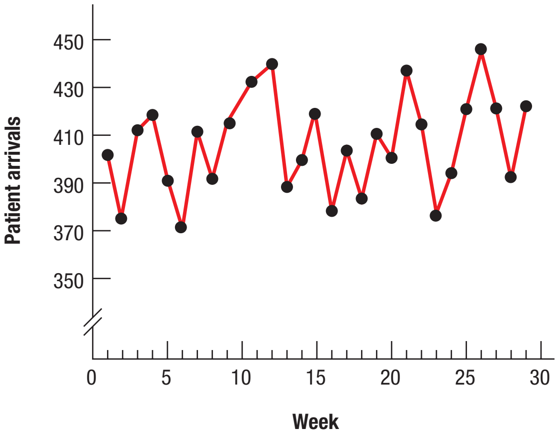
A time-series method whereby the forecast for the next period equals the demand for the current period, or Forecast $= D_t$.

The naïve forecast method may be adapted to take into account a demand trend. The increase (or decrease) in demand observed between the last two periods is used to adjust the current demand to arrive at a forecast. Suppose that last week the demand was 120 units and the week before it was 108 units. Demand increased 12 units in 1 week, so the forecast for next week would be $120 + 12 = 132$ units. The naïve forecast method also may be used to account for seasonal patterns. If the demand last July was 50,000 units, and assuming no underlying trend from one year to the next, the forecast for this July would be 50,000 units. The method works best when the horizontal, trend, or seasonal patterns are stable and random variation is small.

## Horizontal Patterns: Estimating the Average

We begin our discussion of statistical methods of time-series forecasting with demand that has no apparent trend, seasonal, or cyclical patterns. The horizontal pattern in a time series is based on the mean of the demands, so we focus on forecasting methods that estimate the average of a time series of data. The forecast of demand for *any* period in the future is the average of the time series computed in the current period. For example, if the average of past demand calculated on Tuesday is 65 customers, the forecasts for Wednesday, Thursday, and Friday are 65 customers each day.

Consider Figure 8.5, which shows patient arrivals at a medical clinic over the past 28 weeks. Assuming that the time series has only a horizontal and random pattern, one approach is simply to calculate the average of the data. However, this approach has no adaptive quality if there is a trend, seasonal, or cyclical pattern. The statistical techniques that do have an adaptive quality in estimating the average in a time series are (1) simple moving averages, (2) weighted moving averages, and (3) exponential smoothing. Another option is the simple average, but it has no adaptive capability.




▲ **FIGURE 8.5**
Weekly Patient Arrivals at a Medical Clinic

**Simple Moving Averages** The **simple moving average method** simply involves calculating the average demand for the $n$ most recent time periods and using it as the forecast for future time periods. For the next period, after the demand is known, the oldest demand from the previous average is replaced with the most recent demand and the average is recalculated. In this way, the $n$ most recent demands are used, and the average "moves" from period to period.

**simple moving average method**

A time-series method used to estimate the average of a demand time series by averaging the demand for the $n$ most recent time periods.

Specifically, the forecast for period $t + 1$ can be calculated at the end of period $t$ (after the actual demand for period $t$ is known) as

$$F_{t+1} = \frac{\text{Sum of last } n \text{ demands}}{n} = \frac{D_t + D_{t-1} + D_{t-2} + \cdots + D_{t-n+1}}{n}$$

where

$$D_t = \text{actual demand in period } t$$
$$n = \text{total number of periods in the average}$$
$$F_{t+1} = \text{forecast for period } t + 1$$

**EXAMPLE 8.3** **Using the Moving Average Method to Estimate Average Demand**

**a.** Compute a *three-week* moving average forecast for the arrival of medical clinic patients in week 4. The numbers of arrivals for the past 3 weeks were as follows:

| Week | Patient Arrivals |
|---|---|
| 1 | 400 |
| 2 | 380 |
| 3 | 411 |

**b.** If the actual number of patient arrivals in week 4 is 415, what is the forecast error for week 4?

**c.** What is the forecast for week 5?

**MyOMLab**

Active Model 8.2 in MyOMLab provides insight on the impact of varying $n$ using the example in Figure 8.5.

**MyOMLab**

Tutor 8.1 in MyOMLab provides another example to practice making forecasts with the moving average method.

**SOLUTION**

**a.** The moving average forecast at the end of week 3 is

$$F_4 = \frac{411 + 380 + 400}{3} = 397.0$$

**b.** The forecast error for week 4 is

$$E_4 = D_4 - F_4 = 415 - 397 = 18$$

**c.** The forecast for week 5 requires the actual arrivals from weeks 2 through 4, the 3 most recent weeks of data.

$$F_5 = \frac{415 + 411 + 380}{3} = 402.0$$

**DECISION POINT**

Thus, the forecast at the end of week 3 would have been 397 patients for week 4, which fell short of actual demand by 18 patients. The forecast for week 5, made at the end of week 4, would be 402 patients. If a forecast is needed now for week 6 and beyond, it would also be for 402 patients.

The moving average method may involve the use of as many periods of past demand as desired. Large values of $n$ should be used for demand series that are stable, and small values of $n$ should be used for those that are susceptible to changes in the underlying average. If $n$ is set to its lowest level (i.e., 1), it becomes the naïve method.

**weighted moving average method**

A time-series method in which each historical demand in the average can have its own weight; the sum of the weights equals 1.0.

**Weighted Moving Averages** In the simple moving average method, each demand has the same weight in the average—namely, $1/n$. In the **weighted moving average method**, each historical demand in the average can have its own weight. The sum of the weights equals 1.0. For example, in a *three-period* weighted moving average model, the most recent period might be assigned a weight of 0.50, the second most recent might be weighted 0.30, and the third most recent might be weighted 0.20. The average is obtained by multiplying the weight of each period by the value for that period and adding the products together:

$$F_{t+1} = 0.50D_t + 0.30D_{t-1} + 0.20D_{t-2}$$

For a numerical example of using the weighted moving average method to estimate average demand, see Solved Problem 2 and Tutor 8.2 of OM Explorer in MyOMLab.

The advantage of a weighted moving average method is that it allows you to emphasize recent demand over earlier demand. (It can even handle seasonal effects by putting higher weights on prior years in the same season.) The forecast will be more responsive to changes in the underlying average of the demand series than the simple moving average forecast.

**exponential smoothing method**

A weighted moving average method that calculates the average of a time series by implicitly giving recent demands more weight than earlier demands.

**Exponential Smoothing** The **exponential smoothing method** is a sophisticated weighted moving average method that calculates the average of a time series by implicitly giving recent demands more weight than earlier demands, all the way back to the first period in the history file. It is the most frequently used formal forecasting method because of its simplicity and the small amount of data needed to support it. Unlike the weighted moving average method, which requires $n$ periods of past demand and $n$ weights, exponential smoothing requires only three items of data: (1) the last period's forecast; (2) the actual demand for this period; and (3) a smoothing parameter, alpha $(\alpha)$, which has a value between 0 and 1.0. The equation for the exponentially smoothed forecast for period $t + 1$ is calculated

$$F_{t+1} = \alpha D_t + (1 - \alpha)F_t$$

The emphasis given to the most recent demand levels can be adjusted by changing the smoothing parameter. Larger $\alpha$ values emphasize recent levels of demand and result in forecasts more responsive to changes in the underlying average. Smaller $\alpha$ values treat past demand more uniformly and result in more stable forecasts. Smaller $\alpha$ values are analogous to increasing the value of $n$ in the moving average method and giving greater weight to past demand. In practice, various values of $\alpha$ are tried and the one producing the best forecasts is chosen.

Exponential smoothing requires an initial forecast to get started. There are several ways to get this initial forecast. OM Explorer and POM for Windows use as a default setting the actual demand in the first period, which becomes the forecast for the second period. Forecasts and forecast errors then are calculated beginning with period 2. If some historical data are available, the initial forecast can be found by calculating the average of several recent periods of demand. The effect of the initial estimate of the average on successive estimates of the average diminishes over time.

**EXAMPLE 8.4** **Using Exponential Smoothing to Estimate Average Demand**

**a.** Reconsider the patient arrival data in Example 8.3. It is now the end of week 3, so the actual number of arrivals is known to be 411 patients. Using $\alpha = 0.10$, calculate the exponential smoothing forecast for week 4.

**b.** What was the forecast error for week 4 if the actual demand turned out to be 415?

**c.** What is the forecast for week 5?

**MyOMLab**

Active Model 8.3 in MyOMLab provides insight on the impact of varying $\alpha$ in Figure 8.5.

**MyOMLab**

Tutor 8.3 in MyOMLab provides a new practice example of how to make forecasts with the exponential smoothing method.

**SOLUTION**

**a.** The exponential smoothing method requires an initial forecast. Suppose that we take the demand data for the first 2 weeks and average them, obtaining $(400 + 380)/2 = 390$ as an initial forecast. (POM for Windows and OM Explorer simply use the actual demand for the first week as a default setting for the initial forecast for period 1, and do not begin tracking forecast errors until the second period). To obtain the forecast for week 4, using exponential smoothing with $D_3 = 411$, $\alpha = 0.10$, and $F_3 = 390$, we calculate the forecast for week 4 as

$$F_4 = 0.10(411) + 0.90(390) = 392.1$$

Thus, the forecast for week 4 would be 392 patients.

**b.** The forecast error for week 4 is

$$E_4 = 415 - 392 = 23$$

**c.** The new forecast for week 5 would be

$$F_5 = 0.10(415) + 0.90(392.1) = 394.4$$

or 394 patients. Note that we used $F_4$, not the integer-value forecast for week 4, in the computation for $F_5$. In general, we round off (when it is appropriate) only the final result to maintain as much accuracy as possible in the calculations.

**DECISION POINT**

Using this exponential smoothing model, the analyst's forecasts would have been 392 patients for week 4 and then 394 patients for week 5 and beyond. As soon as the actual demand for week 5 is known, then the forecast for week 6 will be updated.

Because exponential smoothing is simple and requires minimal data, it is inexpensive and attractive to firms that make thousands of forecasts for each time period. However, its simplicity also is a disadvantage when the underlying average is changing, as in the case of a demand series with a trend. Like any method geared solely to the assumption of a stable average, exponential smoothing results will lag behind changes in the underlying average of demand. Higher $\alpha$ values may help reduce forecast errors when there is a change in the average; however, the lags will still occur if the average is changing systematically. Typically, if large $\alpha$ values (e.g., $> 0.50$) are required for an exponential smoothing application, chances are good that another model is needed because of a significant trend or seasonal influence in the demand series.

## Trend Patterns: Using Regression

Let us now consider a demand time series that has a trend. A *trend* in a time series is a systematic increase or decrease in the average of the series over time. Where a significant trend is present, forecasts from naïve, moving average, and exponential smoothing approaches are adaptive, but still lag behind actual demand and tend to be below or above the actual demand.

Trend projection with regression is a forecasting model that accounts for the trend with simple regression analysis. To develop a regression model for forecasting the trend, let the dependent variable, $Y$, be a period's demand and the independent variable, $t$, be the time period. For the first period, let $t = 1$; for the second period, let $t = 2$; and so on. The regression equation is

$$F_t = a + bt$$

One advantage of the trend projection with regression model is that it can forecast demand well into the future. The previous models project demand just one period ahead, and assume that demand beyond that will remain at that same level. Of course, all of the models (including the trend projection with regression model) can be updated each period to stay current. One *apparent* disadvantage of the trend with regression model is that it is not adaptive. The solution to this problem comes when you answer the following question. If you had the past sales of Ford automobiles since 1920, would you include each year in your regression analysis, giving equal weight to each year's sales, or include just the sales for more recent years? You most likely would decide to include just the more recent years, making your regression model more adaptive. The trend projection with regression model can thus be made more or less adaptive by the selection of historical data periods to include in the same way that moving average (changing $n$) or exponential smoothing (changing $\alpha$) models do.

The trend projection with regression model can be solved with either the *Trend Projection with Regression* Solver or the *Time Series Forecasting* Solver in OM Explorer. Both solvers provide the regression coefficients, coefficient of determination $r^2$, error measures, and forecasts into the future. POM for Windows has an alternative model (we do not cover in the textbook, although a description is provided in MyOMLab) that includes the trend, called the *Trend-Adjusted Smoothing* model.

MyOMLab

The *Trend Projection with Regression* Solver focuses exclusively on trend analysis. Its graph gives a big-picture view of how well the model fits the actual demand. Its sliders allow you to control when the regression begins, how many periods are included in the regression analysis, and how many periods you want forecasted into the future. The *Time Series Forecasting* Solver, on the other hand, covers all time series models, including the trend projection with regression. It also computes a combination forecast, which we cover in a subsequent section on using multiple techniques.

## EXAMPLE 8.5 Using Trend Projection with Regression to Forecast a Demand Series with a Trend

Medanalysis, Inc., provides medical laboratory services to patients of Health Providers, a group of 10 family-practice doctors associated with a new health maintenance program. Managers are interested in forecasting the number of blood analysis requests per week. Recent publicity about the damaging effects of cholesterol on the heart has caused a national increase in requests for standard blood tests. The arrivals over the last 16 weeks are given in Table 8.1. What is the forecasted demand for the next three periods?

**TABLE 8.1 ARRIVALS AT MEDANALYSIS FOR LAST 16 WEEKS**

| Week | Arrivals | Week | Arrivals |
|---|---|---|---|
| 1 | 28 | 9 | 61 |
| 2 | 27 | 10 | 39 |
| 3 | 44 | 11 | 55 |
| 4 | 37 | 12 | 54 |
| 5 | 35 | 13 | 52 |
| 6 | 53 | 14 | 60 |
| 7 | 38 | 15 | 60 |
| 8 | 57 | 16 | 75 |

### SOLUTION

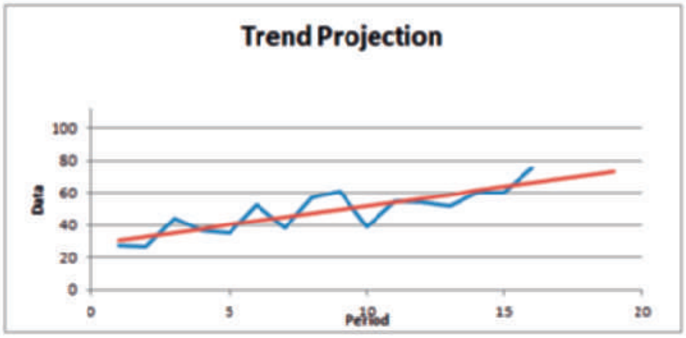
Figure 8.6(a) shows the results using the *Trend Projection with Regression* Solver when all 16 weeks are included in the regression analysis, with Figure 8.6(b) showing the worksheet that goes with it.

Looking at the Results sheet of Figure 8.6(a), we see that the *Y* intercept of the trend line ($a$) is 28.50 and the slope of the line ($b$) is 2.35. Thus, the trend equation is $F_t = a + bt$, where $t$ is the time period for which you are forecasting. The forecast for period 19 is $28.5 + 2.35(19) = 73$. The error terms are CFE $= 0$ (which is to be expected when the regression begins at the same time that error analysis begins), MAD $= 6.21$, MSE $= 52.96$, and MAPE $= 13.53$ percent. The coefficient of determination $r^2$ is decent at 0.69. The trend line is rising gently and reaches 73 for period 19. Each period the forecast predicts an increase of 2.35 arrivals per week.

**FIGURE 8.6(a) ▶**
Trend Projection with Regression Results

**Solver - Trend Projection with Regression**

| | |
|---|---|
| Regression begins in period | 1 |
| Error analysis begins in period | 1 |
| Number of future forecasts | 3 |




| | |
|---|---|
| *a* (Y intercept) | 28.50 |
| *b* (slope or trend) | 2.35 |
| r2 | 0.69 |
| | |
| CFE | 0.00 |
| MAD | 6.21 |
| MSE | 52.96 |
| MAPE | 13.53% |
| | |
| Forecast for period 17 | 68.375 |
| Forecast for period 18 | 70.72059 |
| Forecast for period 19 | 73.06618 |

**▼ FIGURE 8.6(b)**
Detailed Calculations of Forecast Errors

| | | | | CFE | MSE (Averages) | MAD (Averages) | MAPE (Averages) |
|---|---|---|---|---|---|---|---|
| | | | | **0.000** | **52.958** | **6.210** | **13.53%** |
| Period # | Actual Demand | Forecast | Error | Running CFE | Error Squared | Absolute Error | Abs % error |
| 1 | 28 | 31 | -2.846 | -2.846 | 8.097 | 2.846 | 10.16% |
| 2 | 27 | 33 | -6.191 | -9.037 | 38.331 | 6.191 | 22.93% |
| 3 | 44 | 36 | 8.463 | -0.574 | 71.626 | 8.463 | 19.23% |
| 4 | 37 | 38 | -0.882 | -1.456 | 0.779 | 0.882 | 2.38% |
| 5 | 35 | 40 | -5.228 | -6.684 | 27.331 | 5.228 | 14.94% |
| 6 | 53 | 43 | 10.426 | 3.743 | 108.711 | 10.426 | 19.67% |
| 7 | 38 | 45 | -6.919 | -3.176 | 47.874 | 6.919 | 18.21% |
| 8 | 57 | 47 | 9.735 | 6.559 | 94.776 | 9.735 | 17.08% |
| 9 | 61 | 50 | 11.390 | 17.949 | 129.725 | 11.390 | 18.67% |
| 10 | 39 | 52 | -12.956 | 4.993 | 167.855 | 12.956 | 33.22% |
| 11 | 55 | 54 | 0.699 | 5.691 | 0.488 | 0.699 | 1.27% |
| 12 | 54 | 57 | -2.647 | 3.044 | 7.007 | 2.647 | 4.90% |
| 13 | 52 | 59 | -6.993 | -3.949 | 48.897 | 6.993 | 13.45% |
| 14 | 60 | 61 | -1.338 | -5.287 | 1.791 | 1.338 | 2.23% |
| 15 | 60 | 64 | -3.684 | -8.971 | 13.571 | 3.684 | 6.14% |
| 16 | 75 | 66 | 8.971 | 0.000 | 80.471 | 8.971 | 11.96% |

## Seasonal Patterns: Using Seasonal Factors

Seasonal patterns are regularly repeating upward or downward movements in demand measured in periods of less than one year (hours, days, weeks, months, or quarters). In this context, the time periods are called *seasons*. For example, customer arrivals at a fast-food shop on any day may peak between 11 A.M. and 1 P.M. and again from 5 P.M. to 7 P.M.

An easy way to account for seasonal effects is to use one of the techniques already described, but to limit the data in the time series to those time periods in the same season. For example, for a day-of-the-week seasonal effect, one time series would be for Mondays, one for Tuesdays, and so on. Such an approach accounts for seasonal effects, but has the disadvantage of discarding considerable information on past demand.

**multiplicative seasonal method**

A method whereby seasonal factors are multiplied by an estimate of average demand to arrive at a seasonal forecast.

Other methods are available that analyze all past data, using one model to forecast demand for all of the seasons. We describe only the **multiplicative seasonal method**, whereby an estimate of average demand is multiplied by seasonal factors to arrive at a seasonal forecast. The four-step procedure presented here involves the use of simple averages of past demand, although more sophisticated methods for calculating averages, such as a moving average or exponential smoothing approach, could be used. The following description is based on a seasonal pattern lasting one year and seasons of one month, although the procedure can be used for any seasonal pattern and season of any length.

1. For each year, calculate the average demand per season by dividing annual demand by the number of seasons per year.
2. For each year, divide the actual demand for a season by the average demand per season. The result is a *seasonal factor* for each season in the year, which indicates the level of demand relative to the average demand. For example, a seasonal factor of 1.14 calculated for April implies that April's demand is 14 percent greater than the average demand per month.
3. Calculate the average seasonal factor for each season, using the results from step 2. Add the seasonal factors for a season and divide by the number of years of data.
4. Calculate each season's forecast for next year. Begin by forecasting next year's annual demand using the naïve method, moving averages, exponential smoothing, or trend projection with regression. Then, divide annual demand by the number of seasons per year to get the average demand per season. Finally, make the seasonal forecast by multiplying the average demand per season by the appropriate seasonal factor found in step 3.

### EXAMPLE 8.6 Using the Multiplicative Seasonal Method to Forecast the Number of Customers

The manager of the Stanley Steemer carpet cleaning company needs a quarterly forecast of the number of customers expected next year. The carpet cleaning business is seasonal, with a peak in the third quarter and a trough in the first quarter. The manager wants to forecast customer demand for each quarter of year 5, based on an estimate of total year 5 demand of 2,600 customers.

**SOLUTION**

The following table calculates the seasonal factor for each week.

It shows the quarterly demand data from the past 4 years, as well as the calculations performed to get the average seasonal factor for each quarter.

| | YEAR 1 | | YEAR 2 | | YEAR 3 | | YEAR 4 | | |
|---|---|---|---|---|---|---|---|---|---|
| Quarter | Demand | Seasonal Factor (1) | Demand | Seasonal Factor (2) | Demand | Seasonal Factor (3) | Demand | Seasonal Factor (4) | Average Seasonal Factor [(1+2+3+4+)/4] |
| 1 | 45 | 45/250 = 0.18 | 70 | 70/300 = 0.23333 | 100 | 100/450 = 0.22222 | 100 | 100/550 = 0.18182 | 0.2043 |
| 2 | 335 | 335/250 = 1.34 | 370 | 370/300 = 1.23333 | 585 | 585/450 = 1.30 | 725 | 725/550 = 1.31818 | 1.2979 |
| 3 | 520 | 520/250 = 2.08 | 590 | 590/300 = 1.96667 | 830 | 830/450 = 1.84444 | 1160 | 1160/550 = 2.10909 | 2.0001 |
| 4 | 100 | 100/250 = 0.40 | 170 | 170/300 = 0.56667 | 285 | 285/450 = 0.63333 | 215 | 215/550 = 0.39091 | 0.4977 |
| Total | 1,000 | | 1,200 | | 1,800 | | 2,200 | | |
| Average | 1,000/4 = 250 | | 1,200/4 = 300 | | 1,800/4 = 450 | | 2,200/4 = 550 | | |

For example, the seasonal factor for quarter 1 in year 1 is calculated by dividing the actual demand (45) by the average demand for the whole year $(1000/4 = 250)$. When this is done for all 4 years, we then can average the seasonal factors for quarter 1 over all 4 years. The result is a seasonal factor of 0.2043 for quarter 1.

Once seasonal factors are calculated for all four seasons (see last column in the table on the previous page), we then turn to making the forecasts for year 5. The manager suggests a forecast of 2,600 customers for the whole year, which seems reasonable given that the annual demand has been increasing by an average of 400 customers each year (from 1,000 in year 1 to 2,200 in year 4, or $1{,}200/3 = 400$). The computed forecast demand is found by extending that trend, and projecting an annual demand in year 5 of $2{,}200 + 400 = 2{,}600$ customers. (This same result is confirmed using the *Trend Projection with Regression* Solver of OM Explorer.) The quarterly forecasts are straight-forward. First, find the average demand forecast for year 5, which is $2{,}600/4 = 650$. Then multiple this average demand by the average seasonal index, giving us

| Quarter | Forecast |
|---|---|
| 1 | $650 \times 0.2043 = 132.795$ |
| 2 | $650 \times 1.2979 = 843.635$ |
| 3 | $650 \times 2.0001 = 1{,}300.065$ |
| 4 | $650 \times 0.4977 = 323.505$ |

Figure 8.7 shows the computer solution using the *Seasonal Forecasting* Solver in OM Explorer. Figure 8.7(b), the results, confirms all of the calculations made above. Notice in Figure 8.7(a), the inputs sheet that a computer demand forecast is provided as a default for year 5. However, there is an option for user-supplied demand forecast that overrides the computer-supplied forecast if the manager wishes to make a judgmental forecast based on additional information.

**FIGURE 8.7**
Demand Forecasts Using the *Seasonal Forecasting* Solver of *OM Explorer*

| | |
|---|---|
| Period | Quarters |
| Starting Year | 1 |
| Years | 4 |
| Computed Forecast Demand for Year 5 | 2600 |
| User-supplied Forecast Demand for Year 5 | 2600 |

| | Year | | | |
|---|---|---|---|---|
| **Quarter** | 1 | 2 | 3 | 4 |
| 1 | 45 | 70 | 100 | 100 |
| 2 | 335 | 370 | 585 | 725 |
| 3 | 520 | 590 | 830 | 1160 |
| 4 | 100 | 170 | 285 | 215 |

(a) Inputs sheet

| Quarter | Seasonal Index | Forecast |
|---|---|---|
| 1 | 0.2043 | 132.795 |
| 2 | 1.2979 | 843.635 |
| 3 | 2.0001 | 1300.065 |
| 4 | 0.4977 | 323.505 |

(b) Results

**DECISION POINT**

Using this seasonal method, the analyst makes a demand forecast as low as 133 customers in the first quarter and as high as 1,300 customers in the third quarter. The season of the year clearly makes a difference.

**additive seasonal method**

A method in which seasonal forecasts are generated by adding a constant to the estimate of average demand per season.

An alternative to the multiplicative seasonal method is the **additive seasonal method**, whereby seasonal forecasts are generated by adding or subtracting a seasonal constant (say, 50 units) to the estimate of average demand per season. This approach is based on the assumption that the seasonal pattern is constant, regardless of average demand. The amplitude of the seasonal adjustment remains the same regardless of the level of demand.

## Criteria for Selecting Time-Series Methods

Of all the time series forecasting methods available, which should be chosen? Forecast error measures provide important information for choosing the best forecasting method for a service or product. They also guide managers in selecting the best values for the parameters needed for the method: $n$ for the moving average method, the weights for the weighted moving average method, $\alpha$ for the exponential smoothing method, and when regression data begins for the trend projection with regression method. The criteria to use in making forecast method and parameter choices include (1) minimizing bias (CFE); (2) minimizing MAPE, MAD, or MSE; (3) maximizing $r^2$ for trend projections using regression; (4) using a holdout sample analysis; (5) using a tracking signal; (6) meeting managerial expectations of changes in the components of demand; and (7) minimizing the forecast errors in recent periods. The first three criteria relate to statistical measures based on historical performance, the fourth is a test under realistic conditions, the fifth evaluates forecast performance and the potential need to change the method, the sixth reflects expectations of the future that may not be rooted in the past, and the seventh is a way to use whatever method seems to be working best at the time a forecast must be made.

**Using Statistical Criteria** Statistical performance measures can be used in the selection of which forecasting method to use. The following guidelines will help when searching for the best time-series models:

1. For projections of more stable demand patterns, use lower $\alpha$ values or larger $n$ values to emphasize historical experience.
2. For projections of more dynamic demand patterns using the models covered in this chapter, try higher $\alpha$ values or smaller $n$ values. When historical demand patterns are changing, recent history should be emphasized.

**Using a Holdout Sample** Often, the forecaster must make trade-offs between bias (CFE) and the measures of forecast error dispersion (MAPE, MAD, and MSE). Managers also must recognize that the best technique in explaining the past data is not necessarily the best technique to predict the future, and that "overfitting" past data can be deceptive. A forecasting method may have small errors relative to the history file, but may generate high errors for future time periods. For this reason, some analysts prefer to use a **holdout sample** as a final test (see Experiential Learning Exercise 8.1 at the end of this chapter). To do so, they set aside some of the more recent periods from the time series and use only the earlier time periods to develop and test different models. Once the final models have been selected in the first phase, they are tested again with the holdout sample. Performance measures, such as MAD and CFE, would still be used but they would be applied to the holdout sample. Whether this idea is used or not, managers should monitor future forecast errors, and modify their forecasting approaches as needed. Maintaining data on forecast performance is the ultimate test of forecasting power—rather than how well a model fits past data or holdout samples.

**holdout sample**

Actual demands from the more recent time periods in the time series that are set aside to test different models developed from the earlier time periods.

**tracking signal**

A measure that indicates whether a method of forecasting is accurately predicting actual changes in demand.

**Using a Tracking Signal** A **tracking signal** is a measure that indicates whether a method of forecasting is accurately predicting actual changes in demand. The tracking signal measures the number of MADs represented by the cumulative sum of forecast errors, the CFE. The CFE tends to be close to 0 when a correct forecasting system is being used. At any time, however, random errors can cause the CFE to be a nonzero number. The tracking signal formula is

$$\text{Tracking signal} = \frac{\text{CFE}}{\text{MAD}} \text{ or } \frac{\text{CFE}}{\text{MAD}_t}$$

Each period, the CFE and MAD are updated to reflect current error, and the tracking signal is compared to some predetermined limits. The MAD can be calculated in one of two ways: (1) as the simple average of all absolute errors (as demonstrated in Example 8.1) or (2) as a weighted average determined by the exponential smoothing method:

$$\text{MAD}_t = \alpha|E_t| + (1 - \alpha)\text{MAD}_{t-1}$$

If forecast errors are normally distributed with a mean of 0, the relationship between $\sigma$ and MAD is simple:

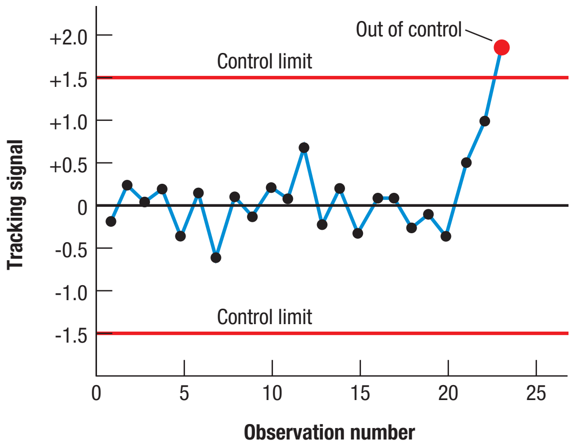
$$\sigma = \left(\sqrt{\pi/2}\right)(\text{MAD}) \cong 1.25(\text{MAD})$$

$$\text{MAD} = 0.7978\sigma \cong 0.8\sigma$$

where

$$\pi = 3.1416$$

This relationship allows use of the normal probability tables to specify limits for the tracking signal. If the tracking signal falls outside those limits, the forecasting model no longer is tracking demand adequately. A tracking system is useful when forecasting systems are computerized because it alerts analysts when forecasts are getting far from desirable limits. Figure 8.8 shows tracking signal results for 23 periods plotted on a *control chart*. The control chart is useful for determining whether any action needs to be taken to improve the forecasting model. In the example, the first 20 points cluster around 0, as we would expect if the forecasts are not biased. The CFE will tend toward 0. When the underlying characteristics of demand change but the forecasting model does not, the tracking signal eventually goes out of control. The steady increase after the 20th point in Figure 8.8 indicates that the process is going out of control. The 21st and 22nd points are acceptable, but the 23rd point is not.




▲ **FIGURE 8.8**
Tracking Signal

# Forecasting as a Process

Often companies must prepare forecasts for hundreds or even thousands of services or products repeatedly. For example, a large network of health care facilities must calculate demand forecasts for each of its services for every department. This undertaking involves voluminous data that must be manipulated frequently. However, software can ease the burden of making these forecasts and coordinating the forecasts between customers and suppliers. Many forecasting software packages are available, including Manugistics, Forecast Pro, and SAS. The forecasting routines in OM Explorer and POM for Windows give some hint of their capabilities. Forecasting is not just a set of techniques, but instead a process that must be designed and managed. While there is no one process that works for everyone, here we describe two comprehensive processes that can be quite effective in managing operations and the supply chain.

## A Typical Forecasting Process

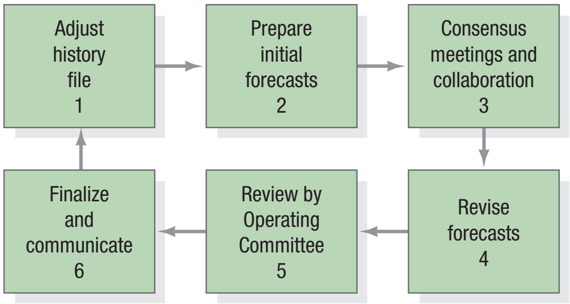
Many *inputs* to the forecasting process are informational, beginning with the *history file* on past demand. The history file is kept up-to-date with the actual demands. Clarifying notes and adjustments are made to the database to explain unusual demand behavior, such as the impact of special promotions and closeouts. Often the database is separated into two parts: *base* data and *nonbase* data. The second category reflects irregular demands. Final forecasts just made at the end of the prior cycle are entered in the history file so as to track forecast errors. Other information sources are from salesforce estimates, outstanding bids on new orders, booked orders, market research studies, competitor behavior, economic outlook, new product introductions, pricing, and promotions. If point-of-sale data are used, as is done by Kimberly-Clark in the opening vignette, then considerable information sharing will take place with customers. For new products, a history database is fabricated based on the firm's experience with prior products and the judgment of personnel.

*Outputs* of the process are forecasts for multiple time periods into the future. Typically, they are on a monthly basis and are projected out from six months to two years. Most software packages have the ability to "roll up" or "aggregate" forecasts for individual stock-keeping units (SKUs) into forecasts for whole product families. Forecasts can also be "blown down" or "disaggregated" into smaller pieces. In a make-to-stock environment, forecasts tend to be more detailed and can get down to specific individual products. In a make-to-order environment, the forecasts tend to be for groups of products. Similarly, if the lead times to buy raw materials and manufacture a product or provide a service are long, the forecasts go farther out into the future.

The forecast process itself, typically done on a monthly basis, consists of structured steps. These steps often are facilitated by someone who might be called a demand manager, forecast analyst, or demand/supply planner. However, many other people are typically involved before the plan for the month is authorized.

***Step 1.*** The cycle begins mid-month just after the forecasts have been finalized and communicated to the stakeholders. Now is the time to update the history file and review forecast accuracy. At the end of the month, enter actual demand and review forecast accuracy.

***Step 2.*** Prepare initial forecasts using some forecasting software package and judgment. Adjust the parameters of the software to find models that fit the past demand well and yet reflect the demand




manager's judgment on irregular events and information about future sales pulled from various sources and business units.

***Step 3.*** Hold consensus meetings with the stakeholders, such as marketing, sales, supply chain planners, and finance. Make it easy for business unit and field sales personnel to make inputs. Use the Internet to get collaborative information from key customers and suppliers. The goal is to arrive at consensus forecasts from all of the important players.

***Step 4.*** Revise the forecasts using judgment, considering the inputs from the consensus meetings and collaborative sources.

***Step 5.*** Present the forecasts to the operating committee for review and to reach a final set of forecasts. It is important to have a set of forecasts that everybody agrees upon and will work to support.

***Step 6.*** Finalize the forecasts based on the decisions of the operating committee and communicate them to the important stakeholders. Supply chain planners are usually the biggest users.

As with all work activity, forecasting is a process and should be continually reviewed for improvements. A better process will foster better relationships between departments such as marketing, sales, and operations. It will also produce better forecasts. This principle is the first one in Table 8.2 to guide process improvements.

**TABLE 8.2 | SOME PRINCIPLES FOR THE FORECASTING PROCESS**

- Better processes yield better forecasts.
- Demand forecasting is being done in virtually every company, either formally or informally. The challenge is to do it well—better than the competition.
- Better forecasts result in better customer service and lower costs, as well as better relationships with suppliers and customers.
- The forecast can and must make sense based on the big picture, economic outlook, market share, and so on.
- The best way to improve forecast accuracy is to focus on reducing forecast error.
- Bias is the worst kind of forecast error; strive for zero bias.
- Whenever possible, forecast at more aggregate levels. Forecast in detail only where necessary.
- Far more can be gained by people collaborating and communicating well than by using the most advanced forecasting technique or model.

*Source:* From Thomas F. Wallace and Robert A. Stahl, *Sales Forecasting: A New Approach* (Cincinnati, OH: T. E. Wallace & Company, 2002), p. 112. Copyright © 2002 T.E. Wallace & Company. Used with permission.

## Using Multiple Forecasting Methods

Step 2 of the forecasting process relates to preparing an initial forecast. However, we need not rely on a single forecasting method. Several different forecasts can be used to arrive at a forecast. Initial statistical forecasts using several time-series methods and regression are distributed to knowledgeable individuals, such as marketing directors and sales teams, (and sometimes even suppliers and customers) for their adjustments. They can account for current market and customer conditions that are not necessarily reflected in past data. Multiple forecasts may come from different sales teams, and some teams may have a better record on forecast errors than others.

**combination forecasts**

Forecasts that are produced by averaging independent forecasts based on different methods, different sources, or different data.

Research during the last two decades suggests that combining forecasts from multiple sources often produces more accurate forecasts. **Combination forecasts** are forecasts that are produced by averaging independent forecasts based on different methods, different sources, or different data. It is intriguing that combination forecasts often perform better over time than even the *best* single forecasting procedure. For example, suppose that the forecast for the next period is 100 units from technique 1 and 120 units from technique 2 and that technique 1 has provided more accurate forecasts to date. The combination forecast for next period, giving equal weight to each technique, is 110 units (or $0.5 \times 100 + 0.5 \times 120$). When this averaging technique is used consistently into the future, its combination forecasts often will be much more accurate than those of any single best forecasting technique (in this example, technique 1). Combining is most effective when the individual forecasts bring different kinds of information into the forecasting process. Forecasters have achieved excellent results by weighting forecasts equally, and this is a good starting point. However, unequal weights may provide better results under some conditions. Managerial Practice 8.1 shows how Fiskars Corporation successfully used combination forecasts.

## MANAGERIAL PRACTICE 8.1 Combination Forecasts and the Forecasting Process

**Fiskars Corporation,** which generated more than $1.1 billion in sales in 2013, is the second oldest incorporated entity in the world and produces a variety of high-quality products such as garden shears, pruners, hand tools, scissors, ratchet tools, screwdrivers, and the like. Business is highly seasonal and prices quite variable. About 10 percent to 15 percent of the annual revenue comes from one-time promotions, and 25 percent to 35 percent of its products are new every year. Quality is very important at Fiskars; its scissors were selected as the Official Net-Cutting Scissors of the NCAA National Championship in 2014.

Given the highly volatile demand environment, Fiskars Brands, Inc., a subsidiary of Fiskars Corporation located in Madison, Wisconsin, needed to improve its forecasting process. It serves 2,000 customers ranging from large discounters to local craft stores providing about 2,300 products. Fiskars Brands introduced a statistical-based analysis in its forecasting process along with a Web-based business intelligence tool for reporting. It put much more emphasis on combination forecasts. Instead of asking members of the sales staff to provide their own forecasts, forecasts were sent to them, and they were asked for their validation and refinement. Their inputs are most useful relative to additions, deletions, and promotions. Converting multiple forecasts into one number (forecasts from time-series techniques, sales input, and customer input) creates more accurate forecasts by product. Fiskars's software has the ability to weigh each input. It gives more weight to a statistical forecast for in-line items, and inputs from the sales staff get much more weight for promoted products and new items.

It also segments products by value and forecastability so as to concentrate forecasting efforts on products that have the biggest impact on the business. High-value items that are easier to forecast (stable demand with low forecast errors to date) tend to do well with the time-series techniques, and **judgmental adjustments** are made with caution. High-value items that are difficult to forecast get top priority in the forecasting effort, and spark the need for collaboration with customers and suppliers. Much less attention is given to improving forecasts for low-value items for which there is some history and fairly steady demand.

Finally, Fiskars instituted a Web-based program that gives the entire company visibility to forecast information in whatever form it needs. For example, Finance wants monthly, quarterly, and yearly projections in dollars, whereas Operations wants projections in units as well as accuracy measures. Everybody can track updated forecast information by customer, brand, and product.

HANDOUT/MCT/Newscom

Fiskars Brands, Inc. totally overhauled its forecasting process for products such as those shown here. It introduced time-series methods, with much emphasis placed on combination forecasts. Sales staff added their judgmental modifications, which were combined with forecasts from several time-series techniques to produce more accurate forecasts down to the level of the product.

*Source:* David Montgomery, "Flashpoints for Changing Your Forecasting Process," *The Journal of Business Forecasting*, (Winter 2006–2007), pp. 35–37; **http://www.fiskars.com**, April 15, 2014.

OM Explorer and POM for Windows allow you to evaluate several forecasting models, and then you can create combination forecasts from them. In fact, the *Time-Series Forecasting* Solver of OM Explorer automatically computes a combination forecast as a weighted average, using the weights that you supply for the various models that it evaluates. The models include the naïve, moving average, exponential smoothing, and regression projector methods. Alternately, you can create a simple Excel spreadsheet that combines forecasts generated by POM for Windows to create combination forecasts. The *Time Series Forecasting* Solver also allows you evaluate your forecasting process with a holdout sample. The forecaster makes a forecast just one period ahead, and learns of given actual demand. Next the solver computes forecasts and forecast errors for the period. The process continues to the next period in the holdout sample with the forecaster committing to a forecast for the next period. To be informed, the forecaster should also be aware of how well the other forecasting methods have been performing, particularly in the recent past.

**judgmental adjustment**

An adjustment made to forecasts from one or more quantitative models that accounts for recognizing which models are performing particularly well in recent past, or take into account contextual information.

Another way to take advantage of multiple techniques is **focus forecasting**, which selects the best forecast (based on past error measures) from a group of forecasts generated by individual techniques. Every period, all techniques are used to make forecasts for each item. The forecasts are made with a computer because there can be 100,000 SKUs at a company, each needing to be forecast. Using the history file as the starting point for each method, the computer generates forecasts for the current period. The

**focus forecasting**

A method of forecasting that selects the best forecast from a group of forecasts generated by individual techniques.

Mark Peterson/CORBIS

Ever wonder how CPFR came into existence? Walmart has long been known for its careful analysis of cash register receipts and for working with suppliers to reduce inventories. To combat the ill effects of forecast errors on inventories, Benchmarking Partners, Inc. was funded in the mid-1990s by Walmart, IBM, SAP, and Manugistics to develop a software package. Walmart initiated the new system with Listerine, a primary product of Warner-Lambert (now produced by Johnson & Johnson). How did it work? Walmart and Warner-Lambert independently calculated the demand they expected for Listerine six months into the future, taking into consideration factors such as past sales trends and sales promotions. If the forecasts differed by more than a predetermined percentage, they exchanged written comments and supporting data. They went through as many cycles as needed to converge to an acceptable forecast. The program was successful; Walmart saw a reduction in stockouts from 15 percent to 2 percent, increased sales, and reduced inventory costs, while Warner-Lambert benefitted from a smoother production plan and lower average costs. The system was later generalized and called collaborative planning, forecasting, and replenishment, or CPFR.

forecasts are compared to actual demand, and the method that produces the forecast with the least error is used to make the forecast for the next period. The method used for each item may change from period to period.

## Adding Collaboration to the Process

In step three of the forecasting process we try to achieve consensus of the forecast. One way to achieve that consensus in a formal way is to employ **collaborative planning, forecasting, and replenishment (CPFR)**, a process for supply chain integration that allows a supplier and its customers to collaborate on making the forecast by using the Internet. Traditionally, suppliers and buyers in most supply chains prepare independent demand forecasts. With CPFR, firms initiate customer-focused operations teams that share with retailers their real-time data and plans, including forecasts, inventories, sales to retailers' shelves, promotions, product plans, and exceptions. CPFR involves four interactive activities:

- **Strategy and Planning:** establish the ground rules for the collaborative relationship such as business goals, scope of collaboration, and assignment of roles and responsibilities.
- **Demand and Supply Management:** develop sales forecasts, procedures for order planning, and inventory positions.
- **Execution:** manage the generation of orders between supplier and customers and the production, shipment, and delivery of products for customer purchase.
- **Analysis:** monitor the planning process and operations for out of bound conditions and evaluate to achievement of business goals.

**collaborative planning, forecasting, and replenishment (CPFR)**

A process for supply chain integration that allows a supplier and its customers to collaborate on making the forecast by using the Internet.

Many firms have used CPFR to coordinate forecasts and plans up and down the supply chain. CPFR enables firms to collaborate with their retailers' distribution centers' customers and increase their ability to forecast effectively. The real key to a successful implementation of CPFR is the forging of a cultural alliance that involves peer-to peer relations and cross-functional teams.

## Forecasting as a Nested Process

Forecasting is not a stand-alone activity, but instead part of a larger process that encompasses the remaining chapters. After all, demand is only half of the equation—the other half is supply. Future plans must be developed to supply the resources needed to meet the forecasted demand. Resources include the workforce, materials, inventories, dollars, and equipment capacity. Making sure that demand and supply plans are in balance begins in the next chapter, Chapter 9, "Managing Inventories," and continues with Chapter 10, "Planning and Scheduling Operations," and Chapter 11, "Efficient Resource Planning."

## LEARNING GOALS IN REVIEW

| Learning Goal | Guidelines for Review | MyOMLab Resources |
|---|---|---|
| 1 Explain how managers can change demand patterns. | Review the section "Managing Demand," pp. 297–300. Focus on "Demand Management Options," and the eight ways managers can change demand patterns. | |
| 2 Describe the two key decisions on making forecasts. | In the section "Key Decisions on Making Forecasts," p. 300, focus on the considerations for deciding what to forecast and choosing the right forecasting technique. | |
| 3 Calculate the five basic measures of forecast errors. | Review the section "Forecast Error," pp. 301–304, to understand CFE, MSE, $\sigma$, MAD, and MAPE.<br>Study Figures 8.2 (a) and (b) for an example. Solved Problem 2 shows an example of MAD and Solved Problem 3 shows MAD and MAPE. | **POM for Windows:** Error Analysis |
| 4 Compare and contrast the four approaches to judgmental forecasting. | The section "Judgment Methods," p. 304, explains the differences between salesforce estimates, executive opinion, market research, and the Delphi method. | |
| 5 Use regression to make forecasts with one or more independent variables. | The "Causal Methods: Linear Regression" section, pp. 304–306, and Example 8.2, p. 305, describe how linear regression, when historical data is available, can express demand as a linear function of one or more independent variables. The computer is an essential tool for linear regression. In addition to Example 8.2, Solved Problem 1 provides the statistics on how well the regression equation fits the data. | **Active Model:** 8.1: Linear Regression<br>**OM Explorer Solver:** Regression Analysis<br>**POM for Windows:** Least Squares – Simple and Multiple Regression<br>**POM for Windows:** Regression Projector |
| 6 Make forecasts using the five most common statistical approaches for time-series analysis. | The "Time-Series Methods" on pp. 306–315 explains the naïve method and the five statistical methods of simple moving average, weighted moving average, exponential smoothing, trend projection with regression, and multiplicative seasonal method that are used. Examples 8.3, 8.4, 8.5, and 8.6 demonstrate the methods, as do Solved Problems 2, 3 and 4. Also see Experiential Learning 8.1 for an in-class exercise requiring the use of time-series models to prepare a combination forecast. | **Active Models:** 8.2: Simple Moving Averages; 8.3: Exponential Smoothing<br>**OM Explorer Tutors:** 8.1: Moving Average Method; 8.2: Weighted Moving Average Method; 8.3: Exponential Smoothing<br>**OM Explorer Solvers:** Time Series Forecasting; Trend Projection with Regression; Seasonal Forecasting<br>**POM for Windows:** Time Series Analysis<br>**Student Data File:** Experiential Exercise 8.1 Data |
| 7 Describe the six steps in a typical forecasting process. | See the section "Forecasting as a Process," pp. 315–318 and the six steps involved. There is much more complexity when you realize the number of SKUs involved and the need to update the history file. Be sure to understand how combination forecasts work into step 2 and how CPFR is integral to step 3. | **Video:** Forecasting and Supply Chain Management at Deckers Outdoor Corporation |

# Key Equations

## Forecast Error

**1.** Forecast error measures:

$$E_t = D_t - F_t$$

$$\text{CFE} = \sum E_t$$

$$\bar{E} = \frac{\text{CFE}}{n}$$

$$\text{MSE} = \frac{\sum E_t^2}{n}$$

$$\sigma = \sqrt{\frac{\sum (E_t - \bar{E})^2}{n - 1}}$$

$$\text{MAD} = \frac{\sum |E_t|}{n}$$

$$\text{MAPE} = \frac{(\sum |E_t| / D_t)(100\%)}{n}$$

## Causal Methods: Linear Regression

**2.** Linear regression:

$$Y = a + bX$$

## Time-Series Methods

**3.** Naïve forecasting:

$$\text{Forecast} = D_t$$

**4.** Simple moving average:

$$F_{t+1} = \frac{D_t + D_{t-1} + D_{t-2} + \cdots + D_{t-n+1}}{n}$$

**5.** Weighted moving average:

$$F_{t+1} = \text{Weight}_1(D_t) + \text{Weight}_2(D_{t-1}) + \text{Weight}_3(D_{t-2}) + \cdots + \text{Weight}_n(D_{t-n+1})$$

**6.** Exponential smoothing:

$$F_{t+1} = \alpha D_t + (1 - \alpha)F_t$$

**7.** Trend Projection using Regression

$$F_t = a + bt$$

**8.** Tracking signal:

$$\frac{\text{CFE}}{\text{MAD}} \text{ or } \frac{\text{CFE}}{\text{MAD}_t}$$

**9.** Exponentially smoothed error:

$$\text{MAD}_t = \alpha |E_t| + (1 - \alpha)\text{MAD}_{t-1}$$

# Key Terms

additive seasonal method 314
aggregation 300
backlog 299
backorder 299
causal methods 300
collaborative planning, forecasting, and replenishment (CPFR) 318
combination forecasts 316
complementary products 298
cumulative sum of forecast errors (CFE) 301
demand management 298
dependent variable 304
Delphi method 304
executive opinion 304
exponential smoothing method 308
focus forecasting 317
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holdout sample 314
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judgment methods 300
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market research 304
mean absolute deviation (MAD) 302
mean absolute percent error (MAPE) 302
mean squared error (MSE) 302
multiplicative seasonal method 312
naïve forecast 307
revenue management 299
salesforce estimates 304
simple moving average method 307
standard deviation of the errors ($\sigma$) 302
stockout 299
technological forecasting 304
time series 297
time-series analysis 300
tracking signal 314
trend projection with regression 301
weighted moving average method 308