FIGURE 10.1 **Different Levels of Planning**

Tactical planning
Planning that covers a shorter period, usually 12 to 24 months out, although the planning horizon may be longer in industries with very long lead times (e.g., engineer-to-order firms).

Detailed planning and control
Planning that covers time periods ranging from weeks down to just a few hours out.

covers a shorter period, usually 12 to 24 months out, although the planning horizon may be longer in industries with very long lead times (e.g., engineer-to-order firms). Tactical planning is typically more detailed, but it is constrained by the longer-term strategic decisions. For example, managers responsible for tactical planning might be able to adjust overall inventory or workforce levels, but only within the constraints imposed by strategic decisions such as the size of the facilities and types of processes used.

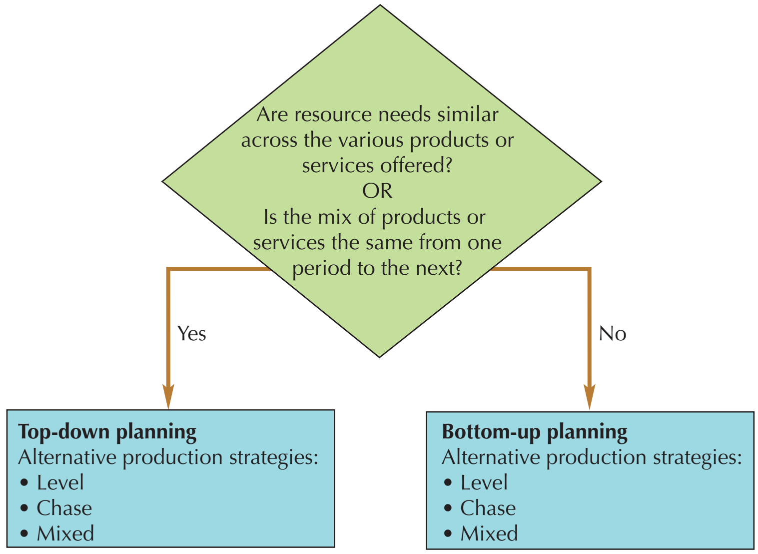
Detailed planning and control covers time periods ranging from weeks down to just a few hours out. Because the planning horizon is so short, managers who do detailed planning and control usually have few, if any, options for adjusting capacity levels. Rather, they must try to make the best use of available capacity in order to get as much work done as possible.

The three approaches differ in (1) the time frame covered, (2) the level of planning detail required, and (3) the degree of flexibility managers have to change capacity. See Figure 10.1. Strategic planning has the longest time horizon, has the least amount of specific information (after all, we are planning for years out), and affords managers the greatest degree of flexibility to change capacity. Detailed planning and control is just the opposite: Planning can cover daily or even hourly activity, and the relatively short time horizons leave managers with few, if any, options for changing capacity. Tactical planning fills the gap between these extremes.

S&OP is aimed squarely at helping businesses develop superior tactical plans. Specifically:

- **S&OP indicates how the organization will use its tactical capacity resources to meet expected customer demand.** Examples of tactical capacity resources include the size of the workforce, inventory, number of shifts, and even availability of subcontractors.
- **S&OP strikes a balance between the various needs and constraints of the supply chain partners.** For example, S&OP must consider not only customer demand but also the capabilities of all suppliers, production facilities, and logistics service providers that work together to provide the product or service. The result is a plan that is not only feasible but also balances costs, delivery, quality, and flexibility.
- **S&OP serves as a coordinating mechanism for the various supply chain partners.** At the end of the S&OP process, there should be a shared agreement about what each of the affected partners—marketing operations, and finance, as well as key suppliers and logistics providers—needs to do to make the plan a reality. Good S&OP makes it very clear what everyone should—and should not—do. This shared agreement allows the different parties to make more detailed decisions with the confidence that their efforts will be consistent with those of other partners.
- **S&OP expresses the business's plans in terms that everyone can understand.** Finance personnel typically think of business activity in terms of cash flows, financial ratios, and other measures of profitability. Marketing managers concentrate on sales levels and market segments, while operations and supply chain managers tend to focus more on the activities associated with the particular products or services being produced. As we shall see, S&OP makes a deliberate effort to express the resulting plans in a format that is easy for all partners to understand and incorporate into their detailed planning efforts.

FIGURE 10.2
Determining the Appropriate Approach to S&OP



Top-down planning
An approach to S&OP in which a single, aggregated sales forecast drives the planning process. For top-down planning to work, the mix of products or services must be essentially the same from one time period to the next *or* the products or services to be provided must have very similar resource requirements.

10.2 MAJOR APPROACHES TO S&OP

Bottom-up planning
An approach to S&OP that is used when the product/service mix is unstable and resource requirements vary greatly across the offerings. Under such conditions, managers will need to estimate the requirements for each set of products or services separately and then add them up to get an overall picture of the resource requirements.

Planning values
Values that decision makers use to translate a sales forecast into resource requirements and to determine the feasibility and costs of alternative sales and operations plans.

There are two major approaches to S&OP: top-down planning and bottom-up planning. Figure 10.2 summarizes the criteria organizations must consider when choosing between the two.

The simplest approach is **top-down planning.** Here a single, aggregated sales forecast drives the planning process. For top-down planning to work, the mix of products or services must be essentially the same from one time period to the next *or* the various products or services must have very similar resource requirements to one another. The key assumption under top-down planning is that managers can make accurate tactical plans based on the *overall* forecast and then divide the resources across individual products or services later on, during the detailed planning and control stage.

Bottom-up planning is used when the product/service mix is unstable and resource requirements vary greatly across the offerings. Under such conditions, a single forecast number is not very helpful in determining resource requirements. Instead, managers will need to estimate the requirements for each set of products or services separately and then add them up to get an overall picture of the resource requirements.

Regardless of the approach used, managers will need planning values to carry out the analysis. **Planning values** are values, based on analysis or historical data, that decision makers use to translate a sales forecast into resource requirements and to determine the feasibility and costs of alternative sales and operations plans. Example 10.1 shows one method of developing planning values when the product mix is stable.

EXAMPLE 10.1
Calculating Planning Values for Ernie's Electrical

Ernie's Electrical performs three services: cable TV installations, satellite TV installations, and digital subscriber line (DSL) installations. Table 10.1 shows Ernie's service mix, as well as the labor hours and supply costs associated with each type of installation.

TABLE 10.1 Service Mix at Ernie's Electrical

SERVICE DESCRIPTION	SERVICE MIX	LABOR HOURS PER INSTALLATION	SUPPLY COSTS PER INSTALLATION
Cable TV installation	40%	2	$15
Satellite TV installation	40%	3	$90
DSL installation	20%	4	$155

Ernie's service mix is the same from one month to the next. As a result, the company can use a single set of planning values, based on the weighted averages of labor hours and supply costs:

Estimated labor hours per installation:

$$40\% * 2 \text{ hours} + 40\% * 3 \text{ hours} + 20\% * 4 \text{ hours} = 2.8 \text{ hours}$$

Estimated supply costs per installation:

$$40\% * \$15 + 40\% * \$90 + 20\% * \$155 = \$73$$

Ernie expects total installations for the next three months to be 150, 175, and 200, respectively. With this sales forecast and the planning values above, Ernie can quickly estimate labor hours and supply costs for each month (Table 10.2).

TABLE 10.2 Estimated Resource Requirements at Ernie's Electrical

MONTH	SALES FORECAST (INSTALLATIONS)	LABOR HOURS (2.8 PER INSTALLATION)	SUPPLY COSTS ($73 PER INSTALLATION)
Month 1	150	420	$10,950
Month 2	175	490	$12,775
Month 3	200	560	$14,600

Top-Down Planning

The process for generating a top-down plan consists of three steps:

1. **Develop the aggregate sales forecast and planning values.** Top-down planning starts with the aggregate sales forecast. The planning values are used in the next two steps to help management translate the sales forecast into resource requirements and determine the feasibility and costs of alternative S&OP strategies.
2. **Translate the sales forecast into resource requirements.** The goal of this second step is to move the analysis from "sales" numbers to the "operations and supply chain" numbers needed for tactical planning. Some typical resources include labor hours, equipment hours, and material dollars, to name a few.
3. **Generate alternative production plans.** In this step, management determines the feasibility and costs for various production plans. We will describe three particular approaches—level production, chase production, and mixed production—in more detail later.

We illustrate top-down planning through a series of examples for a fictional manufacturer, Pennington Cabinets.

EXAMPLE 10.2

Developing the Aggregate Sales Forecast and Planning Values for Pennington Cabinets

RosaIreneBetancourt 6/Alamy Stock Photo

Pennington Cabinets is a manufacturer of several different lines of kitchen and bathroom cabinets that are sold through major home improvement retailers. Pennington's marketing vice president has come up with the following combined sales forecast for the next 12 months:

MONTH	SALES FORECAST (CABINET SETS)
January	750
February	760
March	800
April	800
May	820
June	840
July	910
August	910
September	910
October	880
November	860
December	840

Under top-down planning, managers base the planning process on *aggregated* sales figures, such as those shown here. For example, January's forecast value of 750 reflects total expected demand across Pennington's *entire* line of cabinets. The primary advantage of top-down planning is that it allows managers to see the relationships among *overall* demand, production, and inventory levels. There will be plenty of time to do detailed planning and control later on.

In addition to the sales forecast, Pennington has also developed the planning values shown in Table 10.3.

TABLE 10.3 Planning Values for Pennington Cabinets

CABINET SET PLANNING VALUES	
Regular production cost:	$2,000 per cabinet set
Overtime production cost:	$2,062 per cabinet set
Average monthly inventory holding cost:	$40 per cabinet set, per month
Average labor hours per cabinet set:	20 hours
PRODUCTION PLANNING VALUES	
Maximum regular production per month:	848 cabinet sets
Allowable overtime production per month:	1/10 of regular production
WORKFORCE PLANNING VALUES	
Hours worked per month per employee:	160 hours
Estimated cost to hire a worker:	$1,750
Estimated cost to lay off a worker:	$1,500

Planning values such as these are often developed from company records, detailed analysis, and managerial experience. "Average labor hours per cabinet set," for example, might be derived by looking at past production results, while "Maximum regular production per month" might be based on a detailed analysis of manufacturing capacity (see Chapter 6). In contrast, the human resources (HR) manager might use data on recruiting, interviewing, and training costs to develop estimates of hiring and layoff costs.

The sales forecast shows an expected peak from July through September. As stated in the planning values, Pennington can produce up to 848 cabinet sets a month, using regular production time. Figure 10.3 graphs the expected sales level against maximum regular production per month.

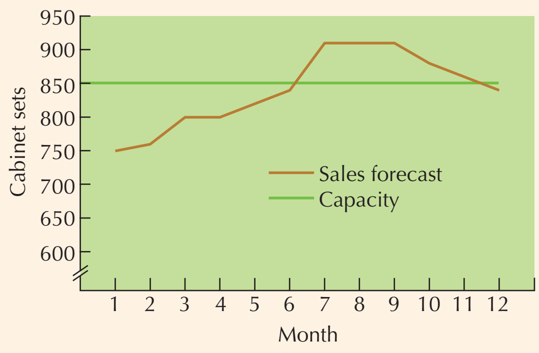


FIGURE 10.3 Graphing Expected Sales Levels versus Capacity

The implication of Figure 10.3 is clear: Pennington won't be able to meet expected demand in the peak months with just regular production.

EXAMPLE 10.3

Translating the Sales Forecast into Resource Requirements at Pennington Cabinets

The next step for Pennington is to translate the sales forecast into resource requirements. The key resource Pennington is concerned about is labor, although other resources could be examined, depending on the needs of the firm. Translating sales into labor hours and, ultimately, workers needed allows Pennington to see how demand drives resource requirements. Table 10.4 shows the start of this process.

TABLE 10.4 Translating Sales into Resource Requirements at Pennington Cabinets

MONTH	SALES FORECAST	SALES (IN LABOR HOURS)	SALES (IN WORKERS)
January	750	15,000	93.75
February	760	15,200	95.00
March	800	16,000	100.00
April	**800** →	**16,000** →	**100.00**
May	820	16,400	102.50
June	840	16,800	105.00
July	910	18,200	113.75
August	910	18,200	113.75
September	910	18,200	113.75
October	880	17,600	110.00
November	860	17,200	107.50
December	840	16,800	105.00

To illustrate, April's demand represents (20 hours per cabinet) $\times$ (800 cabinets) $=$ 16,000 labor hours. If every worker works 160 hours a month, this is the equivalent of (16,000 labor hours)/(160 hours) $=$ 100 workers.

Level, Chase, and Mixed Production Plans

Level production plan
A sales and operations plan in which production is held constant and inventory is used to absorb differences between production and the sales forecast.

Once a firm has translated the sales forecast into resource requirements, the next step is to generate alternative production plans. Three common approaches are level production, chase production, and mixed production plans. The fundamental difference among the three is how production and inventory levels are allowed to vary.

Under a **level production plan,** production is held constant, and inventory is used to absorb differences between production and the sales forecast. This approach is best suited to an

Chase production plan
A sales and operations plan in which production is changed in each time period to match the sales forecast.

Mixed production plan
A sales and operations plan that varies both production and inventory levels in an effort to develop the most effective plan.

environment in which changing the production level is very difficult or extremely costly (e.g., an oil refinery) and the cost of holding inventory is relatively low.

A **chase production plan** is just the opposite. Here production is changed in each time period to match the sales forecast in each time period. The result is that production "chases" demand. This approach is best suited to environments in which holding inventory is extremely expensive or impossible (as with services) or the costs of changing production levels are relatively low.

A mixed production plan falls between these two extremes. Specifically, a **mixed production plan** will vary both production and inventory levels, in an effort to develop the most effective plan.

EXAMPLE 10.4

Generating a Level Production Plan for Pennington Cabinets

After translating the sales forecast into resource requirements (Table 10.4), Pennington management decides to begin its analysis by generating a level production plan. Pennington starts off January with 100 workers and 100 cabinet sets in inventory, and it wants to end the planning cycle with these numbers. Table 10.5 shows a completed level production plan for Pennington Cabinets. Following is a discussion of the highlights of this plan.

TABLE 10.5 Level Production Plan for Pennington Cabinets

MONTH	SALES FORECAST	SALES (IN LABOR HOURS)	SALES (IN WORKERS)	ACTUAL WORKERS	REGULAR PRODUCTION	ALLOWABLE OVERTIME PRODUCTION	OVERTIME PRODUCTION	HIRINGS	LAYOFFS	INVENTORY/ BACK ORDERS
				100.00						100.00
January	750	15,000	93.75	105.00	840.00	84.00	0	5.00	0.00	190.00
February	760	15,200	95.00	105.00	840.00	84.00	0	0.00	0.00	270.00
March	800	16,000	100.00	105.00	840.00	84.00	0	0.00	0.00	310.00
April	800	16,000	100.00	105.00	840.00	84.00	0	0.00	0.00	350.00
May	820	16,400	102.50	105.00	840.00	84.00	0	0.00	0.00	370.00
June	840	16,800	105.00	105.00	840.00	84.00	0	0.00	0.00	370.00
July	910	18,200	113.75	105.00	840.00	84.00	0	0.00	0.00	300.00
August	910	18,200	113.75	105.00	840.00	84.00	0	0.00	0.00	230.00
September	910	18,200	113.75	105.00	840.00	84.00	0	0.00	0.00	160.00
October	880	17,600	110.00	105.00	840.00	84.00	0	0.00	0.00	120.00
November	860	17,200	107.50	105.00	840.00	84.00	0	0.00	0.00	100.00
December	840	16,800	105.00	105.00	840.00	84.00	0	0.00	0.00	100.00
								0	5	
Totals:	10,080				10,080		0	5	5	2,870

Actual Workers and Regular Production

Under the level production plan, the actual workforce is held constant, at 105. Why 105? Because 105 represents the average workforce required over the 12-month planning horizon. By maintaining a workforce of 105 workers, Pennington produces:

$$105(160 \text{ hours per month}/20 \text{ hours per set}) = 840 \text{ sets per month}$$

or:

$$(840 \text{ sets per month})\ (12 \text{ months}) = 10{,}080 \text{ cabinet sets for the year}$$

You may have noticed that this production total matches sales for the entire year. The difference, of course, is in the *timing* of the production and the sales: Inventory builds up when sales are less than the monthly production level and drains down when sales outstrip production. Finally, with 105 workers, Pennington comes close to reaching the regular production maximum of 848 cabinet sets per month but doesn't exceed it.

Hirings and Layoffs

Whenever the workforce level changes, Pennington must hire or release workers. This occurs at two different times in the level production plan. In January, Pennington hires 5 workers to bring the workforce up to 105 from the initial level of 100. To bring the workforce back down to its starting level, Pennington lays off 5 workers at the end of December. While this may seem unrealistic, doing so (at least for calculation purposes) ensures Pennington that it will be able to compare alternative plans under the same beginning and ending conditions.

Inventory Levels

The ending inventory level in any month is calculated as follows:

$$EI_t = EI_{t-1} + RP_t + OP_t - S_t \tag{10.1}$$

where:

EI_t = ending inventory for time period t
RP_t = regular production in time period t
OP_t = overtime production in time period t
S_t = sales in time period t

For January, the ending inventory is:

$$\begin{aligned} EI_{\text{January}} &= EI_{\text{December}} + RP_{\text{January}} + OP_{\text{January}} - S_{\text{January}} \\ &= 100 + 840 + 0 - 750 = 190 \text{ cabinet sets} \end{aligned}$$

Likewise, the ending inventory for February is:

$$\begin{aligned} EI_{\text{February}} &= EI_{\text{January}} + RP_{\text{February}} + OP_{\text{February}} - S_{\text{February}} \\ &= 190 + 840 + 0 - 760 = 270 \text{ cabinet sets} \end{aligned}$$

As expected, the level production plan builds up inventory from January through May (when production exceeds sales) and then drains it down during the peak months of July through December. But look at the ending inventory levels for each month: They are all greater than zero, suggesting that Pennington is holding more cabinet sets than it needs to meet the forecast. This may seem wasteful at first glance. But remember that Pennington is developing a plan based on *forecasted* sales. The extra inventory protects Pennington if actual sales turn out to be higher than the forecast. Otherwise, Pennington might not be able to meet all the demand, resulting in back orders or even lost sales.

The Cost of the Plan

Of course, Pennington has no way of knowing at this point whether a level production plan is the best plan or not. To do so, management will need some way to compare competing plans. Management starts this process by calculating the costs of the level production plan, using the planning values in Table 10.3:

REGULAR PRODUCTION COSTS	
10,080 cabinet sets × ($2,000) =	$20,160,000
HIRING AND LAYOFF COSTS	
5 hirings × ($1,750) + 5 layoffs × ($1,500) =	$16,250
INVENTORY HOLDING COSTS	
2,870 cabinet sets × ($40) =	$114,800
Total:	$20,291,050

EXAMPLE 10.5

Generating a Chase Production Plan for Pennington Cabinets

Table 10.6 shows a chase production plan for Pennington Cabinets. Notice that the first four columns are identical to those for the level production plan (Table 10.5). However, results for the remaining columns are quite different:

- Actual workforce production and overtime production vary so that total production essentially matches sales for each month. Because total production "chases" sales, inventory never builds up, as it did under the level production plan. In fact, it never gets higher than 106 cabinet sets.
- From July through November, monthly sales are higher than the maximum regular production level of 848. Under the chase approach, Pennington will need to make up the difference through overtime production.
- While the chase production plan keeps inventory levels low, it results in more hirings and layoffs and in overtime production costs.
- Because Pennington can't hire fractional workers, the company can't always *exactly* match production to sales. In this example, Pennington ends up with slightly more cabinet sets in inventory at the end of the planning period (106 versus 100). Still, this is close enough to compare with other plans.

TABLE 10.6 Chase Production Plan for Pennington Cabinets

MONTH	SALES FORECAST	SALES (IN LABOR HOURS)	SALES (IN WORKERS)	ACTUAL WORKERS	REGULAR PRODUCTION	ALLOWABLE OVERTIME PRODUCTION	OVERTIME PRODUCTION	HIRINGS	LAYOFFS	INVENTORY/ BACK ORDERS
				100.00						100.00
January	750	15,000	93.75	94.00	752.00	75.20	0	0.00	6.00	102.00
February	760	15,200	95.00	95.00	760.00	76.00	0	1.00	0.00	102.00
March	800	16,000	100.00	100.00	800.00	80.00	0	5.00	0.00	102.00
April	800	16,000	100.00	100.00	800.00	80.00	0	0.00	0.00	102.00
May	820	16,400	102.50	103.00	824.00	82.40	0	3.00	0.00	106.00
June	840	16,800	105.00	105.00	840.00	84.00	0	2.00	0.00	106.00
July	910	18,200	113.75	106.00	848.00	84.80	62	1.00	0.00	106.00
August	910	18,200	113.75	106.00	848.00	84.80	62	0.00	0.00	106.00
September	910	18,200	113.75	106.00	848.00	84.80	62	0.00	0.00	106.00
October	880	17,600	110.00	106.00	848.00	84.80	32	0.00	0.00	106.00
November	860	17,200	107.50	106.00	848.00	84.80	12	0.00	0.00	106.00
December	840	16,800	105.00	105.00	840.00	84.00	0	0.00	1.00	106.00
								0	5	
Totals:	10,080				9,856		230	12	12	1,256

The cost calculations for the chase production plan follow. In this case, 9,856 cabinet sets were produced through regular production, and the remaining 230 were produced using overtime:

REGULAR PRODUCTION COSTS	
9,856 cabinet sets × ($2,000) =	$19,712,000
OVERTIME PRODUCTION COSTS	
230 cabinet sets × ($2,062) =	$474,260
HIRING AND LAYOFF COSTS	
12 hirings × ($1,750) + 12 layoffs × ($1,500) =	$39,000
INVENTORY HOLDING COSTS	
1,256 cabinet sets × ($40) =	$50,240
Total:	$20,275,500

EXAMPLE 10.6

Generating a Mixed Production Plan for Pennington Cabinets

In the real world, the best plan will probably be something other than a pure level or pure chase plan. A mixed production plan varies both production and inventory levels in an effort to develop the best plan. Because there are many different ways to do this, the number of potential mixed plans is essentially limitless.

Suppose Pennington's workers have strong reservations about working overtime during the summer months, a chief requirement under the chase plan. The mixed production plan shown in Table 10.7 limits overtime to just 12 cabinet sets per month in October and November. This is just one example of the type of qualitative issues a management team must consider when developing a sales and operations plan.

TABLE 10.7 Mixed Production Plan for Pennington Cabinets

MONTH	SALES FORECAST	SALES (IN LABOR HOURS)	SALES (IN WORKERS)	ACTUAL WORKERS	REGULAR PRODUCTION	ALLOWABLE OVERTIME PRODUCTION	OVERTIME PRODUCTION	HIRINGS	LAYOFFS	INVENTORY/ BACK ORDERS
				100.00						100.00
January	750	15,000	93.75	100.00	800.00	80.00	0	0.00	0.00	150.00
February	760	15,200	95.00	100.00	800.00	80.00	0	0.00	0.00	190.00
March	800	16,000	100.00	103.00	824.00	82.40	0	3.00	0.00	214.00
April	800	16,000	100.00	106.00	848.00	84.80	0	3.00	0.00	262.00
May	820	16,400	102.50	106.00	848.00	84.80	0	0.00	0.00	290.00
June	840	16,800	105.00	106.00	848.00	84.80	0	0.00	0.00	298.00
July	910	18,200	113.75	106.00	848.00	84.80	0	0.00	0.00	236.00
August	910	18,200	113.75	106.00	848.00	84.80	0	0.00	0.00	174.00
September	910	18,200	113.75	106.00	848.00	84.80	0	0.00	0.00	112.00
October	880	17,600	110.00	106.00	848.00	84.80	12	0.00	0.00	92.00
November	860	17,200	107.50	106.00	848.00	84.80	12	0.00	0.00	92.00
December	840	16,800	105.00	106.00	848.00	84.80	0	0.00	0.00	100.00
								0	6	
Totals:	10,080				10,056		24	6	6	2,210.00

The cost of the mixed production strategy is:

REGULAR PRODUCTION COSTS	
10,056 cabinet sets × ($2,000) =	$20,112,000
OVERTIME PRODUCTION COSTS	
24 cabinet sets × ($2,062) =	$49,488
HIRING AND LAYOFF COSTS	
6 hirings × ($1,750) + 6 layoffs × ($1,500) =	$19,500
INVENTORY HOLDING COSTS	
2,210 cabinet sets × ($40) =	$88,400
Total:	$20,269,388

Bottom-Up Planning

Top-down planning works well in situations where planners can use a single set of planning values to estimate resource requirements and costs. But what happens when this is not the case? As we noted earlier, bottom-up planning is used when the products or services have different resource requirements *and* the mix is unstable from one period to the next. The steps for generating a bottom-up plan are similar to those for creating a top-down plan. The main difference is that the resource requirements must be evaluated individually for each product or service and then added up across all products or services to get a picture of overall requirements.

EXAMPLE 10.7

Bottom-up planning at Philips Toys

Philips Toys produces a summer toy line and a winter toy line. Machine and labor requirements for each product line are given in Table 10.8.

TABLE 10.8 Machine and Labor Requirements for Philips Toys

PRODUCT LINE	MACHINE HOURS/UNIT	LABOR HOURS/UNIT
Summer toys	0.75	0.25
Winter toys	0.85	2.00

Both product lines have fairly similar machine hour requirements. However, they differ greatly with regard to labor requirements; products in the winter line need, on average, eight times as much labor as products in the summer line.

The difference in labor requirements becomes important when the product mix changes. Look at the data in Table 10.9. Even though the *aggregate* forecast across both product lines is 700 units each month, the product mix changes as Philips moves into and then out of the summer season. The impact on resource requirements can be seen in the labor hours needed each month.

TABLE 10.9 Forecasted Demand and Resulting Resource Needs for Philips Toys

	Forecast				
MONTH	SUMMER LINE	WINTER LINE	AGGREGATE FORECAST	MACHINE HOURS	LABOR HOURS
January	0	700	700	595	1,400
February	100	600	700	585	1,225
March	500	200	700	545	525
April	700	0	700	525	175
May	700	0	700	525	175
June	700	0	700	525	175
July	700	0	700	525	175
August	500	200	700	545	525
September	400	300	700	555	700
October	200	500	700	575	1,050
November	0	700	700	595	1,400
December	0	700	700	595	1,400

Load profile
A display of future capacity requirements based on released and/or planned orders over a given span of time.

Figure 10.4 graphs the projected machine hours and labor hours shown in Table 10.9. Such graphs are often referred to as load profiles. A **load profile** is a display of future capacity requirements based on released and/or planned orders over a given span of time.[2] As the load profiles suggest, machine hour requirements are fairly constant throughout the year. This is because both product lines have similar machine time requirements. In contrast, the load profile for labor dips dramatically in the summer months, reflecting the lower labor requirements associated with the summer product line.

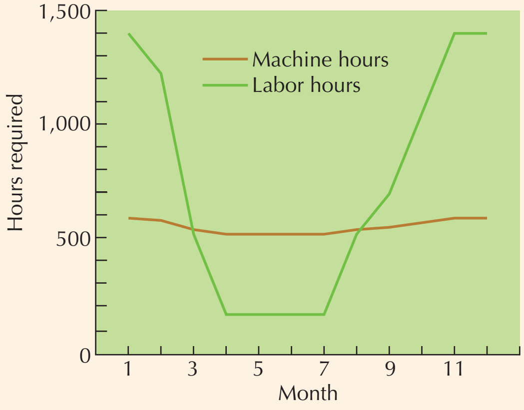


FIGURE 10.4 Load Profiles at Philips Toys

[2]Ibid.

To develop a sales and operations plan, Philips will need to maintain a separate set of planning values for each product line it produces and then total up the requirements. The rest of the planning process will be very similar to top-down planning. Philips will probably have to choose between adjusting the workforce to avoid excess labor costs in the summer months and finding some way to smooth the labor requirements, perhaps by making more winter toys in the summer months. This, however, will drive up inventory levels.

Cash Flow Analysis

Net cash flow
The net flow of dollars into or out of a business over some time period.

One of the key benefits of S&OP is that it expresses business plans in a common language that all partners can understand. Consider for instance the finance area. Among its many responsibilities, finance is charged with making sure that the business has the cash it needs to carry out the sales and operations plan and that any excess cash is put to good use. Finance personnel are therefore very interested in assessing the net cash flow for any production plan. **Net cash flow** is defined as the net flow of dollars into or out of a business over some time period:

$$\text{Net cash flow} = \text{cash inflows} - \text{cash outflows} \tag{10.2}$$

EXAMPLE 10.8
Cash Flow Analysis at Pennington Cabinets

Pennington sells each cabinet set for $2,800, on average. Management has already determined that the regular production cost for a cabinet set is $2,000, the overtime production cost is $2,062, and the monthly holding cost per cabinet set is $40 (Table 10.3).

Now suppose that Pennington incurs these revenues and expenses in the month in which they occur. That is, each sale of a cabinet set generates a cash *inflow* of $2,800, and each cabinet set produced and each cabinet set held in inventory generate cash *outflows* of $2,000 ($2,062 if overtime is used) and $40, respectively. Table 10.10 shows a simplified cash flow analysis for the mixed production plan in Table 10.7.

TABLE 10.10 Cash Flow Analysis for Pennington Cabinets, Mixed Production Plan

MONTH	SALES FORECAST	REGULAR PRODUCTION	OVERTIME PRODUCTION	INVENTORY/ BACK ORDERS	CASH INFLOWS	CASH OUTFLOWS	NET FLOW	CUMULATIVE NET FLOW
January	750	800	0	150	2,100,000	1,606,000	494,000	494,000
February	760	800	0	190	2,128,000	1,607,600	520,400	1,014,400
March	800	824	0	214	2,240,000	1,656,560	583,440	1,597,840
April	800	848	0	262	2,240,000	1,706,480	533,520	2,131,360
May	820	848	0	290	2,296,000	1,707,600	588,400	2,719,760
June	840	848	0	298	2,352,000	1,707,920	644,080	3,363,840
July	910	848	0	236	2,548,000	1,705,440	842,560	4,206,400
August	910	848	0	174	2,548,000	1,702,960	845,040	5,051,440
September	910	848	0	112	2,548,000	1,700,480	847,520	5,898,960
October	880	848	12	92	2,464,000	1,724,424	739,576	6,638,536
November	860	848	12	92	2,408,000	1,724,424	683,576	7,322,112
December	840	848	0	100	2,352,000	1,700,000	652,000	7,974,112

To illustrate, the net cash flow calculation for January is:

$$\begin{aligned}
\text{Net cash flow} &= \text{cash inflows} - \text{cash outflows} \\
&= \text{Sales revenues} - \text{regular production costs} - \text{overtime production costs} \\
&\quad - \text{inventory holding costs} \\
&= \$2{,}800(750 \text{ cabinet sets}) - \$2{,}000(800 \text{ cabinet sets}) \\
&\quad - \$2{,}062(0 \text{ cabinet sets}) - \$40(150 \text{ cabinet sets}) \\
&= \$2{,}100{,}000 - \$1{,}600{,}000 - \$0 - \$6{,}000 = \$494{,}000
\end{aligned}$$

Applying the same logic, the net cash flow in February is $520,400. Finally, Pennington can calculate the cumulative net cash flow through February as $494,000 + $520,000 = $1,014,400. The cash flow analysis expresses the sales and operations plan in terms that are meaningful to financial managers. In this case, the cabinet set business is expected to generate anywhere from around $500,000 to $850,000 in positive cash flow each month and nearly $8 million over the course of the year. These additional funds can be used to cover other expenses, retire debt, or perhaps support additional business investments.

Now let's consider an alternative scenario, shown in Table 10.11. Everything, including total sales for the 12-month planning period, is the same as before, *except* now the *timing* of the sales has changed. Specifically, sales in the first half of the year are much lower than previously, while sales increase dramatically in the last half.

The new sales pattern results in *negative* net cash flows for the first three months of the year and a cumulative negative net cash flow that does not disappear until May. In this case, finance will need to find the funds necessary to support this particular plan, or the company will need to develop an alternative sales and operations plan that is not as burdensome. Finally, you may have noticed that the net cash flow at the end of the year is lower than before ($7,766,512 versus $7,974,112). This difference is due to the fact that the second plan results in higher inventory holding costs. Figure 10.5 compares the cash flow results for Tables 10.10 and 10.11.

TABLE 10.11 Cash Flow Analysis for Pennington Cabinets, *Different Sales Pattern*

MONTH	SALES FORECAST	REGULAR PRODUCTION	OVERTIME PRODUCTION	INVENTORY/ BACK ORDERS	CASH IN FLOWS	CASH OUTFLOWS	NET FLOW	CUMULATIVE NET FLOW
January	500	800	0	400	1,400,000	1,616,000	(216,000)	(216,000)
February	520	800	0	680	1,456,000	1,627,200	(171,200)	(387,200)
March	550	824	0	954	1,540,000	1,686,160	(146,160)	(533,360)
April	700	848	0	1,102	1,960,000	1,740,080	219,920	(313,440)
May	880	848	0	1,070	2,464,000	1,738,800	725,200	411,760
June	960	848	0	958	2,688,000	1,734,320	953,680	1,365,440
July	1,040	848	0	766	2,912,000	1,726,640	1,185,360	2,550,800
August	1,040	848	0	574	2,912,000	1,718,960	1,193,040	3,743,840
September	1,040	848	0	382	2,912,000	1,711,280	1,200,720	4,944,560
October	980	848	12	262	2,744,000	1,731,224	1,012,776	5,957,336
November	970	848	12	152	2,716,000	1,726,824	989,176	6,946,512
December	900	848	0	100	2,520,000	1,700,000	820,000	7,766,512

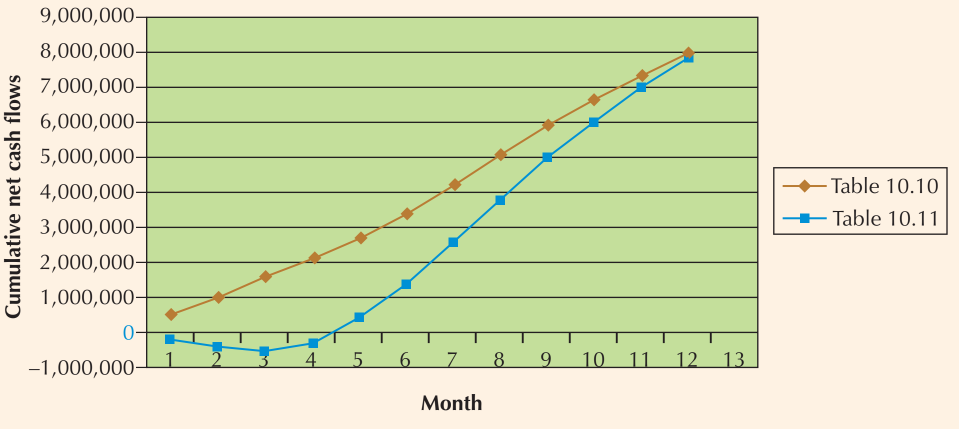


FIGURE 10.5 Cumulative Net Cash Flows under Two Different Sales Scenarios

10.3 ORGANIZING FOR AND IMPLEMENTING S&OP

We have spent a fair amount of time describing the basic calculations associated with S&OP. But S&OP is more than just "running the numbers." Richard Ling put it best when he stated, "S&OP is a people process supported by information."[3] In this section, we address some critical organizational questions associated with S&OP:

- How do we choose between alternative plans?
- How often should S&OP be done?
- How do we implement S&OP in our business environment?

Choosing between Alternative Plans

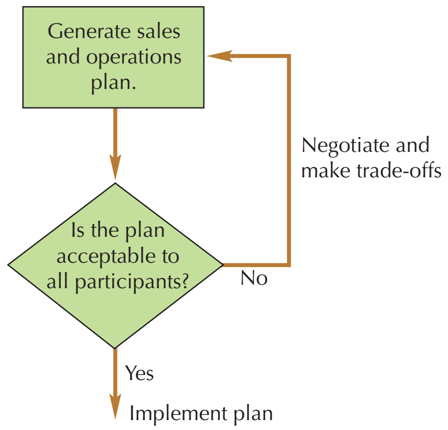
Coming up with a suitable sales and operations plan is an iterative process. An organization may have to change a plan several times before coming up with a plan that is acceptable to all parties. This fine-tuning often means that decision makers will need to make trade-offs. Figure 10.6 illustrates this idea.

A classic example is the trade-off between inventory and customer service. Suppose that after reviewing a plan, finance wants to reduce inventory levels further to bring down costs. Marketing might raise concerns that this could potentially hurt customer service. All parties would have to come to some agreement concerning the right balance between the two competing objectives—cost and customer service. As another example, operations might want marketing to use pricing and promotion to smooth out peaks and valleys in demand. S&OP could be used to see if the cost of these pricing and promotion efforts is more than offset by improvements in production and inventory costs.

In choosing a sales and operations plan, managers must consider all aspects of a plan, not just costs. For example:

- What impact will the plan have on supply chain partners such as key suppliers and transportation providers? This could be particularly important if production levels vary considerably from one period to the next.
- What are cash flows like? Some plans may be profitable at the end of the planning cycle but still include periods in which cash expenses exceed revenues. We discussed earlier how cash flow analysis can be used to evaluate such plans.
- Do the supply chain partners and the firm itself have the space needed to hold any planned inventories?
- Does the plan contain significant changes in the workforce? If so, what would be the impact on workforce satisfaction and productivity? Could the HR department handle the additional workload?
- How flexible is the plan? That is, how easy or difficult would it be to modify the plan as conditions warrant?

FIGURE 10.6
Fine-Tuning the Sales and Operations Plan



[3] R. Ling, "For True Enterprise Integration, Turn First to SOP," *APICS—The Performance Advantage* 10, no. 3 (March 2000): 40–45.

This is just a small sample of the kinds of questions that need to be addressed, but it raises a key point: *Sales and operations plans help managers make decisions. They do not make the decisions for managers.*

EXAMPLE 10.9

Selecting a Plan at Pennington Cabinets

Table 10.12 summarizes the costs, strengths, and weaknesses of the three alternative production strategies we developed for Pennington Cabinets in Examples 10.4 through 10.6. For practical purposes, the costs are too close for us to say that one plan is clearly cheapest. After all, these are plans based on *forecasts* and *planning* values that represent, at best, rough estimates of resource requirements and costs. We can almost guarantee that actual results will be different.

TABLE 10.12 Summary of Alternative Plans at Pennington Cabinet

	LEVEL PLAN	CHASE PLAN	MIXED PLAN
Regular production costs	$20,160,000	$19,712,000	$20,112,000
Overtime production costs	0	$474,260	$49,488
Hiring and layoff costs	$16,250	$39,000	$19,500
Inventory costs	$114,800	$50,240	$88,400
Total costs	$20,291,050	$20,275,500	$20,269,388
Key factors	Flat production level. Inventory levels grow as high as 370 cabinet sets.	Minimal inventory. Significant overtime required in peak months.	Reasonably stable production. Inventory levels grow, but not as high as under a pure level approach. Some overtime required.

To choose a plan, then, Pennington will need to consider other factors. The level plan has the advantage of consistency because the same amount is made each and every month. This eases production planning and allows for workforce stability for Pennington and its partners. Furthermore, it allows Pennington to avoid expensive overtime—but at the cost of holding additional inventory. The build-up of inventory under the level plan does pose a risk: What if actual demand takes a sharp downturn later in the year? If this happens, Pennington will have to cut production drastically or risk being stuck with expensive unwanted inventory.

The chase plan is just the opposite. Inventory levels never rise much above 100 (the starting level), but production levels vary anywhere from 752 in January to 910 in each month of the third quarter. Such instability in production and workforce levels may have unanticipated consequences.

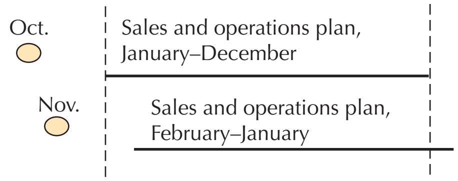
The mixed plan strikes a balance between these extremes. Inventory levels increase over the slower months, but not as drastically as under the level approach. Similarly, the mixed plan uses overtime production, but not to the same extent as the chase plan. Based on these results, Pennington management might select a plan, or even develop another mixed plan in order to derive an even better solution.

Rolling Planning Horizons

Rolling planning horizon
A planning approach in which an organization updates its sales and operations plan regularly, such as on a monthly or quarterly basis.

Sales and operations plans *must* be updated on a regular basis to remain current. Most firms do this by establishing a **rolling planning horizon** which requires them to update the sales and operations plan regularly, usually on a monthly basis. For example, suppose that it is now the beginning of October, and Pennington has just completed the sales and operations plan for January through December of next year. (*Note:* October, November, and December are so close in time that they fall under detailed planning and control, discussed in Chapter 12.) One month later at the beginning of November, Pennington's planning team might come together and

FIGURE 10.7
Updating the Sales and Operations Plan



revisit the plan, rolling it forward one month and planning for February through January. Figure 10.7 illustrates the idea. By establishing a rolling planning horizon, a firm can fine-tune its sales and operations plan as new information becomes available.

Implementing S&OP in an Organization

We have already discussed the steps involved in generating a sales and operations plan. But before these steps can occur, managers have to commit themselves to the S&OP process. Furthermore, managers have to realize that excellent S&OP is an organizational skill that can take months, or even years, to develop. Ling describes the implementation of S&OP as a three-phase process:[4]

- Developing the foundation
- Integrating and streamlining the process
- Gaining a competitive advantage

Developing the Foundation. In the first phase of implementing S&OP, companies build the managerial support and infrastructure needed to make S&OP a success. Key steps include educating all participants about the benefits of S&OP, identifying the appropriate product or service families to plan around, and establishing the information systems needed to provide accurate planning values. Ling stresses the point that even though this phase typically takes six to nine months, many companies never progress further because "they expect the process to work immediately and don't establish the right quality and timing of information."[5]

Integrating and Streamlining the Process. In the second phase of implementing S&OP, S&OP becomes part of the organization's normal planning activities. Managers become accustomed to updating the plan on a regular basis, and more importantly, they use the planning results to guide key demand and resource decisions. The sales and operations plan becomes a focal point for cross-functional coordination. Managers also look for ways to improve the S&OP process further. As Ling puts it, "Because implementing a process like this may not yield the right structure and organization on the first attempt, some restructuring and streamlining usually occurs at this point."[6]

Gaining a Competitive Advantage. In the final phase of implementing S&OP, a few companies reach the point where their S&OP process actually becomes a source of competitive advantage—a core competency, if you will. Companies know they have reached this last phase when:[7]

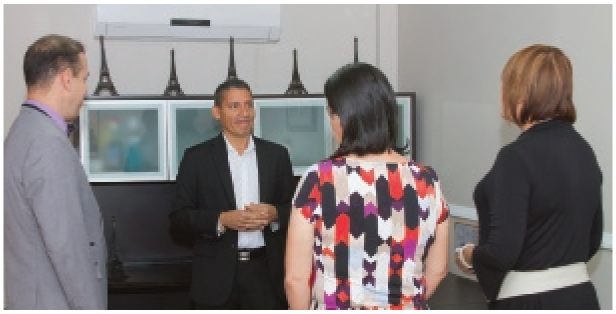
- There is a well-integrated demand planning process, including the use of forecasting models.
- Continuous improvement is planned and monitored as an integral part of the S&OP process.
- Capital equipment planning can be triggered at any time.
- What-if analyses are a way of life, and the S&OP database is networked to provide ready access to S&OP data.

The last two points deserve further discussion. Capital equipment decisions typically fall under the auspices of strategic planning. Yet S&OP can give managers an "early warning" when changes in long-term capacity are needed. Pennington's sales and operations plans (Examples 10.4 through 10.6) all show that demand is bumping up against the company's capacity limits. Top management can use this information to start planning for additional investments in manufacturing capacity.

Finally, most organizations that perform S&OP for any length of time end up developing relatively sophisticated databases and decision tools to support their efforts. These tools, in turn,

[4]Ibid.
[5]Ibid.
[6]Ibid.
[7]Ibid.

PROFESSIONAL PROFILE



Courtesy of Joseph E. Perez Rosario

ESTEBAN PEREZ SUAREZ, PATHEON

As a leading contract development and manufacturing organization (CDMO) for the pharmaceutical industry, Patheon provides pharma and biotech companies with the resources and expertise needed to develop new drugs, as well as the capability to manufacture existing drugs on a commercial scale. With nearly 30 sites worldwide supporting everything from the development of biologics to high-volume tablet production and packaging, Patheon's management recognizes the importance of having an effective S&OP process in place at each of its manufacturing sites.

Enter Esteban Perez Suarez, the senior director of global S&OP at Patheon. In this role, Esteban and his team have developed a best-in-class S&OP process that can be adapted to the unique needs of each site. Sites that have implemented the new S&OP process are seeing improved operational performance, including improved on-time delivery and lower costs.

While Esteban's current role has him focused on S&OP, his operations and supply chain experience goes even deeper. Esteban joined Patheon in 2009 as a supply chain director, and then served as the interim site manager at the Manati, Puerto Rico plant. Before that, he was a manufacturing and materials manager in the pharmaceutical industry, and even served as an instructor for the Institute for Supply Management (ISM).

Given his background in education, it shouldn't be surprising that Esteban is a strong believer in continued learning: "To be successful, you should look for opportunities to learn on the job as well as in the classroom. It's a journey, and you start by adding pieces."

often give managers greater power to perform what-if analyses, in which the sales forecasts or even the planning values themselves can be varied to see how the plan reacts. The result is even more robust sales and operations plans.

The *Professional Profile* describes how Esteban Perez Suarez, senior director of global S&OP at Patheon, has helped implement sales and operations planning at his company, a worldwide manufacturer of pharmaceutical products.

10.4 SERVICES CONSIDERATIONS

In many ways, S&OP is even more critical in a service environment than it is in manufacturing. Service outputs cannot be built ahead of time and stored in inventory. An empty airline seat or an unused hour of a service technician's time is lost forever. For this reason, service capacity must be closely matched to demand in every period. The effect is to limit most services to following some form of a chase production plan.

That said, services have many options for aligning resources with demand. These options fall into two camps:

- Making sales match capacity
- Making capacity (typically the workforce) match sales

Making Sales Match Capacity

Yield management
An approach that services commonly use with highly perishable "products," in which prices are regularly adjusted to maximize total profit.

Firms have long used pricing and promotion to bring sales in line with production capacity. **Yield management** is an approach that services commonly use with *highly perishable* "products," such as airline seats and hotel rooms. These services have a real incentive to make sure every unit of capacity—whether it is an airline seat on the next flight or a hotel room for tonight—contributes to the firm's bottom line.

GoodShoot/AGE Fotostock

Services with highly perishable "products," such as a ski resort, often vary the price of their services to smooth out demand and maximize profits.

Put simply, the goal of yield management is to maximize total profit, where:

Total profit = (average profit per service unit sold) (number of service units sold)

Here's how it works. When demand levels are lower than expected, yield management systems boost demand by lowering the price, but *only if* the expected result is an increase in

Claudia Hechtenberg/Agencja Fotograficzna Caro/Alamy Stock Photo

By selling furniture unassembled, IKEA is able to offload part of the manufacturing task to the consumer, thereby holding down costs.

total profit. Conversely, when demand is higher than expected, prices are raised, but *only if* the expected result is higher total profit.

The idea seems pretty straightforward, but what makes yield management distinctive is the level of sophistication involved. The airline and hotel industries, in particular, have complex yield management systems that regularly and automatically adjust the price of their services for unbooked capacity in an effort to maximize total profit. If you have ever booked a hotel room or made a plane reservation, only to have the price for new reservations change two days later, you have seen yield management in action.

Tiered workforce
A strategy used to vary workforce levels, in which additional full-time or part-time employees are hired during peak demand periods, while a smaller permanent staff is maintained year-round.

Offloading
A strategy for reducing and smoothing out workforce requirements that involves having customers perform part of the work themselves.

Making Capacity Match Sales

We have already seen how overtime can be used to vary capacity. Another example is to use a **tiered workforce.** For example, some service organizations hire additional full-time or part-time employees during peak demand periods, while maintaining a smaller permanent staff year-round. This is common in the retailing, hospitality, and agricultural industries.

Other services use **offloading** to shift part of the work to the customer. Examples include companies that have customers deliver and assemble their own furniture (e.g., IKEA) and handle their own financial transactions online. This *reduces* overall workforce requirements for the service firm, and it also helps to *smooth out* workforce requirements. This is because the customer acts like a part-time employee, showing up just when the demand occurs.

EXAMPLE 10.10
Service Offloading at Adam's Carpet Cleaning Service

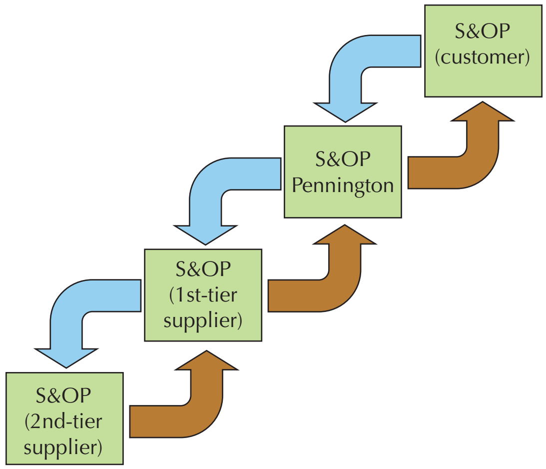
It takes Adam's Carpet Cleaning Service an average of four hours to clean the carpets in a home. This includes three hours of actual cleaning time plus one hour to move the furniture out of the way and then back into position. Adam's is considering modifying its service so that the customer takes responsibility for moving the furniture, in effect offloading 25% of the workload. The impact on Adam's labor hours can be seen in Table 10.13.

TABLE 10.13 Impact of Customer Offloading at Adam's Carpet Cleaning Service

		Labor Hours Needed	
MONTH	FORECAST	NO OFFLOAD TO CUSTOMER	25% OFFLOADED TO CUSTOMER
1	60	240	180
2	55	220	165
3	50	200	150
4	50	200	150
5	30	120	90
6	30	120	90
7	25	100	75
8	30	120	90
9	40	160	120
10	40	160	120
11	45	180	135
12	55	220	165
	Average:	170	127.5
	Lowest:	100	75
	Highest:	240	180
	Difference:	140	105

Average monthly labor requirements drop by 25%, and the absolute difference between the highest and lowest months drops by 25%. Of course, Adam's would need to balance the potential cost savings against the lowered revenues associated with the new service—after all, the customer can't be expected to work for free.

FIGURE 10.8
Linking S&OP Up and Down the Supply Chain



10.5 LINKING S&OP THROUGHOUT THE SUPPLY CHAIN

Earlier, we noted that the S&OP process should consider not only the impact on various parties *within* the firm but also the impact on *outside* parties—the firm's supply chain partners. It makes little sense, for example, to try to implement a plan that cannot be supported by key suppliers or service providers who move or store the goods. This represents the potential downside of *not* considering supply chain partners when developing a plan.

But there is an upside to linking the S&OP process with supply chain partners. For one thing, coordinating plans across the supply chain can help firms do a better job of improving overall supply chain performance, particularly in the area of cost. Pennington, for example, might discover that suppliers are willing to give the company substantial price discounts if Pennington stabilizes its orders for material—something easier to achieve under a level production plan.

Second, linking plans can help eliminate uncertainty, thereby improving synchronization between supply chain partners. For instance, once Pennington decides on a sales and operations plan, its supply chain partners can use the information to plan *their own* activities. By tying their plans to Pennington's, key suppliers can avoid "guessing" what demand will be. Even better, Pennington might try to establish linkages with its downstream partners—that is, its customers—in an effort to get even more accurate sales forecasts. If you've read Chapter 9, you might be saying to yourself, "That sounds a lot like what collaborative planning, forecasting, and replenishment (CPFR) hopes to accomplish," and you'd be right. In fact, the logical ties between CPFR and S&OP are so strong that a leading industry group has put together a road map that describes how businesses can integrate these efforts.[8]

Optimization model
A class of mathematical models used when the user seeks to optimize some objective function subject to some constraints.

Objective function
A quantitative function that an optimization model seeks to optimize (i.e., maximize or minimize).

Of course, the information can flow downstream as well as upstream. If, for example, a key supplier increases its capacity, such information would be useful for Pennington's S&OP effort. This linking of S&OP throughout the supply chain is shown in Figure 10.8. Sharing of plans already takes place in many industries, with the results being greater coordination, improved productivity, and fewer disruptions in the flow of goods and services through the supply chain.

10.6 APPLYING OPTIMIZATION MODELING TO S&OP

Constraint
A quantifiable condition that places limitations on the set of possible solutions. The solution to an optimization model is acceptable only if it does not break any of the constraints.

In Chapter 8, we introduced optimization models. As you will recall, **optimization models** are a class of mathematical models used when the user seeks to optimize some objective function subject to some constraints. An **objective function** is a quantitative function that we hope to optimize (for example, we might want to maximize profits or minimize costs). **Constraints** are quantifiable conditions that place limitations on the set of possible solutions (demand that must

[8]*Linking CPFR and S&OP: A Roadmap to Integrated Business Planning*, 2010, **www.gs1us.org/DesktopModules/Bring2mind/DMX/Download.aspx?command=core_download&entryid=433&language=en-US&PortalId=0&TabId=134.**

be met, limits on materials or equipment time, etc.). A solution is acceptable only if it does not break any of the constraints.

In order for optimization modeling to work, the user must be able to state in mathematical terms both the objective function and the constraints. Once the user is able to do this, special modeling algorithms can be used to generate solutions.

S&OP is ideally suited to such analyses. In particular, managers may be interested in understanding what pattern of resource decisions—labor, inventory, machine time, etc.—will result in the lowest total cost while still meeting the sales forecast. In Example 10.11, we show how Microsoft Excel's Solver function can be used to apply optimization modeling to S&OP.

EXAMPLE 10.11

S&OP Optimization Modeling at Bob Irons Industries

Bob Irons Industries manufactures and sells DNA testing equipment for use in cancer clinics around the globe. Bob, the owner and CEO, has developed a spreadsheet (Figure 10.9) to help calculate the costs associated with various sales and operations plans.

It's worth taking a few minutes to see how Bob's spreadsheet works. The cells that contain the planning values are highlighted, as are the columns for the sales forecast, hirings, and layoffs, indicating that Bob can change these cells. The remaining numbers are all calculated values.

To illustrate, the calculations for January are as follows:

$$\text{Sales (in labor hours)} = \text{B15} * \text{D3} = 500 \text{ units} * 20 \text{ hours per unit}$$
$$= 10{,}000 \text{ labor hours}$$

$$\text{Sales (in worker hours)} = \frac{\text{C15}}{\text{D4}} = \frac{10{,}000 \text{ labor hours}}{160 \text{ hours per worker}} = 62.5 \text{ workers}$$

	A	B	C	D	E	F	G	H	I
1	**S&OP Spreadsheet**								
2									
3			Labor hrs. per unit:	20					
4			Worker hrs. per month:	160					
5			Beginning & ending workforce:	100					
6			Beginning & ending inventory:	100					
7						Total plan cost			
8			Production cost per unit:	$550.00		$6,600,000			
9			Hiring cost:	$300.00		$7,500			
10			Layoff cost:	$200.00		$5,000			
11			Holding cost per unit per month:	$4.00		$54,800			
12						**$6,667,300**	**Grand total**		
13	Month	Sales Forecast	Sales (in labor hrs.)	Sales (in workers)	Actual Workers	Actual Production	Hirings	Layoffs	Ending Inventory/ Back Orders
14					100				100
15	January	500	10,000	62.5	125.00	1,000.00	25.00	0.00	600.00
16	February	600	12,000	75	125.00	1,000.00	0.00	0.00	1,000.00
17	March	700	14,000	87.5	125.00	1,000.00	0.00	0.00	1,300.00
18	April	800	16,000	100	125.00	1,000.00	0.00	0.00	1,500.00
19	May	900	18,000	112.5	125.00	1,000.00	0.00	0.00	1,600.00
20	June	1,000	20,000	125	125.00	1,000.00	0.00	0.00	1,600.00
21	July	1,000	20,000	125	125.00	1,000.00	0.00	0.00	1,600.00
22	August	1,100	22,000	137.5	125.00	1,000.00	0.00	0.00	1,500.00
23	September	1,200	24,000	150	125.00	1,000.00	0.00	0.00	1,300.00
24	October	1,300	26,000	162.5	125.00	1,000.00	0.00	0.00	1,000.00
25	November	1,400	28,000	175	125.00	1,000.00	0.00	0.00	600.00
26	December	1,500	30,000	187.5	125.00	1,000.00	0.00	0.00	100.00
27							0.00	25.00	
28	**Totals:**	**12,000**				**12,000.00**	**25.00**	**25.00**	**13,700.00**
29			**Average =**	**125**					

FIGURE 10.9 S&OP Spreadsheet for Bob Irons Industries (Level Plan)

$$\text{Actual workers} = \text{E14} + \text{G15} - \text{H15} = 100 \text{ beginning workers} + 25 \text{ hires} - 0 \text{ layoffs}$$
$$= 125 \text{ workers}$$
$$\text{Actual production} = \frac{\text{E15*D4}}{\text{D3}} = \frac{125 \text{ workers} * 160 \text{ hours per month}}{20 \text{ hours per unit}} = 1{,}000 \text{ units}$$
$$\text{Ending inventory} = \text{I14} + \text{F15} - \text{B15} = 100 + 1{,}000 - 500 = 600 \text{ units}$$

The plan shown in Figure 10.9 is, in fact, a level production plan with a total cost of $6,667,300. Looking at the plan, Bob wonders if he can do better. As an alternative, Bob updates the spreadsheet to show a chase plan. The results are shown in Figure 10.10.

The results surprise Bob: The total cost for the chase plan is exactly the same as the cost for the level plan. He wonders if there is indeed a better solution that meets all of the constraints.

Bob decides to use the Solver function of Excel to find the lowest-cost solution. To start the process, Bob takes a few moments to identify the objective function, decision variables, and constraints for the optimization model and to match them up to his spreadsheet (Table 10.14).

As Table 10.14 indicates, Bob will need to set up the Solver function to minimize total costs (cell F12) by changing the hiring and layoff values (cells G15–H26). At the same time, the cells containing the ending inventory values must stay at or above 0 for the first 11 months (cells I15–I25), and at or above 100 in the last month (cell I26).

Furthermore, Bob wants to make sure that none of the hiring or layoff numbers (cells G15–H26) is negative. This may seem like a strange requirement, but unless Bob does this, the model will try to reduce costs forever by endlessly offsetting a negative hire with a negative layoff, each iteration of which would "save" $300 + $200 = $500.

	A	B	C	D	E	F	G	H	I
1	**S&OP Spreadsheet**								
2									
3			Labor hrs. per unit:	20					
4			Worker hrs. per month:	160					
5			Beginning & ending workforce:	100					
6			Beginning & ending inventory:	100					
7						Total plan cost			
8			Production cost per unit:	$550.00		$6,600,000			
9			Hiring cost:	$300.00		$37,500			
10			Layoff cost:	$200.00		$25,000			
11			Holding cost per unit per month:	$4.00		$4,800			
12						**$6,667,300**	**Grand total**		
13	Month	Sales Forecast	Sales (in labor hrs.)	Sales (in workers)	Actual Workers	Actual Production	Hirings	Layoffs	Ending Inventory/ Back Orders
14					100				100
15	January	500	10,000	62.5	62.50	500.00	0.00	37.50	100.00
16	February	600	12,000	75	75.00	600.00	12.50	0.00	100.00
17	March	700	14,000	87.5	87.50	700.00	12.50	0.00	100.00
18	April	800	16,000	100	100.00	800.00	12.50	0.00	100.00
19	May	900	18,000	112.5	112.50	900.00	12.50	0.00	100.00
20	June	1,000	20,000	125	125.00	1,000.00	12.50	0.00	100.00
21	July	1,000	20,000	125	125.00	1,000.00	0.00	0.00	100.00
22	August	1,100	22,000	137.5	137.50	1,100.00	12.50	0.00	100.00
23	September	1,200	24,000	150	150.00	1,200.00	12.50	0.00	100.00
24	October	1,300	26,000	162.5	162.50	1,300.00	12.50	0.00	100.00
25	November	1,400	28,000	175	175.00	1,400.00	12.50	0.00	100.00
26	December	1,500	30,000	187.5	187.50	1,500.00	12.50	0.00	100.00
27							0.00	87.50	
28	**Totals:**	**12,000**				**12,000.00**	**125.00**	**125.00**	**1,200.00**
29			Average =	**125**					

FIGURE 10.10 **S&OP Spreadsheet for Bob Irons Industries (Chase Plan)**

TABLE 10.14 Description of the Optimization Problem for Bob Irons Industries

DESCRIPTION	CELL REFERENCE
Objective function:	
Minimize total production, hiring, layoff, and inventory costs	F12
By changing the following decision variables:	
Hiring and layoffs	G15:H26
Subject to the following constraints:	
Inventory in the last period must be at least 100 units	I26 $\geq$ 100
Inventory cannot go below zero (i.e., the sales forecast must be met)	I15:I25 $\geq$ 0
Hiring and layoff values cannot be negative	G15:H26 $\geq$ 0

Figure 10.11 shows the lowest-cost solution, as identified by Solver. The open dialog box illustrates how the problem stated in Table 10.14 was encoded into Solver. The new plan is roughly \$18,000 cheaper than either the level or the chase approach. The suggested solution is to keep the workforce at around 92 workers for the first six months and then bump it up to around 158 workers for the last six months. Under this plan, the inventory level falls to zero only once (at the end of June).

Before making a final decision, Bob has to consider other factors as well. The Solver solution contains fractional workers—will it still work for whole numbers? If so, will Bob be able to hire and train nearly 67 workers in July? Does the company have enough space to store up to 500 units? Is the savings worth the added complexity? Solver can help Bob identify ways to lower costs, but the final decision belongs to *Bob*, not the spreadsheet.

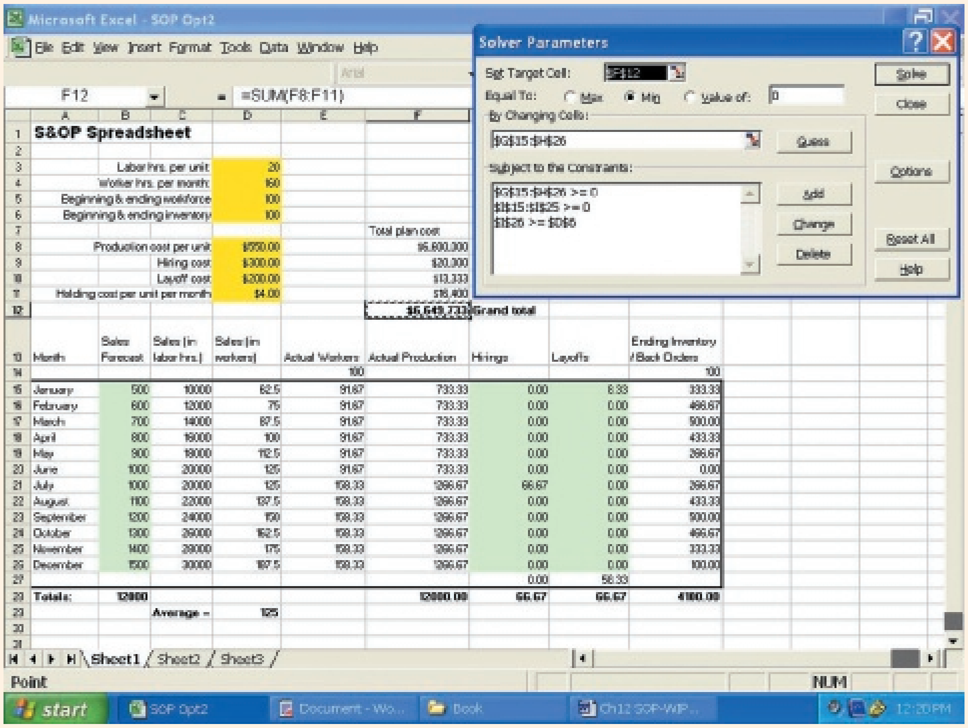


FIGURE 10.11 Solver-Generated Optimal Solution for Bob Irons Industries
Microsoft Excel, Microsoft Corporation

CHAPTER SUMMARY

S&OP fills the gap between long-term strategic planning and short-term planning and control. Through S&OP, firms can not only plan and coordinate efforts in their own functional areas—operations, marketing, finance, human resources, and so on—but also effectively communicate to other members of the supply chain what they expect to accomplish over the intermediate time horizon.

In this chapter, we described several approaches to S&OP and demonstrated the power of the technique. We discussed when and where top-down versus bottom-up planning can be used and showed three basic approaches to S&OP: level, chase, and mixed production.

We also touched on some of the qualitative issues surrounding S&OP: How do we select a plan? How can we use S&OP to foster agreement and cooperation among the various parties? How can we organize for S&OP?

We also argued for increased sharing of S&OP information across the supply chain. As organizations put more emphasis on building supply chain relationships, we can expect to see more and more sharing of S&OP information between supply chain partners. Finally, we ended the chapter with a discussion of how optimization modeling techniques can be applied to the S&OP process.

KEY FORMULAS

Ending inventory level (page 307):

$$EI_t = EI_{t-1} + RP_t + OP_t - S_t \tag{10.1}$$

where:

EI_t = ending inventory for time period t
RP_t = regular production in time period t
OP_t = overtime production in time period t
S_t = sales in time period t

Net cash flow (page 311):

$$\text{Net cash flow} = \text{cash inflows} - \text{cash outflows} \tag{10.2}$$

KEY TERMS

Aggregate planning 300
Bottom-up planning 302
Chase production plan 306
Constraint 319
Detailed planning and control 301
Level production plan 305
Load profile 310
Mixed production plan 306
Net cash flow 311
Objective function 319
Offloading 318
Optimization model 319
Planning values 302
Rolling planning horizon 314
Sales and operations planning (S&OP) 300
Strategic planning 300
Tactical planning 300
Tiered workforce 318
Top-down planning 302
Yield management 316

SOLVED PROBLEM

PROBLEM

Hua Ng Exporters

Hua Ng Exporters makes commercial exercise equipment that is sold primarily in Europe and the United States. Hua Ng's two major product lines are stair steppers and elliptical machines. Resource requirements for both product lines, as well as six-month forecasts, are as follows:

PRODUCT LINE	LABOR HOURS PER UNIT	FABRICATION HOURS PER UNIT	ASSEMBLY LINE HOURS PER UNIT
Stair steppers	2.5	0.8	0.15
Ellipticals	1.0	1.8	0.20

Sales Forecast		
MONTH	STAIR	ELLIPTICALS
1	560	400
2	560	400
3	545	415
4	525	435
5	525	435
6	525	435

Assuming that Hua Ng follows a chase production plan, develop load profiles for the next six months for labor, fabrication, and assembly line hours. Interpret the results.

Solution

The first step is to translate the sales forecasts for the two product lines into resource requirements. This will require us to calculate and then combine the resource needs for both product lines. Table 10.15 shows the results.

To illustrate how we arrived at these results, we calculated the total labor hours for month 1 as follows:

$$(560 \text{ stair steppers})(2.5 \text{ hours}) + (400 \text{ ellipticals})(1 \text{ hour}) = 1{,}400 + 400 = 1{,}800 \text{ hours}$$

The remaining numbers are calculated in a similar fashion. Figure 10.12 shows the load profiles for the three resources.

Total labor hours are expected to fall somewhat over time, while fabrication hours are expected to increase slightly. The reason is the change in the mix of products. Specifically, the forecast for stair steppers is falling, while the forecast for ellipticals is rising.

TABLE 10.15 Resource Requirements at Hua Ng Exporters

	Sales Forecast				
MONTH	STAIR STEPPERS	ELLIPTICALS	TOTAL LABOR HOURS	TOTAL FABRICATION	TOTAL ASSEMBLY
1	560	400	1,800	1,168	164
2	560	400	1,800	1,168	164
3	545	415	1,777.5	1,183	164.75
4	525	435	1,747.5	1,203	165.75
5	525	435	1,747.5	1,203	165.75
6	525	435	1,747.5	1,203	165.75

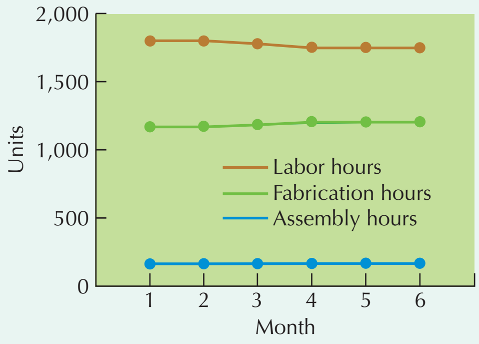


FIGURE 10.12 Load Profiles for Hua Ng Exporters

DISCUSSION QUESTIONS

1. Some people have argued that the *process* of developing a sales and operations plan is as important as the final numbers. How could this be?
2. How does S&OP differ from strategic capacity planning? From detailed planning and control? What role does S&OP play in the overall planning activities of an organization?
3. In general, under what conditions might a firm favor a level production plan over a chase plan? A chase production plan over a level plan?
4. Services, in general, cannot put "products" in inventory to be consumed at some later time. How does this limit service firms' S&OP alternatives?
5. Why is it important to update a sales and operations plan on a regular basis, using a rolling time horizon approach?
6. Ling suggests that superior S&OP planning can provide a firm with a competitive advantage. Do you agree? Can you think of any organizations you know that might benefit from better sales and operations planning?
7. What are the advantages to a firm of coordinating its S&OP process with key supply chain partners? What are the potential drawbacks?

PROBLEMS

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

Problems for Section 10.2: Major Approaches to S&OP

1. Consider the following information for Sandy's Cleaning Service:

SERVICE	SERVICE MIX	LABOR HOURS PER JOB
Light cleaning	20%	0.20
Medium cleaning	60%	0.25
Deep cleaning	20%	0.35

   a. (*) Calculate the weighted planning value for labor hours per job.
   b. (**) Recalculate the weighted planning value based on a new service mix of 10%, 65%, and 25% for light, medium, and deep cleaning, respectively. What happened?

2. Consider the following information for Covolo Diving Gear:

GAUGE SET	PRODUCT MIX	MACHINE HOURS PER UNIT	LABOR HOURS PER UNIT
A20	60%	0.20	0.15
B30	15%	0.35	0.10
C40	25%	0.25	0.12

   a. (*) Calculate weighted planning values for machine hours and labor hours per gauge set. Interpret these planning values.
   b. (**) Recalculate the weighted planning values based on a new product mix of 45%, 30%, and 25% for the A20, B30, and C40 sets, respectively. What happened?

3. The typical monthly production mix at Bangor Industries is as follows:

Deluxe models	45%
Regular models	30%
Economy models	25%

   Each deluxe model typically requires 5 hours of labor and 10 hours of machine time. Each regular model takes 4 hours of labor and 8 hours of machine time. Finally, the economy model needs, on average, 3.5 hours of labor and 6 hours of machine time.

   a. (**) What should the weighted per-unit planning values be for labor? For machine time? What assumptions must be made in order to use these values?
   b. (**) Suppose that for the next month the mix is expected to change to 30% deluxe, 30% regular, and 40% economy models. How would this affect the planning values?
   c. (**) When the product mix changes from month to month, should Bangor Industries use a top-down or a bottom-up approach to sales and operations planning? Explain.

4. (**) On average, each unit produced by the Kantor Company takes 0.90 worker hours and 0.02 hours of machine time. Furthermore, each worker and machine is available 160 hours a month. Use these planning values and the following sales forecast to estimate (1) the number of worker hours and machine hours needed each month and (2) the number of workers and machines needed each month. Round your estimates of the number of workers and machines needed to the nearest whole number.

MONTH	SALES FORECAST
October	44,000
November	52,000
December	68,000
January	69,000
February	58,000
March	46,000

5. Consider the following sales forecasts for products A and B:

	Sales Forecasts	
MONTH	PRODUCT A	PRODUCT B
January	3,500	700
February	3,300	1,000
March	3,200	1,200
April	3,000	1,500
May	2,700	1,900
June	2,600	2,100

Each unit of product A takes approximately 2.5 labor hours, while each unit of product B takes only 1.8 hours.

a. (**) What is the combined (aggregate) sales forecast for products A and B? If this were the *only* information you had, would you expect resource requirements to increase or decrease from January to June?

b. (**) Use the planning value information to calculate total labor hour requirements in each month. Compare your calculations to your answer to part a. Interpret the results.

c. (**) Would top-down planning or bottom-up planning be better suited to S&OP in this situation? Explain.

6. (**) Complete the *level production plan*, using the following information. The only costs you need to consider here are layoff, hiring, and inventory costs. If you complete the plan correctly, your hiring, layoff, and inventory costs should match those given here.

	LAYOFF	HIRING	INVENTORY
Totals:	25	25	32,224
Costs:	$50,000	$75,000	$193,344
Cost of plan:		$318,344	
Planning values			
Starting inventory:			1,000
Starting and ending workforce:			227
Hours worked per month per worker:			160
Hours per unit:			20
Hiring cost per worker:			$3,000
Layoff cost per worker:			$2,000
Monthly per-unit holding cost:			$6

Second Table for Problem 6

MONTH	FORECASTED SALES	SALES IN WORKER HOURS	WORKERS NEEDED TO MEET SALES AVERAGE = 252	ACTUAL WORKERS	ACTUAL PRODUCTION	LAYOFFS	HIRINGS	ENDING INVENTORY
March	1,592							
April	1,400							
May	1,200							
June	1,000							
July	1,504							
August	1,992							
September	2,504							
October	2,504							
November	3,000							
December	3,000							
January	2,504							
February	1,992							

7. (**) Complete the *chase production plan*, using the following information. The only costs you need to consider here are layoff, hiring, and inventory costs. If you complete the plan correctly, your hiring, layoff, and inventory costs should match those given here.

	LAYOFF	HIRING	INVENTORY
Totals:	250	250	12,000
Costs:	$500,000	$750,000	$72,000
Cost of plan:		$1,322,000	
Planning values			
Starting inventory:			1,000
Starting and ending workforce:			227
Hours worked per month per worker:			160
Hours per unit:			20
Hiring cost per worker:			$3,000
Layoff cost per worker:			$2,000
Monthly per-unit holding cost:			$6

Second Table for Problem 7

MONTH	FORECASTED SALES	SALES IN WORKER HOURS	WORKERS NEEDED TON MEET SALES AVERAGE = 252	ACTUAL EMPLOYEES	ACTUAL PRODUCTION	LAYOFFS	HIRINGS	ENDING INVENTORY
March	1,592							
April	1,400							
May	1,200							
June	1,000							
July	1,504							
August	1,992							
September	2,504							
October	2,504							
November	3,000							
December	3,000							
January	2,504							
February	1,992							

8. (**) Consider the following partially completed sales and operations plan. Using the planning values and filled-in values as a guide, complete the plan and calculate the layoff, hiring, and inventory costs. Does this sales and operations plan reflect a chase, level, or mixed strategy? Explain.

	LAYOFF	HIRING	INVENTORY
Totals:			
Costs:			
Cost of plan:			
Planning values			
Starting inventory:			500
Starting and ending workforce:			50
Hours worked per month per worker:			160
Hours per unit:			4
Hiring cost per worker:			$300
Layoff cost per worker:			$200
Monthly per-unit holding cost:			$4

Second Table for Problem 8

MONTH	FORECASTED SALES	SALES IN WORKER HOURS	WORKERS NEEDED TO MEET SALES AVERAGE = 252	ACTUAL WORKERS	ACTUAL PRODUCTION	LAYOFFS	HIRINGS	ENDING INVENTORY
March		8,000				3	0	380
April		7,680				0	0	
May		7,360				0	0	
June	1,800	7,200				0	0	
July	1,800					0	0	
August	1,800					0	0	
September	1,750					11	0	
October	1,640					0	0	
				50		0	14	

9. (***) (*Microsoft Excel problem*) Note that problems 6 through 8 could all be solved by using a *single* spreadsheet that allows the user to change the planning, "Forecasted Sales," and "Actual Workers" values. **Create this spreadsheet.** Your spreadsheet should calculate new results anytime the planning, "Forecasted Sales," or "Actual Workers" values change. Verify that your spreadsheet works by determining whether it generates the same costs for a level production plan and a chase production plan shown in problems 6 and 7.

10. Castergourd Home Products makes two types of butcher-block tables: the Beefeater and the Deutschlander. The two tables are made in the same facility and require the same amount of labor and equipment. In addition, we know the following:

- Each table costs $300 to make, and each requires, on average, 3.2 hours of labor.
- Each employee works 160 hours per month, and there is no effective limit on the number of employees.
- The cost of hiring or laying off an employee is $300.
- The monthly holding cost for a table is $15.
- For planning purposes, Castergourd will begin and end with 20 employees and 0 tables in inventory.

Forecasted sales for the tables are as follows:

MONTH	BEEFEATER	DEUTSCHLANDER
November 2019	650	3,048
December	676	2,899
January 2020	624	3,198
February	624	2,671
March	696	2,919
April	475	3,102
May	566	2,964
June	819	2,409
July	754	3,381
August	982	3,965

a. (***) Develop a top-down *level production plan* for Castergourd for the 10-month planning period. Calculate the total production, hiring, layoff, and inventory costs for your plan.

b. (***) Repeat part a, except in this case develop a *chase production plan*.

c. (**) Suppose hiring and layoff costs increase dramatically. In general, will this make a level plan look better or worse than a chase plan? Explain.

11. (**) Consider the level production plan for Pennington Cabinets shown in Table 10.5. Perform a cash flow analysis for this production plan, using the cash flow analysis in Example 10.8 as a guide. Assume that each cabinet set sold generates a cash inflow of $2,800, while each unit produced using regular time generates a cash outflow of $2,000 and each cabinet set held in inventory at the end of the month generates a cash outflow of $40. How does this cash flow compare with the one for the mixed strategy (Table 10.10)? Which plan do you think finance would prefer?

12. Consider the following information:

MONTH	FORECASTED SALES	REGULAR PRODUCTION	OVERTIME PRODUCTION	ENDING INVENTORY
January	800 units	1,150 units	0 units	350 units
February	1,000	1,150	0	500
March	1,200	1,150	0	450
April	1,400	1,150	0	200
May	1,600	1,150	150	0
June	1,500	1,150	350	0

Each unit sells for $500. Regular production and overtime production costs are $350 and $450 per unit, respectively. The cost to hold a unit in inventory for one month is $10.

a. (**) Develop a cash flow analysis for this problem. Be sure to calculate net cash flow and cumulative net cash flow for each month.

b. (**) Why do the net cash flows for April and May look so much better than those for the other months? What are the implications for building up and draining down inventories under a level production plan?

13. (***) (*Microsoft Excel problem*) Re-create the S&OP spreadsheet used in Table 10.10 and Example 10.11. (You do *not* have to build in the optimization model using the Solver function.) While your formatting may differ, your answers should be the same. Your spreadsheet should generate new results any time any of the planning, sales forecast, or hiring/layoff values are changed. To test your spreadsheet, change the planning values to match the following:

	A	B	C	D
3			Labor hrs. per unit:	24
4			Worker hrs. per month:	150
5			Beginning & ending workforce:	100
6			Beginning & ending inventory:	100
7				
8			Production cost per unit:	$475.00
9			Hiring cost:	$400.00
10			Layoff cost:	$300.00
11			Holding cost per unit per month:	$3.00

If your spreadsheet works correctly, the new total cost for a *level production plan* should be $5,769,100, and for a *chase production plan*, it should be $5,755,600.

14. (***) (*Microsoft Excel problem*) Kumquats Unlimited makes large batches of kumquat paste for use in the food industry. These batches are made on automated production lines. Kumquats Unlimited has the capability to start up or shut down lines at the beginning of each month, but at a cost. If a line is up, management has determined that it's best to keep the line busy, even if the resulting batches must be put in inventory.

Management has created the following Excel spreadsheet, which uses the Solver function to find the lowest-cost solution to the S&OP problem. **Re-create this spreadsheet, including the Solver optimization model** (using Example 10.11 as a guide). Your formatting does not have to be the same, but your answers should be. Your spreadsheet should allow the user to make changes *only* to the planning values, the sales forecast, and the number of production line start-ups and shutdowns. All other values should be calculated. Be sure that Solver does not let inventory drop below zero at the end of any month or end June with less inventory than was available at the beginning of January. To test your spreadsheet, modify the spreadsheet so that each batch requires 32 hours of production line time. The new optimal cost should be $16,215,000.

	A	B	C	D	E	F	G	H	I
1	Sales & Operations Planning Spreadsheet for Kumquats Unlimited								
2	(with Solver optimization)								
3									
4			Production cost per batch:	$ 2,400				Production costs:	$
5			Line hours per batch:	16				Line start-up costs:	$ 125,000
6			Production line hours per month:	320	hours			Line shutdown costs:	$ 75,000
7			Cost to start up a line:	$ 25,000				Inventory holding costs:	$ 165,000
8			Cost to shut down a line:	$ 6,000					
9			Inventory holding cost:	$ 300	per batch, per month			Grand total:	$14,964,000
10			Beginning and ending lines:	55	production lines				
11			Beginning and ending inventory:	100	batches				
12									
13	Month	Sales Forecast	Sales (in line hours)	Sales (in production lines)	Actual Production Lines	Actual Production	Production Line Start-ups	Production Line Shutdowns	Ending Inventory
14					55				100
15	January	1,000	16,000	50	55.00	1,100	0	0	200
16	February	1,200	19,200	60	55.00	1,100	0	0	100
17	March	1,200	19,200	60	55.00	1,100	0	0	0
18	April	1,000	16,000	50	50.00	1,000	0	5	0
19	May	800	12,800	40	43.00	860	0	7	60
20	June	800	12,800	40	43.00	860	0	0	120
21					55		5	0	
22	**Total =**	**6000**				**6,020**	5	**12.5**	**480**
23			**Average =**	**50**					

CASE STUDY

Covolo Diving Gear, Part 2

June 15, 2020—Two weeks have passed since Covolo Diving Gear's contentious semiannual planning meeting, and the senior staff members for Covolo Diving Gear are getting ready to start their first monthly S&OP meeting. Gina Covolo, CEO, gets the ball rolling:

> *I know it's been a busy two weeks for all of you, and I appreciate you working extra time to get ready for this meeting. Production is already set for the next two months, so we're going to start by planning for this September through the following August. I've had Patricia from marketing develop a sales forecast for these 12 months, and I've also had David from manufacturing estimate manufacturing costs and labor requirements, as well as capacity in the plant. Mary from HR was good enough to come up with some estimates of how much it costs to hire and train new workers, as well as the cost of laying off folks. Finally, Jack from supply management was able to get the accounting folks to estimate the cost of holding a gauge set in inventory for a month. So let's see what we've got.*

Mary passes out the following information to all of the attendees:

MONTH	SALES FORECAST
September 2020	30,000 gauge sets
October	31,500
November	35,000
December	37,000
January 2021	22,000
February	18,000
March	17,500
April	27,000
May	38,000
June	40,000
July	42,000
August	40,000

(Continued)

- Manufacturing cost per gauge set: $74.50
- Holding cost: $8 per gauge set per month
- Average labor hours required per gauge set: 0.25 hours
- Labor hours available per employee per month: 160
- Plant capacity: 35,000 gauge sets per month
- Cost to hire and train a new employee: $1,250
- Cost to lay off an employee: $500
- Beginning and ending workforce: 50
- Beginning inventory: 10,000

Questions

1. Develop a *level production plan* for Covolo Diving Gear. What are the advantages and disadvantages of this plan? Could Covolo implement a pure chase plan, given the

current capacity? Why? If sales continue to grow, what are the implications for production capacity at Covolo?

2. Patricia Rodriguez, vice president of marketing, states, "I've got to tell you all that I'm pretty comfortable with the forecasts for September through November, but after that, a lot could change. It's just very hard to forecast for four or more months out in this kind of market." How will a monthly S&OP update with rolling planning horizons help alleviate Patricia's concerns? Are there still advantages to S&OP, even though the forecasts may change?
3. After looking over the level production plan, David Griffin, vice president of manufacturing, speaks up: "This looks OK, but you know what bugs me about it? The assumption that if a worker is available, that worker *has* to be making gauge sets, even if we don't need any more. It might make sense in some cases to just have the worker *not* produce rather than lay off a worker in one month and hire someone else back the next." Do you agree? What are the holding costs associated with having an extra worker produce gauge sets for one month? How do these compare to the layoff and hiring costs? How might a strategy of keeping extra workers idle affect the estimated manufacturing costs for the gauge sets? (*Hint:* Labor costs have to be accounted for *somewhere*.)

REFERENCES

Books and Articles

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

Ling, R., "For True Enterprise Integration, Turn First to SOP," *APICS—The Performance Advantage* 10, no. 3 (March 2000): 40–45.

Internet

Linking CPFR and S&OP: A Roadmap to Integrated Business Planning, 2010, **www.gs1us.org/DesktopModules/Bring2mind/DMX/Download.aspx?command=core_download&entryid=433&language=en-US&PortalId=0&TabId=134.**

Paul A. Souders/Corbis/VCG/Getty Images

CHAPTER
eleven

Managing Inventory throughout the Supply Chain

CHAPTER OUTLINE

CHAPTER OBJECTIVES

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

- Describe the various roles of inventory, including the different types of inventory and inventory drivers.
- Distinguish between independent demand and dependent demand inventory.
- Calculate the restocking level for a periodic review system.
- Calculate the economic order quantity (*EOQ*) and reorder point (*ROP*) for a continuous review system.
- Determine the best order quantity when volume discounts are available.
- Calculate the target service level and target stocking point for a single-period inventory system.
- Describe how inventory decisions affect other areas of the supply chain. In particular, describe the bullwhip effect, inventory positioning issues, and the impacts of transportation, packaging, and material handling considerations.

INVENTORY MANAGEMENT AT AMAZON.COM

Baumgarten/VARIO Images/SIPA/Newscom

Employees pick items off the shelves at an Amazon.com warehouse in Leipzig, Germany.

When they first started appearing in the late 1990s, Web-based "e-tailers" such as Amazon.com hoped to replace the "bricks" of traditional retailing with the "clicks" of online ordering. Rather than opening dozens or even hundreds of stores filled with expensive inventory, an e-tailer could run a single virtual store that served customers around the globe. Their business model suggested that inventory could be kept at a few key sites, chosen to minimize costs and facilitate quick delivery to customers. In theory, e-tailers were highly "scalable" businesses that could add new customers with little or no additional investment in inventory or facilities. (Traditional retailers usually need to add stores to gain significant increases in their customer base.)

But how has this actually played out for Amazon over the years? Table 11.1 contains sales and inventory figures, pulled from the company's annual reports, for Amazon for the years 1997 through 2015. The first column reports net sales for each calendar year, and the second column contains the amount of inventory on hand at the end of the year. The third column shows inventory turns, which is calculated as (net sales/ending inventory). Retailers generally want *higher* inventory turns, which indicate that they can support the same level of sales with less inventory. Inventory turns is often thought of as a key measure of asset productivity.

Looking at Amazon's performance over the years provides some interesting insights. Consider Figure 11.1. In late 1999, Amazon learned that managing inventory can be challenging even for e-tailers. That was the year the company expanded into new product lines, such as electronics and housewares, with which it had little experience. Amazon's purchasing managers were faced with the question of how many of these items to hold in inventory. Too little, and they risked losing orders and alienating customers; too much, and they could lock up the company's resources in unsold products. Only later, when sales for the

TABLE 11.1 Amazon.com Financial Results, 1997–2015

YEAR	NET SALES ($MILLIONS)	INVENTORY ($MILLIONS) (DEC. 31)	INVENTORY TURNS
1997	$148	$9	16.4
1998	$610	$30	20.3
1999	$1,640	$221	7.4
2000	$2,762	$175	15.8
2001	$3,122	$143	21.8
2002	$3,933	$202	19.5
2003	$5,264	$294	17.9
2004	$6,921	$480	14.4
2005	$8,490	$566	15.0
2006	$10,711	$877	12.2
2007	$14,835	$1,200	12.4
2008	$19,166	$1,399	13.7
2009	$24,509	$2,171	11.3
2010	$34,204	$3,202	10.7
2011	$48,077	$4,992	9.6
2012	$61,093	$6,031	10.1
2013	$74,452	$7,411	10.0
2014	$88,988	$8,299	10.7
2015	$107,006	$10,243	10.4

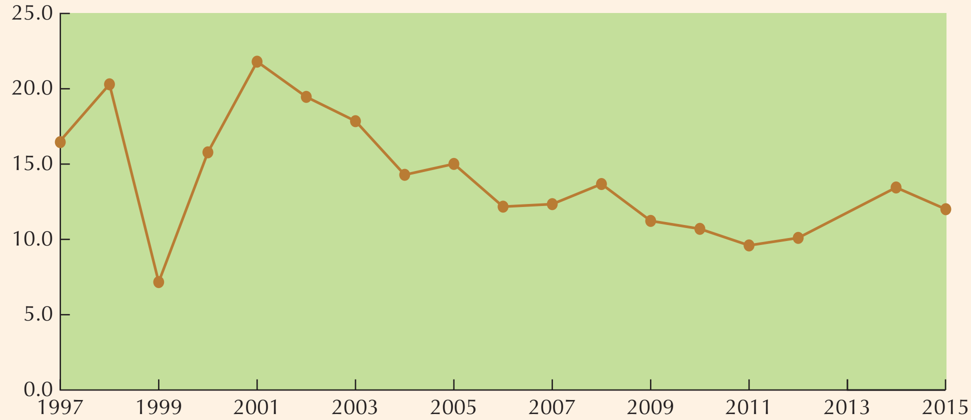


FIGURE 11.1 **Inventory Turns at Amazon.com, 1997–2015**

1999 holiday season fell flat and Amazon's inventory levels skyrocketed, did the purchasing managers realize they had overstocked. In fact, as the figures show, by the end of 1999, Amazon's inventory turnover ratio was 7.4—*worse* than that of the typical brick-and-mortar retailer at the time.

After 1999, Amazon seemed to learn its lesson. Inventory turns rose to nearly 22 in 2001, but have since fallen and stabilized at around 10 turns per year, even as Amazon's sales have risen sharply. But why? The decline in inventory turns over the past 15 years is due in large part to a shift in Amazon's business strategy. Instead of trying to build competitive advantage based on low-cost books (Amazon's original business model), the company now seeks to provide customers with convenient shopping and fast delivery for a wide range of products. Such a strategy requires more inventory to support the same level of sales.

So today, how does Amazon compare to its brick-and-mortar competitors? Amazon handily beats traditional book retailer Barnes & Noble, whose inventory turns for 2016 were just 4.5. Yet Best Buy, which sells computers, phones, video games, and appliances, generated 7.8 inventory turns in 2016, a noticeable improvement over the 6.9 inventory turns in 2013—not bad, especially considering all the retail stores Best Buy must support.

INTRODUCTION

Inventory
According to APICS, "those stocks or items used to support production (raw materials and work-in-process items), supporting activities (maintenance, repair, and operating supplies) and customer service (finished goods and spare parts)."

APICS defines **inventory** as "those stocks or items used to support production (raw materials and work-in-process items), supporting activities (maintenance, repair, and operating supplies) and customer service (finished goods and spare parts)."[1] In this chapter, we discuss the critical role of inventory—why it is necessary, what purposes it serves, and how it is controlled.

As Amazon's experience suggests, inventory management is still an important function, even in the age of online retailing. In fact, many managers seem to have a love–hate relationship with inventory. Michael Dell once talked about inventory velocity—the speed at which components move through Dell Computer's operations—as a key measure of his company's performance.[2] In his mind, the less inventory the company has sitting in the warehouse, the better. Victor Fung of the Hong Kong–based trading firm Li & Fung goes so far as to say, "Inventory is the root of all evil."[3]

Yet look what happened to the price of gasoline in the southeastern United States during the fall of 2016. It skyrocketed due to an explosion in a major pipeline combined with inadequate reserves.[4] And if you have ever visited a store only to find that your favorite product is

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

[2] J. Magretta, "The Power of Virtual Integration: An Interview with Dell Computer's Michael Dell," *Harvard Business Review* 76, no. 2 (March–April 1998): 72–84.

[3] J. Magretta, "Fast, Global, and Entrepreneurial: Supply Chain Management, Hong Kong Style," *Harvard Business Review* 76, no. 5 (September–October 1998): 102–109.

[4] C. Isodore, "Gas Price Spikes and Shortages Coming after Fatal Pipeline Blast," *CNN Money*, November 3, 2016, **http://money.cnn.com/2016/11/01/news/colonial-pipeline-explosion-gasoline-price-spike/.**

sold out, you might think the *lack* of inventory is the root of all evil. The fact is, inventory is both a valuable resource and a potential source of waste.

11.1 THE ROLE OF INVENTORY

Consider WolfByte Computers, a fictional manufacturer of laptops, tablets, and e-readers. Figure 11.2 shows the supply chain for WolfByte's laptop computers. WolfByte assembles the laptops from components purchased from companies throughout the world, three of which are shown in the figure. Supplier 1 provides the displays, Supplier 2 manufactures the hard drives, and Supplier 3 produces the keyboards.

Looking downstream, WolfByte sells its products through independent retail stores and through its own Web site. At retail stores, customers can buy a laptop off the shelf, or they can order one to be customized and shipped directly to them. On average, WolfByte takes about two days to ship a computer from its assembly plant to a retail store or a customer. Both WolfByte and the retail stores keep spare parts on hand to handle customers' warranty claims and other service requirements.

With this background, let's discuss the basic types of inventory and see how they fit into WolfByte's supply chain.

Inventory Types

Cycle stock
Components or products that are received in bulk by a downstream partner, gradually used up, and then replenished again in bulk by the upstream partner.

Two of the most common types of inventory are cycle stock and safety stock. **Cycle stock** refers to components or products that are received in bulk by a downstream partner, gradually used up, and then replenished again in bulk by the upstream partner. For example, suppose Supplier 3 ships 20,000 keyboards at a time to WolfByte. Of course, WolfByte can't use all those components at once. More likely, workers pull them out of inventory as needed. Eventually, the inventory runs down, and WolfByte places another order for keyboards. When the new order arrives, the inventory level rises and the cycle is repeated. Figure 11.3 shows the classic sawtooth pattern associated with cycle stock inventories.

Cycle stock exists at other points in WolfByte's supply chain. Almost certainly, Suppliers 1 through 3 have cycle stocks of raw materials that they use to make components. And retailers need to keep cycle stocks of both completed computers and spare parts in order to serve their customers.

Safety stock
Extra inventory that a company holds to protect itself against uncertainties in either demand or replenishment time.

Cycle stock is often thought of as active inventory because companies are constantly using it up, and their suppliers constantly replenishing it. **Safety stock,** on the other hand, is extra inventory that companies hold to protect themselves against uncertainties in either demand levels or replenishment time. Companies do not plan on using their safety stock any more than you plan on using a fire extinguisher; it is there *just in case.*

FIGURE 11.2
WolfByte Computers's Supply Chain

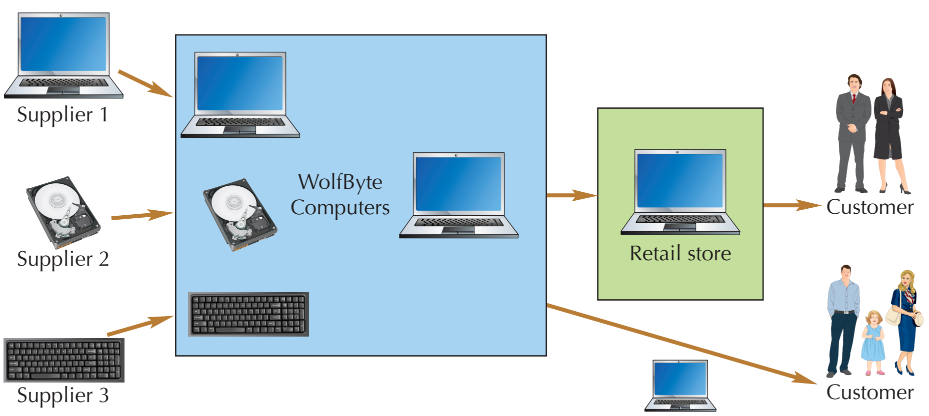
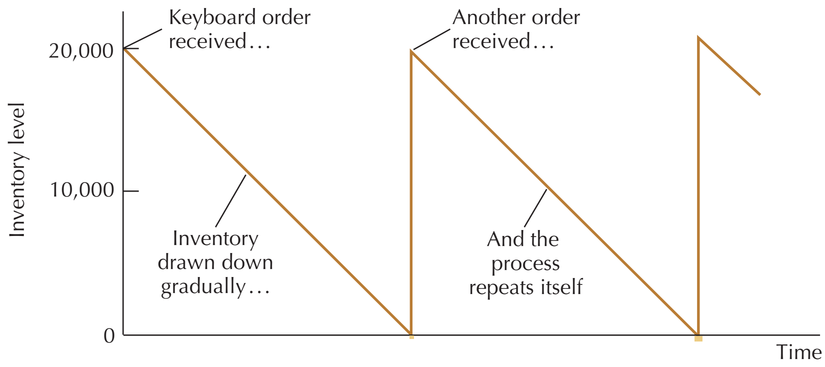


FIGURE 11.3
Cycle Stock at WolfByte Computers



Let's return to the keyboard example in Figure 11.3. WolfByte has timed its orders so that a new batch of keyboards comes in just as the old batch is used up. But what if Supplier 3 is late in delivering the devices? What if demand makes inventory levels fall faster than expected? If either or both these conditions occur, WolfByte could run out of keyboards before the next order arrives.

Imagine the resulting chaos: Assembly lines would have to shut down, customers' orders couldn't be filled, and WolfByte would have to notify customers, retailers, and shippers about the delays.

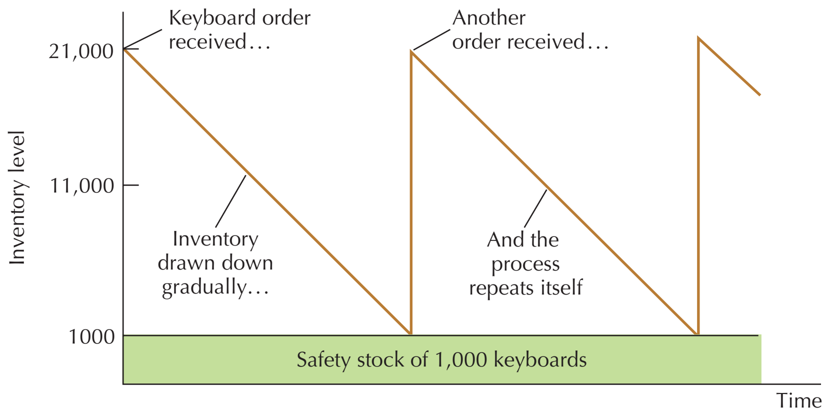
One solution is to hold some extra inventory, or safety stock, of keyboards to protect against fluctuations in demand or replenishment time. Figure 11.4 shows what WolfByte's inventory levels would look like if the company decided to hold safety stock of 1,000 keyboards. As you can see, safety stock provides valuable protection, but at the cost of higher inventory levels. Later in the chapter, we discuss ways of calculating appropriate safety stock levels.

Anticipation inventory
Inventory that is held in anticipation of customer demand.

Hedge inventory
According to APICS, a "form of inventory buildup to buffer against some event that may not happen. Hedge inventory planning involves speculation related to potential labor strikes, price increases, unsettled governments, and events that could severely impair the company's strategic initiatives."

There are four other common types of inventory: anticipation, hedge, transportation, and smoothing. **Anticipation inventory,** as the name implies, is inventory that is held in anticipation of customer demand. Anticipation inventory allows instant availability of items when customers want them. **Hedge inventory,** according to APICS, is "a form of inventory buildup to buffer against some event that may not happen. Hedge inventory planning involves speculation related to potential labor strikes, price increases, unsettled governments, and events that could severely impair the company's strategic initiatives."[5] In this sense, hedge inventories can be thought of as a special form of safety stock. WolfByte has stockpiled a hedge inventory of two months' worth of hard drives because managers have heard that Supplier 2 may experience a temporary shutdown over the next two months.

FIGURE 11.4
Safety Stock at WolfByte Computers



[5]Blackstone, *APICS Dictionary*.

Transportation inventory Inventory that is moving from one link in the supply chain to another.

Transportation inventory represents inventory that is "in the pipeline," moving from one link in the supply chain to another. When the physical distance between supply chain partners is long, transportation inventory can represent a considerable investment. Suppose, for example, that Supplier 2 is located in South Korea, and WolfByte is located in Texas. Hard drives may take several weeks to travel the entire distance between the two companies. As a result, multiple orders could be in the pipeline on any particular day. One shipment of hard drives might be sitting on the docks in Kimhae, South Korea; two others might be halfway across the Pacific; a fourth might be found on Route I-10, just outside Phoenix, Arizona. In fact, the transportation inventory of hard drives alone might dwarf the total cycle and safety stock inventories in the rest of the supply chain.

Smoothing inventory Inventory that is used to smooth out differences between upstream production levels and downstream demand.

Finally, **smoothing inventory** is used to smooth out differences between upstream production levels and downstream demand. Suppose management has determined that WolfByte's assembly plant is most productive when it produces 3,000 laptops a day. Unfortunately, demand from retailers and customers will almost certainly vary from day to day. As a result, WolfByte's managers may decide to produce a constant 3,000 laptops per day, building up finished goods inventory during periods of slow demand and drawing it down during periods of high demand. (Figure 11.5 illustrates this approach.) Smoothing inventories allow individual links in the supply chain to stabilize their production at the most efficient level and to avoid the costs and headaches associated with constantly changing workforce levels and/or production rates. If you think you may have heard of this idea before, you have: It's part of the rationale for following a level production strategy in developing a sales and operations plan (see Chapter 10).

Inventory Drivers

From this discussion, we can see that inventory is a useful resource. However, companies don't want to hold more inventory than necessary. Inventory ties up space and capital: A dollar invested in inventory is a dollar that cannot be used somewhere else. Likewise, the space used to store inventory can often be put to more productive use. Inventory also poses a significant risk of obsolescence, particularly in supply chains with short product life cycles. Consider what happens when Samsung announces its next generation of cell phones. Would you want to be stuck holding the old-generation cell phones when the new ones hit the market?

Finally, inventory is too often used to hide problems that management really should resolve. In this sense, inventory can serve as a kind of painkiller, treating the symptom without solving the underlying problem. Consider our discussion of safety stock. Suppose WolfByte's managers decide to hold additional safety stock of hard drives because of quality problems they have been experiencing with units received from Supplier 2. While the safety stock may buffer WolfByte from these quality problems, it does so at a cost. A better solution might be to improve the quality of incoming units, thereby reducing both quality-related costs and the need for additional safety stock.

FIGURE 11.5
Smoothing Inventories at WolfByte Computers

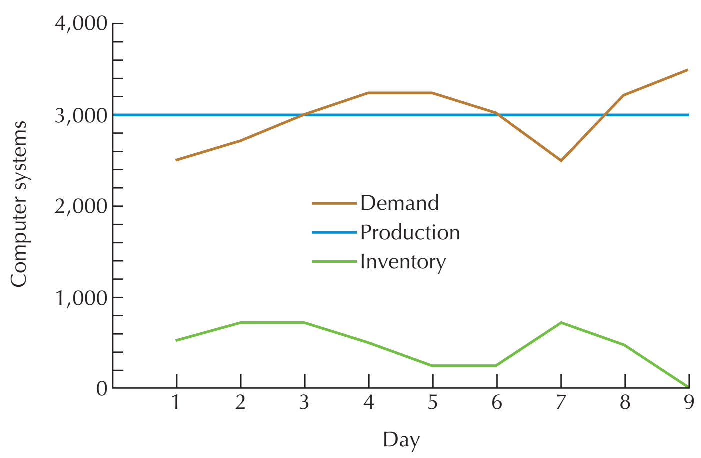


TABLE 11.2
Inventory Drivers and Their Impact

INVENTORY DRIVER	IMPACT
Uncertainty in supply or demand	Safety stock, hedge inventory
Mismatch between a downstream partner's demand and the most efficient production or shipment volumes for an upstream partner	Cycle stock
Mismatch between downstream demand levels and upstream production capacity	Smoothing inventory
Mismatch between timing of customer demand and supply chain lead times	Anticipation inventory, transportation inventory

Inventory drivers
Business conditions that force companies to hold inventory.

With these concerns in mind, let's turn our attention to **inventory drivers**—business conditions that force companies to hold inventory. Table 11.2 summarizes the ways in which various inventory drivers affect different types of inventory. To the extent that organizations can manage and control the drivers of inventories, they can reduce the supply chain's need for inventory.

Supply uncertainty
The risk of interruptions in the flow of components from upstream suppliers.

In managing inventory, organizations face uncertainty throughout the supply chain. On the upstream (supplier) end, they face **supply uncertainty,** or the risk of interruptions in the flow of components they need for their internal operations. In assessing supply uncertainty, managers need to answer questions such as these:

- How consistent is the quality of the goods being purchased?
- How reliable are the supplier's delivery estimates?
- Are the goods subject to unexpected price increases or shortages?

Problems in any of these areas can drive up supply uncertainty, forcing an organization to hold safety stock or hedging inventories.

Demand uncertainty
The risk of significant and unpredictable fluctuations in downstream demand.

On the downstream (customer) side, organizations face **demand uncertainty,** or the risk of significant and unpredictable fluctuations in the demand for their products. For example, many suppliers of automobile components complain that the big automobile manufacturers' forecasts are unreliable and that order sizes are always changing, often at the last minute. Under such conditions, suppliers are forced to hold extra safety stock to meet unexpected jumps in demand or changes in order size.

In dealing with uncertainty in supply and demand, the trick is to determine what types of uncertainty can be reduced and then to focus on reducing them. For example, poor quality is a source of supply uncertainty that can be substantially reduced or even eliminated through business process or quality improvement programs, such as those we discussed in Chapters 4 and 5. On the other hand, forecasting may help to reduce demand uncertainty, but it can never completely eliminate it.

Another common inventory driver is the mismatch between demand and the most efficient production or shipment volumes. Let's start with a simple example—facial tissue. When you blow your nose, how many tissues do you use? Most people would say 1, yet tissues typically come in boxes of 200 or more. Clearly, a mismatch exists between the number of tissues you need at any one time and the number you need to purchase. The reason, of course, is that packaging, shipping, and selling facial tissues one at a time would be highly inefficient, especially because the cost of holding a cycle stock of facial tissues is trivial. On an organizational scale, mismatches between demand and efficient production or shipment volumes are the main drivers of cycle stocks. As we will see later in this chapter, managers can often alter their business processes to reduce production or shipment volumes, thereby reducing the mismatch with demand and the resulting need for cycle stocks.

Likewise, mismatches between overall demand levels and production capacity can force companies to hold smoothing inventories (Figure 11.5). Of course, managers can reduce smoothing inventories by varying their capacity to better match demand or by smoothing demand to better match capacity. As we saw in Chapter 10, both strategies have pros and cons.

The last inventory driver we will discuss is a mismatch between the timing of the customer's demand and the supply chain's lead time. When you go to the grocery store, you expect to find fresh produce ready to buy; your expected waiting time is zero. But produce can come from almost anywhere in the world, depending on the season. To make sure that bananas and lettuce will be ready and waiting for you at your local store, someone has to initiate their movement through the supply chain days or even weeks ahead of time and determine how much anticipation inventory to hold. Whenever the customer's maximum waiting time is shorter than the supply chain's lead time, companies must have transportation and anticipation inventories to ensure that the product will be available when the customer wants it.

How can businesses reduce the need to hold anticipation inventory? Often they do so both by shrinking their own lead time and by persuading customers to wait longer. It's hard to believe now, but personal computers once took many weeks to work their way through the supply chain. As a result, manufacturers were forced to hold anticipation inventories to meet customer demand. Today manufacturers assemble and ship a *customized* laptop or tablet directly to the customer's front door in just a few days. Customers get fast and convenient delivery of a product that meets their exact needs. At the same time, the manufacturer can greatly reduce or even eliminate anticipation inventory.

In the remainder of this chapter, we examine the systems that are used in managing various types of inventory. Before beginning a detailed discussion of these tools and techniques of inventory management, however, we need to distinguish between two basic inventory categories: independent demand and dependent demand inventory. The distinction between the two is crucial because the tools and techniques needed to manage each are *very* different.

Independent versus Dependent Demand Inventory

Independent demand inventory
Inventory items whose demand levels are beyond a company's complete control.

Dependent demand inventory
Inventory items whose demand levels are tied directly to a company's planned production of another item.

In general, **independent demand inventory** refers to inventory items whose demand levels are beyond a company's complete control. **Dependent demand inventory,** on the other hand, refers to inventory items whose demand levels are tied directly to the company's planned production of another item. Because the required quantities and timing of dependent demand inventory items can be predicted with great accuracy, they are under a company's *complete* control.

A simple example of an independent demand inventory item is a kitchen table. While a furniture manufacturer may use forecasting models to predict the demand for kitchen tables and may try to use pricing and promotions to manipulate demand, the *exact* demand for kitchen tables is unpredictable. The fact is that *customers* determine the demand for these items, so finished tables clearly fit the definition of independent demand inventory.

But what about the components that are used to make the tables, such as legs? Suppose that a manufacturer has decided to produce 500 tables five weeks from now. With this information, a manager can quickly calculate exactly how many legs will be needed:

$$500 \times 4 \text{ legs per table} = 2{,}000 \text{ legs}$$

Furthermore, the manager can determine exactly when the legs will be needed, based on the company's production schedule. Because the timing and quantity of the demand for table legs are completely predictable and under the manager's total control, the legs fit the definition of dependent demand items. Dependent demand items require an entirely different approach to managing than do independent demand items. We discuss ways of managing dependent demand items in more depth in Chapter 12.

Periodic review system
An inventory system that is used to manage independent demand inventory. The inventory level for an item is checked at regular intervals and restocked to some predetermined level.

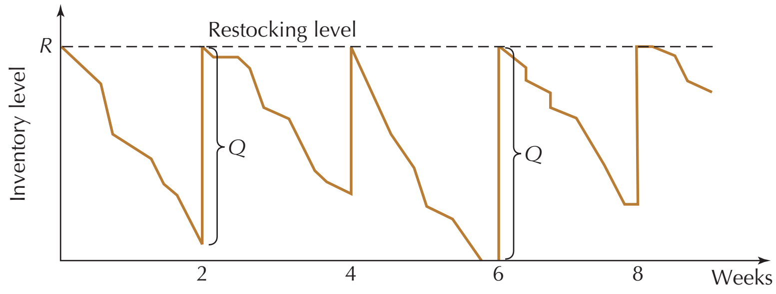
Three basic approaches are used to manage independent demand inventory items: periodic review systems, continuous review systems, and single-period inventory systems. We examine all three approaches in the following sections.

11.2 PERIODIC REVIEW SYSTEMS

One of the simplest approaches to managing independent demand inventory is based on a periodic review of inventory levels. In a **periodic review system,** a company checks the inventory level of an item at regular intervals and restocks to some predetermined level, R. The actual order quantity, Q, is the amount required to bring the inventory level back up to R. Stated more formally:

$$Q = R - I \tag{11.1}$$

FIGURE 11.6
Periodic Review System



where:

Q = order quantity
R = restocking level
I = inventory level at the time of review

Figure 11.6 shows the fluctuations in the inventory levels of a single item under a two-week periodic review system. As the downward-sloping line shows, the inventory starts out full and then drains down as units are pulled from it. (Note that the line will be straight only if demand is constant.) After two weeks, the inventory is replenished, and the process begins again.

A periodic review system nicely illustrates the use of both cycle stock and safety stock. By replenishing inventory every two weeks, rather than daily or even hourly, the organization spreads the cyclical cost of restocking across more units. And the need to hold safety stock helps to determine the restocking level. Increasing the restocking level effectively increases safety stock: The higher the level, the less likely the organization is to run out of inventory before the next replenishment period. On the flip side, because inventory is checked only at regular intervals, the company could run out of an item before the inventory is replenished. In fact, that is exactly what happens just before week 6 in Figure 11.6. If you have ever visited your favorite vending machine, only to find that the item you wanted has been sold out, you have been the victim of a periodic review system stockout.

As you might imagine, a periodic review system is best suited to items for which periodic restocking is economical and the cost of a high restocking level (and hence a large safety stock) is not prohibitive. A classic example is a snack food display at a grocery store. Constantly monitoring inventory levels for low-value items such as pretzels or potato chips makes no economic sense. Rather, a vendor will stop by a store regularly and top off the supply of all the items, usually with more than enough to meet demand until the next replenishment date.

Restocking Levels

The key question in setting up a periodic review system is determining the restocking level, R. In general, R should be high enough to meet all but the most extreme demand levels during the reorder period (RP) and the time it takes for the order to come in (L). Specifically:

$$R = \mu_{RP+L} + z\sigma_{RP+L} \qquad \textbf{(11.2)}$$

where:

μ_{RP+L} = average demand during the reorder period and the order lead time
σ_{RP+L} = standard deviation of demand during the reorder period and the order lead time
z = number of standard deviations above the average demand (higher z values increase the restocking level, thereby lowering the probability of a stockout)

Service level
A term used to indicate the amount of demand to be met under conditions of demand and supply uncertainty.

Equation (11.2) assumes that the demand during the reorder period and the order lead time is normally distributed. By setting R a certain number of standard deviations above the average, a firm can establish a **service level,** which indicates what percentage of the time inventory levels will be high enough to meet demand during the reorder period. For example, setting

$z = 1.28$ would make R large enough to meet expected demand 90% of the time (i.e., provide a 90% service level), while setting $z = 2.33$ would provide a 99% service level. Different z values and the resulting service levels are listed in the following table. (More values can be derived from the normal curves area table in Appendix I.)

z VALUE	RESULTING SERVICE LEVEL
1.28	90%
1.65	95%
2.33	99%
3.08	99.9%

EXAMPLE 11.1

Establishing a Periodic Review System for McCreery's Chips

McCreery's Chips sells large tins of potato chips at a grocery superstore. Every 10 days, a McCreery's deliveryperson stops by and checks the inventory level. He then places an order, which is delivered 3 days later. Average demand during the reorder period and order lead time (13 days total) is 240 tins. The standard deviation of demand during this same time period is 40 tins. The grocery superstore wants enough inventory on hand to meet demand 95% of the time. In other words, the store is willing to take a 5% chance that it will run out of tins before the next order arrives.

Using this information, McCreery's establishes the following restocking level:

$$\begin{aligned} R &= \mu_{RP+L} + z\sigma_{RP+L} \\ &= 240 \text{ tins} + 1.65 * 40 \text{ tins} = 306 \text{ tins} \end{aligned}$$

Suppose the next time the delivery person stops by, he counts 45 tins. Based on this information, he will order $Q = 306 - 45 = 261$ tins, which will be delivered in 3 days.

11.3 CONTINUOUS REVIEW SYSTEMS

Continuous review system An inventory system used to manage independent demand inventory. The inventory level for an item is constantly monitored, and when the reorder point is reached, an order is released.

While the periodic review system is straightforward, it is *not* well suited to managing critical and/or expensive inventory items. A more sophisticated approach is needed for these types of inventory. In a **continuous review system,** the inventory level for an item is constantly monitored, and when the reorder point is reached, an order is released.

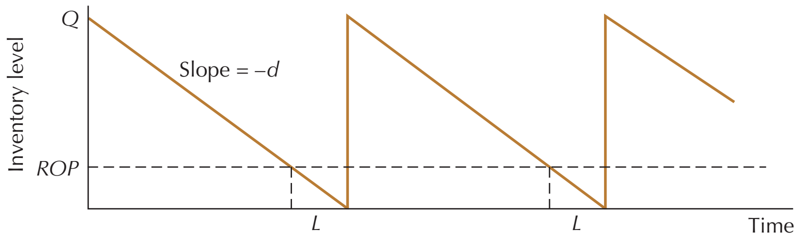
A continuous review system has several key features:

1. Inventory levels are monitored constantly, and a replenishment order is issued only when a preestablished reorder point has been reached.
2. The size of a replenishment order is typically based on the trade-off between holding costs and ordering costs.
3. The reorder point is based on both demand and supply considerations, as well as on how much safety stock managers want to hold.

To simplify our discussion of continuous review systems, we will begin by assuming that the variables that underlie the system are constant. Specifically:

1. The inventory item we are interested in has a constant demand per period, d. That is, there is no variability in demand from one period to the next. Demand for the year is D.
2. L is the lead time, or number of periods that must pass before a replenishment order arrives. L is also constant.
3. H is the cost of holding a single unit in inventory for a year. It includes the cost of the space needed to store the unit, the cost of potential obsolescence, and the opportunity cost of tying up the organization's funds in inventory. H is known and fixed.
4. S is the cost of placing an order, regardless of the order quantity. For example, the cost to place an order might be \$100, whether the order is for 2 or 2,000 units. S is also known and fixed.
5. P, the price of each unit, is fixed.

FIGURE 11.7
Continuous Review System (with Constant Demand Rate *d*)



Under these assumptions, the fluctuations in the inventory levels for an item will look like those in Figure 11.7. Inventory levels start out at Q, the order quantity, and decrease at a constant rate, *d*. Because this is a continuous review system, the next order is issued when the reorder point, labeled *ROP*, is reached. What should the reorder point be? In this simple model, in which the demand rate and lead time are constant, we should reorder when the inventory level reaches the point where there are just enough units left to meet requirements until the next order arrives:

$$ROP = dL \qquad \textbf{(11.3)}$$

For example, if the demand rate is 50 units a week and the lead time is 3 weeks, the manager should place an order when the inventory level drops to 150 units. If everything goes according to plan, the firm will run out of units just as the next order arrives. Finally, because the inventory level in this model goes from Q to 0 over and over again, the average inventory level is $\frac{Q}{2}$.

The Economic Order Quantity (*EOQ*)

How do managers of a continuous review system choose the order quantity (Q)? Is there a "best" order quantity, and if so, how do holding costs (*H*) and ordering costs (*S*) affect it? To understand the role of holding and ordering costs in a continuous review system, let's see what happens if the order quantity is sliced in half, to Q′ as shown in Figure 11.8. The result: With quantity Q′ the manager ends up ordering twice as often, which doubles the company's ordering costs. On the other hand, cutting the order quantity in half also halves the average inventory level, which lowers holding costs.

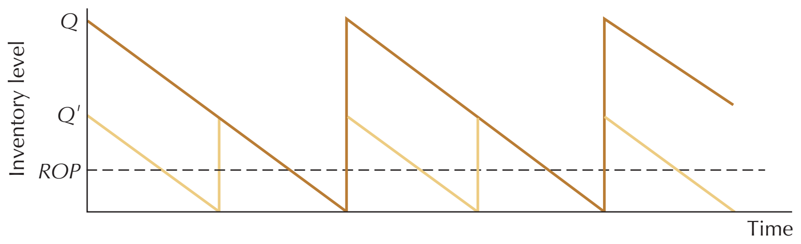
The relationship between holding costs and ordering costs can be seen in the following equation:

$$\begin{aligned}\text{Total holding and ordering cost for the year} &= \text{total yearly holding cost} \\ &\quad + \text{total yearly ordering cost} \\ &= \left(\frac{Q}{2}\right)H + \left(\frac{D}{Q}\right)S \qquad \textbf{(11.4)}\end{aligned}$$

Yearly holding cost is calculated by taking the average inventory level (Q/2) and multiplying it by the per-unit holding cost. Yearly ordering cost is calculated by calculating the number of times we order per year (*D*/Q) and multiplying this by the fixed ordering cost.

As Equation (11.4) suggests, there is a trade-off between yearly holding costs and ordering costs. Reducing the order quantity, Q, will decrease holding costs, but force the organization to order more often. Conversely, increasing Q will reduce the number of times an order must be placed but result in higher average inventory levels.

FIGURE 11.8
The Effect of Halving the Order Quantity



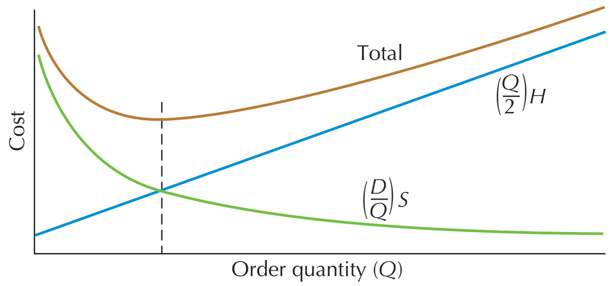


FIGURE 11.9 The Relationships among Yearly Holding Costs, Yearly Ordering Costs, and the Order Quantity, *Q*

Figure 11.9 shows graphically how yearly holding and ordering costs react as the order quantity, Q, varies. In addition to showing the cost curves for yearly holding costs and yearly ordering costs, Figure 11.9 includes a total cost curve that combines these two. If you look closely, you can see that the lowest point on the total cost curve also happens to be where yearly holding costs equal yearly ordering costs.

Economic order quantity (*EOQ*) The order quantity that minimizes annual holding and ordering costs for an item.

Figure 11.9 illustrates the **economic order quantity (EOQ),** the particular order quantity (Q) that minimizes holding costs and ordering costs for an item. This special order quantity is found by setting yearly holding costs equal to yearly ordering costs and solving for Q:

$$\left(\frac{Q}{2}\right)H = \left(\frac{D}{Q}\right)S$$

$$Q^2 = \frac{2DS}{H} \qquad \textbf{(11.5)}$$

$$Q = \sqrt{\frac{2DS}{H}} = EOQ$$

where:

Q = order quantity
H = annual holding cost per unit
D = annual demand
S = ordering cost

As Figure 11.9 shows, order quantities that are higher than the *EOQ* will result in annual holding costs that are higher than ordering costs. Conversely, order quantities that are lower than the *EOQ* will result in annual ordering costs that are higher than holding costs.

EXAMPLE 11.2

Calculating the *EOQ* at Boyer's Department Store

You are in charge of ordering items for Boyer's Department Store, located in Seattle. For one of the products Boyer's carries, the Hudson Valley Model Y ceiling fan, you have the following information:

$$\text{Annual demand } (D) = 4{,}000 \text{ fans a year}$$
$$\text{Annual holding cost } (H) = \$15 \text{ per fan}$$
$$\text{Ordering cost } (S) = \$50 \text{ per order}$$

Your predecessor ordered fans four times a year, in quantities (Q) of 1,000. The resulting annual holding and ordering costs were:

$$\text{Holding costs for the year} + \text{ordering costs for the year}$$
$$= (1{,}000/2) + (4{,}000/1{,}000)\$50$$
$$= \$7{,}500 + \$200 = \$7{,}700$$

Because holding costs are much higher than ordering costs, we know that the *EOQ* must be much lower than 1,000 fans. In fact:

$$EOQ = \sqrt{\frac{2*4{,}000*\$50}{\$15}}, \text{ which rounds to 163 fans per order}$$

The number 163 seems strange, so let's check to see if it results in lower annual costs:

$$\begin{aligned}&\text{Holding costs} + \text{ordering costs}\\&\quad = (163/2)\$15 + (4{,}000/163)\$50\\&\quad = \$1{,}222.50 + \$1{,}226.99 = \$2{,}449.49\end{aligned}$$

Notice that holding costs and ordering costs are essentially equal, as we would expect. More important, *simply by ordering the right quantity*, you could reduce annual holding and ordering costs for this item by

$$\$7{,}700 - \$2{,}449 = \$5{,}251$$

Now suppose Boyer's carries 250 other products with cost and demand structures similar to that of the Hudson Valley Model Y ceiling fan. In that case, you might be able to save 250*\$5,251 = \$1,312,750 per year in ordering and holding costs just by ordering the right quantities!

Of course, the *EOQ* has some limitations. Holding costs (H) and ordering costs (S) cannot always be estimated precisely, so managers may not always be able to calculate the true *EOQ*. However, as Figure 11.9 suggests, total holding and ordering costs are relatively flat over a wide range around the *EOQ*. So order quantities can be off a little and still yield total costs that are close to the minimum.

A more valid criticism of the *EOQ* is that it does not take into account volume discounts, which can be particularly important if suppliers offer steep discounts to encourage customers to order in large quantities. Later in the chapter, we examine how volume discounts affect the order quantity decision.

Other factors that limit the application of the *EOQ* model include ordering costs that are not always fixed and demand rates that vary throughout the year. However, the *EOQ* is a good starting point for understanding the impact of order quantities on inventory-related costs.

Reorder Points and Safety Stock

The *EOQ* tells managers *how much* to order but not *when* to order. We saw in Equation (11.3) that when the demand rate (d) and lead time (L) are constant, the reorder point is easily calculated as:

$$ROP = dL$$

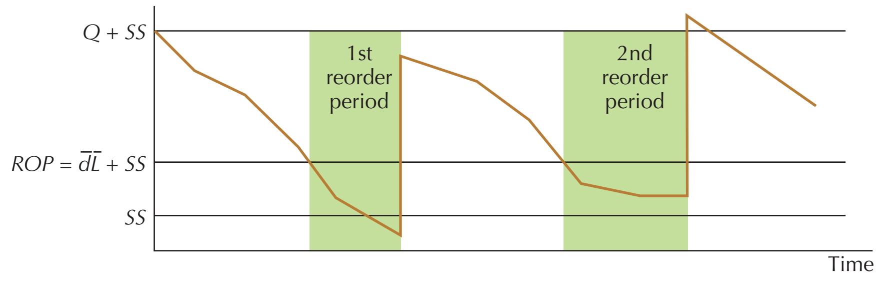
But d and L are rarely fixed. Consider the data in Table 11.3, which lists 10 different combinations of demand rates and lead times. The average demand rate, $\bar{d}$, and average lead

TABLE 11.3
Sample Variations in Demand Rate and Lead Time

DEMAND RATE (d) IN UNITS PER WEEK	LEAD TIME (L), IN WEEKS	DEMAND DURING LEAD TIME (dL), IN UNITS
60	3	180*
40	4	160*
55	2	110
45	3	135
50	3	150
65	3	195*
35	3	105
55	3	165*
45	4	180*
50	2	100
Average = 50 units	Average = 3 weeks	Average = 148 units

*Demand greater than $\overline{dL}$

FIGURE 11.10
The Impact of Varying Demand Rates and Lead Times



time, $\bar{L}$, are 50 units and 3 weeks, respectively. Our first inclination in this case might be to set the reorder point at $\overline{d}\overline{L} = 150$ units. Yet 5 out of 10 times, dL exceeds 150 units (see Table 11.3). A better solution—one that takes into account the variability in demand rate and lead time—is needed.

When either lead time or demand—or both—varies, a better solution is to set the reorder point higher than $ROP = dL$. Specifically:

$$ROP = \overline{d}\overline{L} + SS \quad \textbf{(11.6)}$$

where:

$SS =$ safety stock

Recall that WolfByte Computers carried a safety stock of 1,000 keyboards (Figure 11.4). Again, safety stock (SS) is an extra amount beyond that needed to meet average demand during lead time. This is added to the reorder point to protect against variability in both demand and lead time. Safety stock raises the reorder point, forcing a company to reorder earlier than usual. In doing so, it helps to ensure that future orders will arrive before the existing inventory runs out.

Figure 11.10 shows how safety stock works when both the demand rate and the lead time vary. We start with an inventory level of Q plus the safety stock ($Q + SS$). When we reach the new reorder point of $\overline{d}\overline{L} + SS$, an order is released. But look what happens during the first reorder period: Demand exceeds $\overline{d}\overline{L}$, forcing workers to dip into the safety stock. If the safety stock had not been there, the inventory would have run out. In the second reorder period, even though the lead time is longer than before, demand flattens out so much that workers do not need the safety stock.

In general, the decision of how much safety stock to hold depends on five factors:

1. The variability of demand
2. The variability of lead time
3. The average length of lead time
4. The desired service level
5. The average demand

Let's talk about each of these factors. First, the more the demand level and the lead time vary, the more likely it is that inventory will run out. Therefore, higher variability in demand and lead time will tend to force a company to hold more safety stock. Furthermore, a longer average lead time exposes a firm to this variability for a longer period. When lead times are extremely short, as they are in just-in-time (JIT) environments (see Chapter 13), safety stocks can be very small.

The service level is a managerial decision. Service levels are usually expressed in statistical terms, such as "During the reorder period, we should have stock available 90% of the time." While the idea that management might agree to accept even a small percentage of stockouts may seem strange, in reality, whenever demand or lead time varies, the *possibility* exists that a firm will run out of an item, no matter how large the safety stock. The higher the desired service level, the less willing management is to tolerate a stockout, and the more safety stock is needed.

EXAMPLE 11.3

Calculating the Reorder Point and Safety Stock at Boyer's Department Store

Let's look at one approach to calculating the reorder point with safety stock. Like other approaches, this one is based on simple statistics. To demonstrate the math, we'll return to Boyer's Department Store and the Hudson Valley Model Y ceiling fan. Boyer's sells, on average, 16 Hudson Valley Model Y ceiling fans a day ($\bar{d} = 16$), with a standard deviation in daily demand of 3 fans ($\sigma_d = 3$). This demand information can be estimated easily from past sales history.

If the store reorders fans directly from the manufacturer, the fans will take, on average, 9 days to arrive ($\bar{L} = 9$), with a standard deviation in lead time of 2 days ($\sigma_L = 2$). The store manager has decided to maintain a 95% service level. In other words, the manager is willing to run out of fans only 5% of the time before the next order arrives.

From these numbers, we can see that:

$$\text{Average demand during the reorder period} = \bar{d}\bar{L} = 144 \text{ fans}$$

Taking the analysis a step further, we can show using basic statistics that:

$$\begin{aligned}\text{Standard deviation of demand during the reorder period} \\ &= \sigma_{dL} \\ &= \sqrt{\bar{L}\sigma_d^2 + \bar{d}^2\sigma_L^2} = \sqrt{9*9 + 256*4} \qquad \textbf{(11.7)} \\ &= 33.24\end{aligned}$$

To ensure that Boyer's meets its desired service level, we need to set the reorder point high enough to meet demand during the reorder period 95% of the time. Put another way, the reorder point (*ROP*) should be set at the 95th percentile of demand during the reorder period. Because demand during the reorder period is often normally distributed, basic statistics tells us that:

$$\begin{aligned}\text{Reorder point } (ROP) &= \text{95th percentile of demand during the reorder period} \\ &= \bar{d}\bar{L} + z\sigma_{dL} \\ &= 144 + 1.65*33.24 \\ &= 198.8, \text{ or } 199\end{aligned}$$

In this equation, 1.65 represents the number of standard deviations (*z*) above the mean that corresponds to the 95th percentile of a normally distributed variable. (Other *z* values and their respective service levels are shown in Table 11.4.) The more general formula for calculating the reorder point is, therefore:

$$ROP = \bar{d}\bar{L} + z\sqrt{\bar{L}\sigma_d^2 + \bar{d}^2\sigma_L^2} \qquad \textbf{(11.8)}$$

where:

$\bar{d}$ = average demand per time period
$\bar{L}$ = average lead time
σ_d^2 = variance of demand per time period
σ_L^2 = variance of lead time
z = number of standard deviations above the average demand during lead time (higher *z* values lower the probability of a stockout)

TABLE 11.4 ***z*** **Values Used in Calculating Safety Stock**

z VALUE	ASSOCIATED SERVICE LEVEL
0.84	80%
1.28	90
1.65	95
2.33	99

Notice that the first part of the equation, $\bar{d}\bar{L}$, covers only the average demand during the reorder period. The second part of the equation, $z\sqrt{\bar{L}\sigma_d^2 + \bar{d}^2\sigma_L^2}$, represents the safety stock. For Boyer's, then, the amount of safety stock needed is:

$$z\sqrt{\bar{L}\sigma_d^2 + \bar{d}^2\sigma_L^2} = 1.65 * 33.24 = 54.88, \text{ or } 55 \text{ fans}$$

Of course, there are other methods for determining safety stock. Some managers consider variations in both the lead time and the demand rate; others use a definition of service level that includes the frequency of reordering. (Firms that reorder less often than others are less susceptible to stockouts.) In practice, many firms take an unscientific approach to safety stock, such as setting the reorder point equal to 150% of expected demand. Whatever the method used, however, these observations will still hold: The amount of safety stock needed will be affected by the variability of demand and lead time, the length of the average lead time, and the desired service level.

Quantity Discounts

In describing the economic order quantity, one of our assumptions was that the price per unit, P, was fixed. This was a convenient assumption because it allowed us to focus on minimizing just the total holding and ordering costs for the year (Equation [11.3]). But what if a supplier offers a price discount for ordering larger quantities? How will this affect the EOQ?

When quantity discounts are in effect, we must modify our analysis to look at total ordering, holding, *and item costs* for the year:

$$\text{Total holding, ordering, and item costs for the year} = \left(\frac{Q}{2}\right)H + \left(\frac{D}{Q}\right)S + DP \quad \textbf{(11.9)}$$

where:

Q = order quantity
H = holding cost per unit
D = annual demand
P = price per unit (which can now vary)
S = ordering cost

Because the EOQ formula (Equation [11.5]) considers only holding and ordering costs, the EOQ may not result in lowest total costs when quantity discounts are in effect. To illustrate, suppose we have the following information:

D = 1,200 units per year
H = \$10 per unit per year
S = \$30 per order
P = \$35 per unit for orders less than 90; \$32.50 for orders of 90 or more

If we ignore the price discounts and calculate the EOQ, we get the following:

$$EOQ = \sqrt{\frac{2*1{,}200*\$30}{\$10}}, \text{ which rounds to 85 units}$$

Total annual holding, ordering, and item costs for an order quantity of 85 are:

$$\left(\frac{85}{2}\right)\$10 + \left(\frac{1{,}200}{85}\right)\$30 + \$35x1{,}200$$
$$= \$425 + \$423.53 + \$42{,}000$$
$$= \$42{,}848.53$$

But note that if we increase the order size by just 5 units, to 90, we can get a discount of $\$35 - \$32.50 = \$2.50$ per unit. Selecting an order quantity of 90 would give us the following annual holding, ordering, and item costs:

$$\left(\frac{90}{2}\right)\$10 + \left(\frac{1{,}200}{90}\right)\$30 + \$32.50x1{,}200$$
$$= \$450 + \$400 + \$39{,}000$$
$$= \$39{,}850.00$$

When volume price discounts are in effect, we must follow a two-step process:

1. Calculate the *EOQ*. If the *EOQ* number represents a quantity that can be purchased for the lowest price, stop—we have found the lowest cost order quantity. Otherwise, we go to step 2.
2. Compare total holding, ordering, and item costs at the *EOQ* quantity with total costs at each price break *above* the *EOQ*. There is no reason to look at quantities below the *EOQ*, as these would result in higher holding and ordering costs, as well as higher item costs.

EXAMPLE 11.4

Volume Discounts at Hal's Magic Shop

Robert Landau/Alamy Stock Photo

Hal's Magic Shop purchases masks from a Taiwanese manufacturer. The manufacturer has quoted the following price breaks to Hal:

ORDER QUANTITY	PRICE PER MASK
1–100	$15
101–200	$12.50
201 or more	$10

Hal sells 1,000 masks a year. The cost to place an order is $20, and the holding cost per mask is about $3 per year. How many masks should Hal order at a time?

Solving for the *EOQ*, Hal gets the following:

$$EOQ = \sqrt{\frac{2*1{,}000*\$20}{\$3}} = 115 \text{ masks}$$

Unfortunately, Hal cannot order 115 masks and get the lowest price of $10 per mask. Therefore, he compares total holding, ordering, and item costs at $Q = 115$ masks to those at the next price break, which occurs at 201 masks:

Total annual holding, ordering, and item costs for an order quantity of 115 masks =

$$\left(\frac{115}{2}\right)\$3 + \left(\frac{1{,}000}{115}\right)\$20 + \$12.50x1{,}000$$
$$= \$172.50 + \$173.91 + \$12{,}500$$
$$= \$12{,}846.41$$

Total annual holding, ordering, and item costs for an order quantity of 201 masks =

$$\left(\frac{201}{2}\right)\$3 + \left(\frac{1{,}000}{201}\right)\$20 + \$10.00x1{,}000$$
$$= \$301.50 + \$99.50 + \$10{,}000$$
$$= \$10{,}401.00$$

So even though an order quantity of 115 would minimize holding and ordering costs, the price discount associated with ordering 201 masks more than offsets this. Hal should use an order quantity of 201 masks.

11.4 SINGLE-PERIOD INVENTORY SYSTEMS

So far, our discussions have assumed that any excess inventory we order can be held for future use. But this is not always true. In some situations, excess inventory has a very limited life and must be discarded, sold at a loss, or even hauled away at additional cost if not sold in the period intended. Examples include fresh fish, magazines and newspapers, and Christmas trees. In other cases, inventory might have such a specialized purpose (such as spare parts for a specialized machine) that any unused units cannot be used elsewhere. When such conditions apply, a company must weigh the cost of being short against the cost of having excess units, where:

$$\text{Shortage cost} = C_{\text{Shortage}} = \text{value of the item } \textit{if} \text{ demanded} - \text{item cost} \quad \textbf{(11.10)}$$

$$\text{Excess cost} = C_{\text{Excess}} = \text{item cost} + \text{disposal cost} - \text{salvage value} \quad \textbf{(11.11)}$$

For example, say that an item that costs \$50 sells for \$200, but must be disposed of at a cost of \$5 if not sold. This item has the following shortage and excess costs:

$$C_{\text{Shortage}} = \$200 - \$50 = \$150$$
$$C_{\text{Excess}} = \$50 + \$5 = \$55$$

Single-period inventory system
A system used when demand occurs in only a single point in time.

Target service level (SL_T)
For a single-period inventory system, the service level at which the expected cost of a shortage equals the expected cost of having excess units.

Target stocking point (TS)
For a single-period inventory system, the stocking point at which the expected cost of a shortage equals the expected cost of having excess units.

The goal of a **single-period inventory system** is to establish a stocking level that strikes the *best balance* between expected shortage costs and expected excess costs. Developing a single-period system for an item is a two-step process:

1. Determine a **target service level (SL_T)** that strikes the best balance between shortage costs and excess costs.
2. Use the target service level to determine the **target stocking point (TS)** for the item.

We describe each of these steps in more detail in the following sections.

Target Service Level

For the single-period inventory system, service level is simply the probability that there are enough units to meet demand. Unlike a periodic and continuous review system, there is no reorder period to consider here—either there is enough inventory or there isn't. The target service level, then, is the service level at which the expected cost of a shortage equals the expected cost of having excess units:

$$\text{Expected shortage cost} = \text{expected excess cost}$$

or:

$$(1 - p)C_{\text{Shortage}} = pC_{\text{Excess}} \quad \textbf{(11.12)}$$

where:

p = probability that there are enough units to meet demand

$(1 - p)$ = probability that there is a shortage

C_{Shortage} = shortage cost

C_{Excess} = excess cost

The target service level (SL_T) is the p value at which Equation (11.12) holds true:

$$(1 - SL_T)C_{\text{Shortage}} = SL_T C_{\text{Excess}}$$

$$SL_T = \frac{C_{\text{Shortage}}}{C_{\text{Shortage}} + C_{\text{Excess}}} \tag{11.13}$$

where:

C_{Shortage} = shortage cost

C_{Excess} = excess cost

Let's use Equation (11.13) to test our intuition. Suppose the shortage cost and the excess cost for an item are both \$10. In this case, we would be indifferent to either outcome, and we would set the inventory level so that each outcome would be equally likely. Equation (11.13) confirms our logic:

$$SL_T = \frac{C_{\text{Shortage}}}{C_{\text{Shortage}} + C_{\text{Excess}}} = \frac{\$10}{\$10 + \$10} = 0.50, \text{ or } 50\%$$

But what if the cost associated with a shortage is much higher—say, \$90? In this case, we would want a much higher target service level because shortage costs are so much more severe than excess costs. Again, Equation (11.13) supports our reasoning:

$$\frac{C_{\text{Shortage}}}{C_{\text{Shortage}} + C_{\text{Excess}}} = \frac{\$90}{\$90 + \$10} = 0.9, \text{ or } 90\%$$

EXAMPLE 11.5

Determining the Target Service Level at Don's Lemonade Stands

Don Washing is trying to determine how many gallons of lemonade to make each day. Don needs to consider a single-period system because whatever lemonade is left over at the end of the day must be thrown away due to health regulations. Every gallon he mixes costs him \$2.50 but will generate \$10 in revenue if sold.

In terms of the single-period inventory problem, Dan's shortage and excess costs are defined as follows:

$$C_{\text{Shortage}} = \text{revenue per gallon} - \text{cost per gallon} = \$10.00 - \$2.50 = \$7.50$$

$$C_{\text{Excess}} = \text{cost per gallon} = \$2.50$$

From this information, Don can calculate his target service level:

$$SL_T = \frac{C_{\text{Shortage}}}{C_{\text{Shortage}} + C_{\text{Excess}}} = \frac{\$7.50}{\$7.50 + \$2.50} = 0.75, \text{ or } 75\%$$

Interpreting the results, Don should make enough lemonade to meet all demand approximately 75% of the time.

EXAMPLE 11.6

Determining the Target Service Level at Fran's Flowers

Every day, Fran Chapman of Fran's Flowers makes floral arrangements for sale at the local hospital. The arrangements cost her approximately \$12 to make, but they sell for \$25. Any leftover arrangements can be sold at a heavily discounted price of \$5 the following day. Fran wants to know what her target service level should be.

Fran's shortage and excess costs are as follows:

$$C_{\text{Shortage}} = \text{revenue per arrangement} - \text{cost per arrangement} = \$25 - \$12 = \$13$$
$$C_{\text{Excess}} = \text{cost per arrangement} - \text{salvage value} = \$12 - \$5 = \$7$$

Fran's target service level is, therefore:

$$SL_T = \frac{C_{\text{Shortage}}}{C_{\text{Shortage}} + C_{\text{Excess}}} = \frac{\$13}{\$13 + \$7} = 0.65, \text{ or } 65\%$$

Fran should make enough arrangements to meet all demand approximately 65% of the time.

Target Stocking Point

To complete the development of a single-period inventory system, we next have to translate the target service level (a probability) into a target stocking point. To do so, we have to know something about how demand is distributed. Depending on the situation, we can approximate the demand distribution from historical records, or we can use a theoretical distribution, such as the normal distribution or Poisson distribution. Furthermore, the distribution may be continuous (i.e., demand can take on fractional values) or discrete (i.e., demand can take on only integer values). Example 11.7 shows how the process works when we can model demand by using the normal distribution, while Example 11.8 demonstrates the process for a historically based discrete distribution.

EXAMPLE 11.7

Determining the Target Stocking Point for Normally Distributed Demand

In Example 11.5, Don Washing determined that the target service level for lemonade was:

$$\frac{C_{\text{Shortage}}}{C_{\text{Shortage}} + C_{\text{Excess}}} = \frac{\$7.50}{\$7.50 + \$2.50} = 0.75, \text{ or } 75\%$$

Don knows from past experience that the daily demand follows a normal distribution. Therefore, Don wants to set a target stocking point (*TS*) that is higher than approximately 75% of the area under the normal curve. Figure 11.11 illustrates the idea.

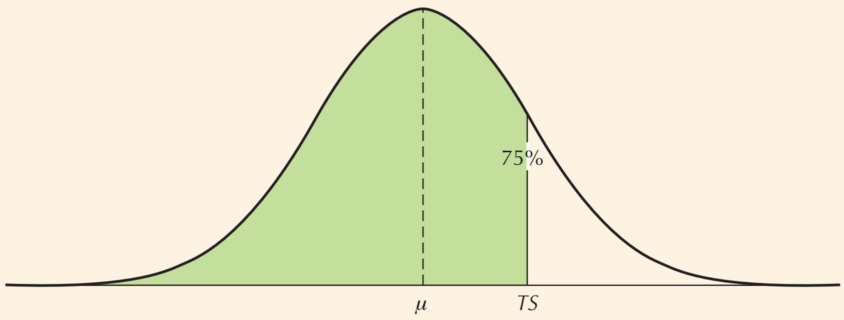


FIGURE 11.11 Target Stocking Point for Don's Lemonade Stands

The general formula for calculating the target stocking point when demand is normally distributed is:

$$\text{Target stocking point (normally distributed demand)} = \mu + z_{SLT}{}^*\sigma \qquad \textbf{(11.14)}$$

where:

μ = mean demand per time period

z_{SLT} = number of standard deviations above the mean required to meet the target service level

σ = standard deviation of demand per period

To further complicate things, Don also knows that the mean values and standard deviations for demand differ by day of the week (Table 11.5). Therefore, he will have to calculate different target stocking points for Monday through Friday, Saturday, and Sunday.

TABLE 11.5 Demand Values for Don's Lemonade Stands

DAY OF THE WEEK	MEAN DEMAND, μ	STANDARD DEVIATION OF DEMAND, σ
Monday–Friday	422 gallons	67 gallons
Saturday	719 gallons	113 gallons
Sunday	528 gallons	85 gallons

Using Equation (11.14) and the cumulative normal table (Table I.2 in Appendix I), Don quickly determines that a service level of 75% would require the target stocking point to be approximately 0.68 standard deviations above the mean. Therefore, the target stocking points are as follows:

$$\mu + z_{SLT}{}^{*}\sigma$$

Monday–Friday:	422 + 0.68*67 = 467.56 gallons
Saturday:	719 + 0.68*113 = 795.84 gallons
Sunday:	528 + 0.68*85 = 585.8 gallons

EXAMPLE 11.8

Determining the Target Stocking Point for Discrete Demand

In Example 11.6, Fran Chapman calculated her target service level for floral arrangements:

$$\frac{C_{\text{Shortage}}}{C_{\text{Shortage}} + C_{\text{Excess}}} = \frac{\$13}{\$13 + \$7} = 0.65, \text{ or } 65\%$$

Fran has kept track of arrangement sales for the past 34 days and has recorded the demand numbers shown in Table 11.6.

TABLE 11.6 Demand History for Fran's Flowers

DAILY DEMAND	NO. OF DAYS WITH THIS DEMAND LEVEL DURING THE PAST 34 DAYS	PERCENTAGE OF DAYS EXPERIENCING THIS DEMAND LEVEL	CUMULATIVE PERCENTAGE
10 or fewer	0	0/34 = 0%	0%
11	2	2/34 = 5.9%	5.9%
12	5	5/34 = 14.7%	20.6%
13	5	5/34 = 14.7%	35.3%
14	6	6/34 = 17.6%	52.9%
15	7	7/34 = 20.6%	73.5%
16	5	5/34 = 14.7%	88.2%
17	3	3/34 = 8.8%	97.0%
18	1	1/34 = 2.9%	100%
19 or more	0	0%	100%

Looking at Table 11.6, Fran realizes that if she wants to meet her target service level of 65%, she will need to stock 15 arrangements each day. This is because 15 arrangements is the first stocking point at which the probability of meeting expected demand (73.5%) is greater than the target service level of 65%. Conversely, if Fran stocked just 14 arrangements, according to Table 11.6, she would meet demand only 52.9% of the time.

11.5 INVENTORY IN THE SUPPLY CHAIN

So far, we have discussed the functions and drivers of inventory, and we have identified some basic techniques for managing independent demand inventory items. In this section, we broaden our scope to consider the ramifications of inventory decisions for the rest of the supply chain.

The Bullwhip Effect

Bullwhip effect
According to APICS, "an extreme change in the supply position upstream in a supply chain generated by a small change in demand downstream in the supply chain."

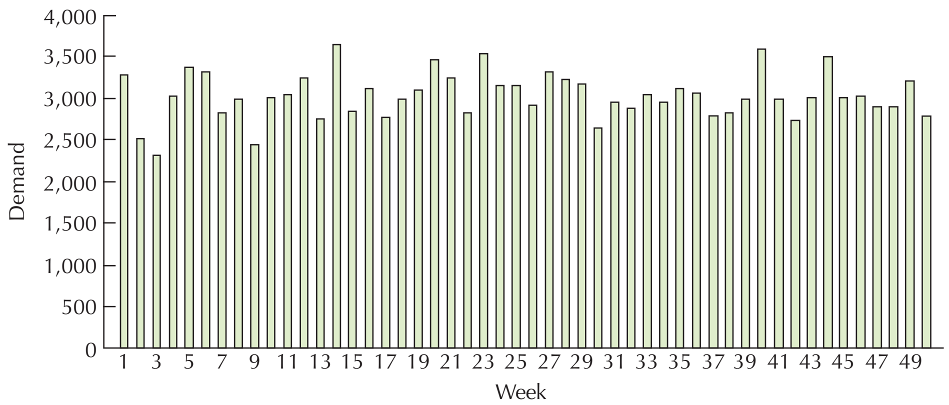
A major limitation of the *EOQ* model is that it considers the impact on costs for only a single firm. No consideration is given to how order quantity decisions for one firm affect other members of the supply chain. Therefore, even though the *EOQ* minimizes costs for a particular firm, it can cause problems for other partners and may actually increase *overall* supply chain costs. An example of this is the bullwhip effect.[6] APICS defines the **bullwhip effect** as "an extreme change in the supply position upstream in a supply chain generated by a small change in demand downstream in the supply chain."[7]

To illustrate, suppose the ABC plant makes pool cleaners that are sold through six distributors. The distributors have similar demand patterns and identical *EOQ* and *ROP* quantities:

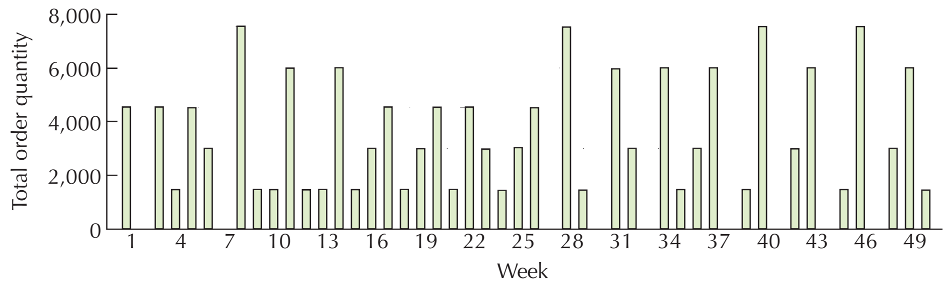
Average weekly demand for each distributor = 500 pool cleaners (standard deviation = 100)
Reorder quantity for each distributor = 1,500
Reorder point for each distributor = 750

Figure 11.12 shows the results of a simulation covering 50 weeks of simulated demand across the six distributors. Even though total weekly *demand* across the six distributors ranged from 2,331 to 3,641, the quantities *ordered by the distributors to be shipped from the plant* ranged from 0 to 7,500 in any one week.

FIGURE 11.12
Total Demand across the Six Distributors

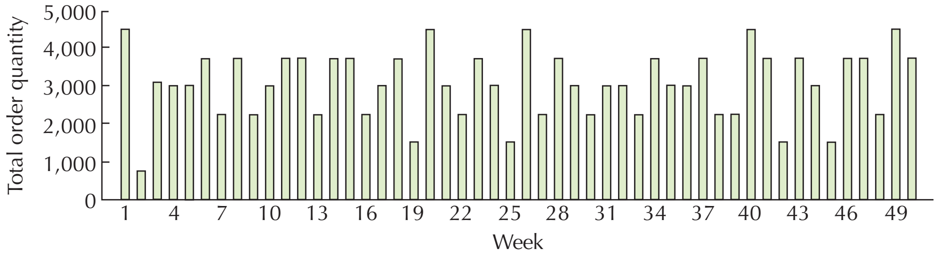


Resulting Total Quantities (Q = 1,500 for Each Distributor) Ordered from the ABC Plant



[6] Hau L. Lee, V. Padmanabhan, and S. Whang, "The Bullwhip Effect in Supply Chain," *Sloan Management Review* 38, no. 3 (Spring 1997): 70–77.
[7] Blackstone, *APICS Dictionary*.

FIGURE 11.13 Resulting Total Quantities ($Q = 750$ for Each Distributor) Ordered from the ABC Plant



What causes this? Quite simply, if a distributor reaches its reorder point, it places a large order. Otherwise, it does nothing. Therefore, a single-unit change in demand may determine whether or not a distributor places an order. So even though the distributors may be following good inventory practice by ordering in quantities of 1,500, the impact on the supply chain is to increase demand variability at the plant. Ultimately, this demand variability will drive up costs at the plant, which will then be forced to pass on at least some of these costs to the distributors.

In order to reduce the bullwhip effect, many supply chain partners are working together to reduce order quantities by removing volume discount incentives and reducing ordering costs. Figure 11.13 shows, for example, what the quantities ordered from the plant would look like if order quantities were cut in half, to 750. Now the orders range from 750 to 4,500; this is not perfect, but it's a big improvement over what the range was before.

Inventory Positioning

Managers must decide *where* in the supply chain to hold inventory. In general, the decision about where to position inventory is based on two general truths:

1. The cost and value of inventory increase as materials move down the supply chain.
2. The flexibility of inventory decreases as materials move down the supply chain.

That is, as materials work their way through the supply chain, they are transformed, packaged, and moved closer to their final destination. All these activities add both cost and value. Take breakfast cereal, for example. By the time it reaches the stores, cereal has gone through such a significant transformation and repackaging that it appears to have little in common with the basic materials that went into it. But the value added goes beyond transformation and packaging; it includes location as well. A product that is in stock and available immediately is always worth more to the customer than the same product available later.

What keeps organizations from pushing inventory as far down the supply chain as possible? Cost, for one thing. By delaying the transformation and movement of materials, organizations can postpone the related costs. Another reason for holding inventory back in the supply chain is flexibility. Once materials have been transformed, packaged, and transported down the chain, reversing the process becomes very difficult, if not impossible. Wheat that has been used to make a breakfast cereal cannot be changed into flour that is suitable for making a cake. Likewise, repackaging shampoo into a different-sized container is impractical once it has been bottled. The same goes for transportation: Repositioning goods from one location to another can be quite expensive, especially compared to the cost of delaying their movement until demand has become more certain. This loss of flexibility is a major reason materials are often held back in the supply chain. In short, supply chain managers are constantly trying to strike a balance between costs on the one hand and flexibility on the other in deciding where to position inventory.

Inventory pooling
Holding safety stock in a single location instead of multiple locations. Several locations then share safety stock inventories to lower overall holding costs by reducing overall safety stock levels.

EXAMPLE 11.9

Pooling Safety Stock at Boyer's Department Store

An especially good case for holding back inventory can be made if an organization can hold all of its safety stock in a single central location while still providing reasonably fast service to customers. This is one example of **inventory pooling,** in which several locations share safety stock inventories in order to lower overall holding costs. Suppose, for instance, that Boyer's has eight stores in the Chicago area. Each store sells, on average, 10 ceiling fans a day. Suppose that the standard deviation of daily demand at each store is 3 ($\sigma_d = 3$) and the average lead time from the fan manufacturer is 9 days, with a standard deviation of 2 days. We showed in Example 11.3 that to maintain a 95% service level ($z = 1.65$), a store would need to maintain a safety stock of 55 fans. The total safety stock across all eight stores would therefore be $8*55 = 440$ fans.

But what if Boyer's could pool the safety stock for all eight stores at a single store that could provide same-day service to the other seven stores? Because a single location would have a demand variance equal to n times that of n individual stores:

$$\text{Standard deviation of demand during lead time, across } n \text{ locations} = \sqrt{n}*\sigma_{dL}$$

For Boyer's, this calculates out to:

$$\begin{aligned} &= \sqrt{8}*\sqrt{\bar{L}*\sigma_d^2 + \bar{d}^2*\sigma_L^2} \\ &= \sqrt{8}*33.24 \\ &= 94 \text{ fans} \end{aligned}$$

And the pooled safety stock would be:

$$z*94 = 1.65*94 = 155.1, \text{ or } 155 \text{ fans}$$

By pooling its safety stock, Boyer's could reduce the safety stock level by $(440 - 155) = 285$ fans, or 65%. Considering the *thousands* of items stocked in Boyer's eight stores, centralizing Boyer's safety stock could produce significant savings.

Transportation, Packaging, and Material Handling Considerations

We will wrap up our discussion of inventory in the supply chain by considering how inventory decisions—most notably, order quantities—are intertwined with transportation, packaging, and material handling issues. The point of this discussion is to recognize that, in the real world, there is more to determining order quantities than just holding, ordering, and item price.

SUPPLY CHAIN CONNECTIONS

INVENTORY MANAGEMENT AND POOLING GROUPS AT AUTOMOTIVE DEALERSHIPS

Greg Balfour Evans/Alamy Stock Photo

Automobile dealerships face a classic dilemma in deciding how to manage their inventories of service parts. On the one hand, customers expect their cars to be fixed promptly. On the other hand, dealerships typically do not have the space or financial resources to stock all the possible items a customer's car may need. If this wasn't difficult enough, most dealerships do not have the inventory expertise on site to deal with these issues.

To address these concerns, many automotive manufacturers have developed information systems in which the manufacturer makes inventory decisions for dealerships, based on calculated reorder points. Of course, the dealerships may override these recommendations if they like. And if a part placed in the dealership under the recommendation of the system sits at the dealership too long, the manufacturer will typically buy it back.

In addition, dealerships in the same geographic region typically establish "pooling groups." These dealerships agree to share safety stocks for expensive or slow-moving items. If one dealership runs out of the part, it can instantly check on the part's availability within the pooling group (via an information system) and arrange to have the item picked up. The result is lower overall inventories and better parts availability for customers.

Consider an example. Borfax Industries buys specialized chemicals from a key supplier. These chemicals can be purchased in one of two forms:

FORM	QUANTITY	WEIGHT	DIMENSIONALITY (WIDTH/DEPTH/HEIGHT)	PRICE PER BAG
Carton	144 bags	218 lb.	2′ × 2′ × 1′	$25
Pallet	12 cartons; 1,728 bags	2,626 lb.	4′ × 4′ × 3.5′	$18

First, notice that the chemicals can be purchased in multiples of 144 (cartons) or 1,728 (pallets). It is highly unlikely that any *EOQ* value calculated by Borfax will fit perfectly into either of these packaging alternatives.

If Borfax purchases a full pallet, it can get a substantial price discount. The supplier will also make a direct truck shipment if Borfax purchases five or more pallets at a time. This will reduce the lead time from 15 days to 5. However, pallets require material handling equipment capable of carrying nearly 3,000 pounds, as well as suitable storage space. On the other hand, the cartons are less bulky but will still require some specialized handling due to their weight. In choosing the best order quantity, Borfax must not only look at the per-bag price but also consider its material handling capabilities, transportation costs, and inventory holding costs.

CHAPTER SUMMARY

Inventory is an important resource in supply chains, serving many functions and taking many forms. But like any other resource, it must be managed well if an organization is to remain competitive. We started this chapter by examining the various types of inventory in a simple supply chain. We also discussed what drives inventory. To the extent that organizations can leverage inventory drivers, they can bring down the amount of inventory they need to hold in order to run their supply chains smoothly.

In the second part of this chapter, we introduced some basic tools for managing independent demand inventory. These tools provide managers with simple models for determining how much to order and when to order. We then examined the relationship between inventory decisions and the bullwhip effect, the decision about where to position inventory in the supply chain, and how transportation, packaging, and material handling considerations might impact inventory decisions.

KEY FORMULAS

Restocking level under a periodic review system (page 339):

$$R = \mu_{RP+L} + z\sigma_{RP+L} \tag{11.2}$$

where:

μ_{RP+L} = average demand during the reorder period and the order lead time
σ_{RP+L} = standard deviation of demand during the reorder period and the order lead time
z = number of standard deviations above the average demand (higher z values lower the probability of a stockout)

Total holding and ordering costs for the year (page 341):

$$\left(\frac{Q}{2}\right)H + \left(\frac{D}{Q}\right)S \tag{11.4}$$

where:

Q = order quantity
H = annual holding cost per unit
D = annual demand
S = ordering cost

Economic order quantity (*EOQ*) (page 342):

$$Q = \sqrt{\frac{2DS}{H}} = EOQ \tag{11.5}$$

where:

Q = order quantity
H = annual holding cost per unit
D = annual demand
S = ordering cost

Reorder point under a continuous review system (page 345):

$$ROP = \bar{d}\bar{L} + z\sqrt{\bar{L}\sigma_d^2 + \bar{d}^2\sigma_L^2} \tag{11.8}$$

where:

$\bar{d}$ = average demand per time period
$\bar{L}$ = average lead time
σ_d^2 = variance of demand per time period
σ_L^2 = variance of lead time
z = number of standard deviations above the average demand during lead time (higher z values lower the probability of a stockout)

Total holding, ordering, and item costs for the year (page 346):

$$\left(\frac{Q}{2}\right)H + \left(\frac{D}{Q}\right)S + DP \tag{11.9}$$

where:

Q = order quantity
H = holding cost per unit
D = annual demand
P = price per unit
S = ordering cost

Target service level under a single-period inventory system (page 349):

$$SL_T = \frac{C_{\text{Shortage}}}{C_{\text{Shortage}} + C_{\text{Excess}}} \tag{11.13}$$

where:

C_{Shortage} = shortage cost
C_{Excess} = excess cost

KEY TERMS

Anticipation inventory 335
Bullwhip effect 352
Continuous review system 340
Cycle stock 334
Demand uncertainty 337
Dependent demand inventory 338
Economic order quantity (*EOQ*) 342
Hedge inventory 335
Independent demand inventory 338
Inventory 333
Inventory drivers 337
Inventory pooling 353
Periodic review system 338
Safety stock 334
Service level 339
Single-period inventory system 348
Smoothing inventory 336
Supply uncertainty 337
Target service level (SL_T) 348
Target stocking point (*TS*) 348
Transportation inventory 336

USING EXCEL IN INVENTORY MANAGEMENT

Several of the models described in this chapter depend on estimates of average demand and average lead time and on associated measures of variance (σ^2) or standard deviation (σ). The spreadsheet model in Figure 11.14 shows how such values can be quickly estimated from historical data, using Microsoft Excel's built-in functions. The spreadsheet contains historical demand data for 20 weeks, as well as lead time information for 15 prior orders. From this information, the spreadsheet calculates average values and variances and then uses these values to calculate average demand during lead time, safety stock, and the reorder point. The highlighted cells represent the input values. The calculated cells are as follows:

Cell C32 (average weekly demand):	= AVERAGE(C12:C31)
Cell C33 (variance of weekly demand):	= VAR(C12:C31)
Cell G27 (average order lead time):	= AVERAGE(G12:G26)
Cell G28 (variance of lead time):	= VAR(G12:G26)
Cell F5 (average demand during lead time):	= C32*G27
Cell F6 (safety stock):	= F3*SQRT (G27*C33 + C32^2*G28)
Cell F7 (reorder point):	= F5 + F6

	A	B	C	D	E	F	G	H	I
1	**Calculating the Reorder Point from Demand and Order History**								
2									
3		z value (for desired service level:)				1.65			
4									
5			Average demand during lead time:			280.72	units		
6					+ Safety stock:	125.47	units		
7					Reorder point:	406.19	units	(Equation 10-6)	
8									
9		*** Demand History ***				*** Order History ***			
10							Lead time		
11		Week	Demand			Order	(days)		
12		1	33			1	10		
13		2	14			2	6		
14		3	18			3	12		
15		4	37			4	9		
16		5	34			5	10		
17		6	53			6	8		
18		7	31			7	8		
19		8	21			8	8		
20		9	19			9	7		
21		10	44			10	3		
22		11	43			11	8		
23		12	37			12	9		
24		13	45			13	7		
25		14	43			14	8		
26		15	36			15	8		
27		16	40			Average:	8.07		
28		17	28			Variance:	4.07		
29		18	41						
30		19	36						
31		20	43						
32		Average:	34.80						
33		Variance:	106.27						

FIGURE 11.14 Excel Solution to the Reorder Point Problem

SOLVED PROBLEMS

PROBLEM 1

Jake Fleming sells graphic card update kits for computers. Jake purchases these kits for $20 and sells about 250 kits a year. Each time Jake places an order, it costs him $25 to cover shipping and paperwork. Jake figures that the cost of holding an update kit in inventory is about $3.50 per kit per year. What is the economic order quantity? How many times per year will Jake place an order? How much will it cost Jake to order and hold these kits each year?

Solution

The economic order quantity for the kits is:

$$\sqrt{\frac{2*250*\$25}{\$3.50}} = 59.76\text{, or } 60 \text{ kits}$$

The number of orders placed per year is:

$$\frac{250}{60} = 4.17 \text{ orders per year}$$

The total holding and ordering costs for the year (not counting any safety stock Jake might hold) are:

$$\frac{60}{2}\$3.50 + \frac{250}{60}\$25 = \$105 + \$104.17 = \$209.17$$

PROBLEM 2

The manufacturer of the graphic card update kits has agreed to charge Jake just \$15 per kit if Jake orders 250 kits at a time. Should Jake accept the manufacturer's offer?

Solution

For the *EOQ*, the total holding, ordering, and item costs for the year are:

$$\frac{60}{2}\$3.50 + \frac{250}{60}\$25 = 250{*}\$20 = \$105 + \$104.17 + \$5{,}000 = \$5{,}209.17$$

If Jake takes the volume discount, he will order 250 kits at a time (after all, ordering more than 250 would only move him further away from the *EOQ*, which minimizes holding and ordering costs):

$$\frac{250}{2}\$3.50 + \frac{250}{250}\$25 + 250{*}\$15 = \$437.50 + \$25 + \$3{,}750 = \$4{,}212.50$$

Therefore, Jake should take the volume discount and order just once a year.

DISCUSSION QUESTIONS

1. You hear someone comment that *any* inventory is a sign of waste. Do you agree or disagree? Can managers simultaneously justify holding inventories and still seek out ways to lower inventory levels?
2. In your own words, what is an inventory driver? What is the difference between a controllable inventory driver and an uncontrollable inventory driver? Give examples.
3. Which of the following are independent demand inventory items? Dependent demand inventory items?
   - **a.** Bicycles in a toy store
   - **b.** Bicycle wheels in a bicycle factory
   - **c.** Blood at a blood bank
   - **d.** Hamburgers at a fast-food restaurant
   - **e.** Hamburger buns at a plant that produces frozen dinners
4. In a supply chain, what are the pros and cons of pushing inventory downstream, closer to the final customer? How might modular product designs (Chapter 15) make it more profitable for companies to postpone the movement of inventory down the supply chain?
5. (Use the *EOQ* and *ROP* formulas to answer this question.) Which variables could you change if you wanted to reduce inventory costs in your organization? Which ones would you prefer to change? Why?
6. The JIT/lean production movement has long argued that firms should:
   - **a.** Maximize their process flexibility so that ordering costs are minimized;
   - **b.** Stabilize demand levels;
   - **c.** Shrink lead times as much as possible; and
   - **d.** Assign much higher holding costs to inventory than has traditionally been the case.

   Using the *EOQ* and *ROP* formulas, explain how such efforts would be consistent with JIT's push for lower inventory levels.

PROBLEMS

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

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

Problems for Section 11.2: Periodic Review Systems

1. Jimmy's Delicatessen sells large tins of Tom Tucker's Toffee. The deli uses a periodic review system, checking inventory levels every 10 days, at which time an order is placed for more tins. Order lead time is 3 days. Average daily demand is 7 tins, so average demand during the reorder period and order lead time (13 days) is 91 tins. The standard deviation of demand during this same 13-day period is 17 tins.
   - **a.** (*) Calculate the restocking level. Assume that the desired service level is 90%.
   - **b.** (**) Suppose that the standard deviation of demand during the 13-day period drops to 4 tins. What happens to the restocking level? Explain why.
   - **c.** (***) Draw a sawtooth diagram similar to the one in Figure 11.3. Assume that the beginning inventory level is equal to the restocking level and that the demand rate is a *constant* 7 tins per day. What is the safety stock level? (*Hint:* Look at the formula for calculating restocking level.) What is the average inventory level?
2. Mountain Mouse makes freeze-dried meals for hikers. One of Mountain Mouse's biggest customers is a sporting goods superstore. Every 5 days, Mountain Mouse checks the inventory level at the superstore and places an order to restock the meals. These meals are delivered by UPS in 2 days. Average demand during the reorder period and order lead time is 100 meals, and the standard deviation of demand during this same time period is about 20 meals.

a. (**) Calculate the restocking level for Mountain Mouse. Assume that the superstore wants a 90% service level. What happens to the restocking level if the superstore wants a higher level of service—say, 95%?
b. (*) Suppose there are 20 meals in the superstore when Mountain Mouse checks inventory levels. How many meals should be ordered, assuming a 90% service level?

Problems for Section 11.3: Continuous Review Systems

3. Pam runs a mail-order business for gym equipment. Annual demand for TricoFlexers is 16,000. The annual holding cost per unit is \$2.50, and the cost to place an order is \$50.

   a. (*) What is the economic order quantity?
   b. (**) Suppose demand for TricoFlexers doubles, to 32,000. Does the *EOQ* also double? Explain what happens.
   c. (**) The manufacturer of TricoFlexers has agreed to offer Pam a price discount of \$5 per unit (\$45 rather than \$50) if she buys 1,500. Assuming that annual demand is still 16,000, how many units should Pam order at a time?

4. KraftyCity is a large retailer that sells power tools and other hardware supplies. One of its products is the Krafty-Man workbench. Information on the workbench is as follows:

$$\text{Annual demand} = 1{,}200$$
$$\text{Holding cost} = \$15 \text{ per year}$$
$$\text{Ordering cost} = \$200 \text{ per order}$$

   a. (*) What is the economic order quantity for the workbench?
   b. (**) Suppose that KraftyCity has to pay \$50 per workbench for orders under 200 but only \$42 per workbench for orders of 201 or more. Using the information provided in problem 3-4, what order quantity *should* KraftyCity use?
   c. (*) The lead time for KraftyCity workbenches is 3 weeks, with a standard deviation of 1.2 weeks, and the average weekly demand is 24, with a standard deviation of 8 workbenches. What should the reorder point be if KraftyCity wants to provide a 95% service level?
   d. (**) Now suppose the supplier of workbenches guarantees KraftyCity that the lead time will be a constant 3 weeks, with no variability (i.e., standard deviation of lead time = 0). Recalculate the reorder point, using the demand and service level information in problem 3-6. Is the reorder point higher or lower? Explain why.

5. Ollah's Organic Pet Shop sells about 4,000 bags of free-range dog biscuits every year. The fixed ordering cost is \$15, and the cost of holding a bag in inventory for a year is \$2.

   a. (*) What is the economic order quantity for the biscuits?
   b. (**) Suppose Ollah decides to order 200 bags at a time. What would the total ordering and holding costs for the year be? (For this problem, don't consider safety stock when calculating holding costs.)
   c. (**) Average weekly demand for free-range dog biscuits is 80 bags per week, with a standard deviation of 16 bags. Ollah uses a continuous inventory review system to manage inventory of the biscuits. Ollah wants to set the reorder point high enough that there is only a 5% chance of running out before the next order comes in. Assuming that the lead time is a constant 2 weeks, what should the reorder point be?
   d. (**) Suppose Ollah decides to use a periodic review system to manage the free-range dog biscuits, with the vendor checking inventory levels every week. Under this scenario, what would the restocking level be, assuming the same demand and lead time characteristics listed in problem 13 and the same 95% service level? (Note that because the standard deviation of weekly demand is 16, basic statistics tells us the standard deviation of demand over 3 weeks will be $\sqrt{3} \times 16 \approx 28$.)

6. Ollah's Organic Pet Shop sells bags of cedar chips for pet bedding or snacking (buyer's choice). The supplier has offered Ollah the following terms:

   Order 1–100 bags, and the price is \$6.00 a bag.
   Order 101 or more bags, and the price is \$4.50 a bag.

   Annual demand is 630, fixed ordering costs are \$9 per order, and the per-bag holding cost is estimated to be around \$2 per year.

   a. (*) What is the economic order quantity for the bags?
   b. (**) What order quantity should Ollah order, based on the volume discount? Is this different from the *EOQ*? If so, how could this be?
   c. (**) Suppose the lead time for bags is a constant 2 weeks, and average weekly demand is 12.6 bags, with a standard deviation of 3.2 bags. If Ollah wants to maintain a 98% service level, what should her reorder point be?

Problems for Section 11.4: Single-Period Inventory Systems

7. (**) David Polston prints up T-shirts to be sold at local concerts. The T-shirts sell for \$20 each but cost David only \$6.50 each. However, because the T-shirts have concert-specific information on them, David can sell a leftover shirt for only \$3. Suppose the demand for shirts can be approximated with a normal distribution and the mean demand is 120 shirts, with a standard deviation of 35. What is the target service level? How many shirts should David print up for a concert?
8. Sherry Clower is trying to figure out how many custom books to order for her class of 25 students. In the past, the number of students buying books has shown the following demand pattern:

NUMBER OF STUDENTS WHO BOUGHT A BOOK	PERCENTAGE OF OBSERVATIONS
16 or fewer	0%
17	4%
18	15%
19	17%
20	18%
21	26%
22	10%
23	6%
24	4%
25	0%

a. (**) Suppose each custom book costs Sherry $12 to print, and she sells the books to the students for $50 each. Excess books must be scrapped. What is the target service level? What is the target stocking point?

b. (**) Suppose printing costs increase to $22. Recalculate the new target service level and target stocking point. What happens?

9. One of the products sold by OfficeMax is a Hewlett-Packard LaserJet Z99 printer. As purchasing manager, you have the following information for the printer:

Average weekly demand (52 weeks per year):	60 printers
Standard deviation of weekly demand:	12 printers
Order lead time:	3 weeks
Standard deviation of order lead time:	0 (lead times are constant)
Item cost:	$120 per printer
Cost to place an order:	$2
Yearly holding cost per printer:	$48
Desired service level during reordering period:	99% ($z = 2.33$)

a. (*) What is the economic order quantity for the printer?

b. (**) Calculate annual ordering costs and holding costs (ignoring safety stock) for the *EOQ*. What do you notice about the two?

c. (**) Suppose OfficeMax currently orders 120 printers at a time. How much more or less would OfficeMax pay in holding and ordering costs per year if it ordered just 12 printers at a time? Show your work.

d. (**) What is the reorder point for the printer? How much of the reorder point consists of safety stock?

For parts e and f, use the following formula to consider the impact of safety stock (*SS*) on average inventory levels and annual holding costs:

$$\left(\frac{Q}{2} + SS\right)H$$

e. (***) What is the annual cost of holding inventory, including the safety stock? How much of this cost is due to the safety stock?

f. (***) Suppose OfficeMax is able to cut the lead time to a constant 1 week. What would the new safety stock level be? How much would this reduce annual holding costs?

10. (***) OfficeMax is considering using the Internet to order printers from Hewlett-Packard. The change is expected to make the cost of placing orders drop to almost nothing, although the lead time will remain the same. What effect will this have on the order quantity? On the holding and ordering costs for the year? Explain, using any formulas and examples you find helpful.

11. Through its online accessory store, Gateway sells its own products, as well as products made by other companies. One of these products is the WB150 WolfByte laptop computer:

Estimated *annual* demand:	15,376 laptops (50 weeks per year)
Cost:	$640 per laptop
Lead time:	2 weeks
Standard deviation of weekly demand:	16 laptops
Standard deviation of lead time:	0.3 weeks
Holding cost per unit per year:	40% of item cost
Ordering cost:	$25 per order
Desired service level:	95% ($z = 1.65$)

a. (*) What is the economic order quantity for the laptops? Calculate annual ordering costs and holding costs (ignoring safety stock) for the *EOQ*.

b. (**) What is the reorder point for the laptops? How much of the reorder point consists of safety stock?

c. (**) Suppose Gateway decides to order 64 laptops at a time. What would its yearly ordering and holding costs (ignoring safety stock) for the monitor be?

d. (**) Because computer technologies become obsolete so quickly, Gateway is thinking about raising holding costs from 40% of item cost to some higher percentage. What will be the impact on the economic order quantity for laptops? Explain why.

For parts e and f, use the following formula to consider the impact of safety stock (*SS*) on average inventory levels and annual holding costs:

$$\left(\frac{Q}{2} + SS\right)H$$

e. (***) What is the annual cost of holding inventory, including the safety stock? How much of this cost is due to the safety stock?

f. (***) Suppose Gateway is able to cut the lead time to a constant 1 week. What would the new safety stock level be? How much would this reduce annual holding costs?

12. One of the products stocked by a Sam's Club store is *Sams Cola*, which is sold in cases. The demand level for *Sams Cola* is highly seasonal:

- During the *slow season*, the demand rate is approximately 650 cases a month, which is the same as a yearly demand rate of $650*12 = 7{,}800$ cases.
- During the *busy season*, the demand rate is approximately 1,300 cases a month, or 15,600 cases a year.
- The cost to place an order is $5, and the yearly holding cost for a case of *Sams Cola* is $12.

a. (**) According to the *EOQ* formula, how many cases of *Sams Cola* should be ordered at a time during the slow season? How many cases of *Sams Cola* should be ordered during the busy season?

b. (**) Suppose Sam's Club decides to use the same order quantity, $Q = 150$, throughout the year. Calculate total holding and ordering costs for the year. Do not consider safety stock in your calculations. (Annual demand can be calculated as an average of the slow and busy rates given above.)

13. (**) During the busy season, the store manager has decided that 98% of the time, she does not want to run out of *Sams Cola* before the next order arrives. Use the following data to calculate the reorder point for *Sams Cola*:

Weekly demand during the busy season:	325 cases per week
Lead time:	0.5 weeks
Standard deviation of weekly demand:	5.25
Standard deviation of lead time:	0 (lead time is constant)
Number of standard deviations above the mean needed to provide a 98% service level (z):	2.05

14. (**) Dave's Sporting Goods sells Mountain Mouse freeze-dried meals. Dave's uses a continuous review system to manage meal inventories. Suppose Mountain Mouse offers the following volume discounts to its customers:

1–500 meals: $7 per meal
501 or more meals: $6.50 per meal

Annual demand is 2,000 meals, and the cost to place an order is $15. Suppose the holding cost is $2 per meal per year. How many meals should Dave's order at a time? What are the total holding, ordering, and item costs associated with this quantity?

15. (***) (*Microsoft Excel problem*) The following figure shows an Excel spreadsheet that compares total ordering and holding costs for some current order quantity to the same costs for the *EOQ* and calculates how much could be saved by switching to the *EOQ*. **Re-create this spreadsheet in Excel.** You should develop the spreadsheet so that the results will be recalculated if any of the values in the highlighted cells are changed. Your formatting does not have to be exactly the same, but the numbers should be. (As a test, see what happens if you just change the annual demand and cost per order to 5,000 and $25, respectively. Your new *EOQ* should be 91.29, and the total savings under the *EOQ* should be $5,011.39.)

	A	B	C	D	E	F
1	**Calculating Savings under *EOQ***					
2						
3			Annual demand:	4,000		
4			Annual holding cost, per unit:	$30.00		
5			Cost per order:	$30.00		
6						
7			Current order quantity:	500		
8			Current annual holding cost:	$7,500.00		
9			Current annual ordering cost:	$240.00		
10			Total cost:	$7,740.00		
11						
12			Economic order quantity:	89.44		
13			*EOQ* annual holding cost:	$1,341.64		
14			*EOQ* annual ordering cost:	$1,341.64		
15			Total cost:	$2,683.28		
16						
17			**Total savings under *EOQ*:**	**$5,056.72**		
18						

16. (***) (*Microsoft Excel problem*) The following figure shows an Excel spreadsheet that calculates the benefit of pooling safety stock. Specifically, the sheet calculates how much could be saved in annual holding costs if the safety stocks for three locations were held in a single location. **Re-create this spreadsheet in Excel.** You should develop the spreadsheet so that the results will be recalculated if any of the values in the highlighted cells are changed. Your formatting does not have to be exactly the same, but the numbers should be. (As a test, see what happens if you change Location 1's average daily demand and variance of daily demand to 100 and 15, respectively. Your new pooled safety stock should be 30.34, and the total savings due to pooling safety stock should be $108.21.)

	A	B	C	D	E	F	G
1	**Calculating Savings Due to Pooling Safety Stock**						
2							
3	Annual holding cost per unit:			$5.00			
4	Lead time (fixed):			8	days		
5	z value (for desired service level):			2.33			
6							
7						Average demand	
8			Average	Variance of	Reorder	during	
9			daily demand	daily demand	point	lead time	Safety stock
10		Location 1	50	4.5	413.98	400.00	13.98
11		Location 2	40	6.2	336.41	320.00	16.41
12		Location 3	30	5	254.74	240.00	14.74
13						Total units:	45.13
14						**Total annual holding cost:**	**$225.63**
15							
16						Average demand	
17			Average	Variance of	Reorder	during	
18			daily demand	daily demand	point	lead time	Safety stock
19		**Pooled SS**	120	15.7	986.11	960.00	26.11
20						**Total annual holding cost:**	**$130.56**
21							
22						**Savings due to pooling safety stock:**	**$95.07**

CASE STUDY

Northcutt Bikes: The Service Department

SJ Travel Photo and Video/Shutterstock

Introduction

Several years ago, Jan Northcutt, owner of Northcutt Bikes, recognized the need to organize a separate department to deal with service parts for the bikes her company makes. Because the competitive strength of her company was developed around customer responsiveness and flexibility, she felt that creating a separate department focused exclusively on aftermarket service was critical in meeting that mission.

When she established the department, she named Ann Hill, one of her best clerical workers at the time, to establish and manage the department. At first, the department occupied only a corner of the production warehouse, but now it has grown to occupy its own 100,000-square-foot warehouse. The service business has also grown significantly, and it now represents over 15% of the total revenue of Northcutt Bikes. The exclusive mission of the service department is to provide parts (tires, seats, chains, etc.) to the many retail businesses that sell and service Northcutt Bikes.

While Ann has turned out to be a very effective manager (and now holds the title of Director of Aftermarket Service), she still lacks a basic understanding of materials management. To help her develop a more effective materials management program, she hired Mike Alexander, a recent graduate of an outstanding business management program at North Carolina State University, to fill the newly created position of Materials Manager of Aftermarket Service.

The Current Situation

During the interview process, Mike got the impression that there was a lot of opportunity for improvement at Northcutt Bikes. It was only after he selected his starting date and requested some information that he started to see the full extent of the challenges that lay ahead. His first day on the job really opened his eyes. One of the first items he had requested was a status report on inventory history and shipped orders. In response, the following note was on his desk the first day from the warehouse supervisor, Art Demming:

> *We could not compile the history you requested, as we keep no such records. There's just too much stuff in here to keep a close eye on it all. Rest assured, however, that we think the inventory positions on file are accurate, as we just completed our physical count of inventory last week. I was able to track down a demand history for a couple of our items, and that is attached to this memo. Welcome to the job!*

Mike decided to investigate further. Although the records were indeed difficult to track down and compile, by the end of his second week he had obtained a fairly good picture of the situation, based on an investigation of 100 parts selected at random. He learned, for example, that although there was an average of over 70 days' worth of inventory (annual sales/average inventory), the fill rate for customer orders was less than 80%, meaning that only 80% of the items requested were in inventory; the remaining orders were backordered. Unfortunately, the majority of customers viewed service parts as generic and would take their business elsewhere when parts were not available from Northcutt Bikes.

What really hurt was when those businesses sometimes canceled their entire order for parts and placed it with another parts supplier. The obvious conclusion was that while there was plenty of inventory overall, the timing and quantities were misplaced. Increasing the inventory did not appear to be the answer, not only because a large amount was already being held but also because the space in the warehouse (built less than two years ago) had increased from being 45% utilized just after it moved in to its present utilization of over 95%.

Mike decided to start his analysis and development of solutions on the two items for which Art had already provided demand history. He felt that if he could analyze and correct any problems with those two parts, he could expand the analysis to most of the others. The two items on which he had history and concentrated his initial analysis were the FB378 Fender Bracket and the GS131 Gear Sprocket. Northcutt Bikes purchases the FB378 from a Brazilian source. The lead time has remained constant, at three weeks, and the estimated cost of a purchase order for these parts is given at $35 per order. Currently Northcutt Bikes uses an order lot size of 120 for the FB378 and buys the items for $5 apiece.

The GS131 part, on the other hand, is a newer product only recently being offered. A machine shop in Nashville, Tennessee, produces the part for Northcutt Bikes, and it gives Northcutt Bikes a fairly reliable six-week lead time. The cost of placing an order with the machine shop is only about $15, and currently Northcutt Bikes orders 850 parts at a time. Northcutt Bikes buys the item for $10.75.

Following is the demand information that Art gave to Mike on his first day for the FB378 and the GS131:

	FB378		GS131	
WEEK	FORECAST	ACTUAL DEMAND	FORECAST	ACTUAL DEMAND
1	30	34		
2	32	44		
3	35	33		
4	34	39		
5	35	48		
6	38	30		
7	36	26		
8	33	45		
9	37	33		
10	37	30		
11	36	47	10	16
12	37	40	18	27
13	38	31	30	35
14	36	38	42	52
15	36	32	55	51
16	35	49	54	44
17	37	24	52	57
18	35	41	53	59
19	37	34	53	46
20	36	24	52	62
21	34	52	53	51
22	36	41	53	60
23	37	30	54	46
24	36	37	53	58
25	36	31	54	42
26	35	45	53	57
27	36		53	

Mike realized he also needed input from Ann about her perspective on the business. She indicated that she felt strongly that with better management, Northcutt Bikes should be able to use the existing warehouse for years to come, even with the anticipated growth in business. Currently, however, she views the situation as a crisis because "we're bursting at the seams with inventory. It's costing us a lot of profit, yet our service level is very poor, at less than 80%. I'd like to see us maintain a 95% or better service level without back orders, yet we need to be able to do that with a net reduction in total inventory. What do you think, Mike? Can we do better?"

Questions

1. Use the available data to develop inventory policies (order quantities and reorder points) for the FB378 and GS131. Assume that the holding cost is 20% of unit price.
2. Compare the inventory costs associated with your suggested order quantities with those of the current order quantities. What can you conclude?
3. Do you think the lost customer sales should be included as a cost of inventory? How would such an inclusion impact the ordering policies you established in question 1?

REFERENCES

Books and Articles

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

Isodore, C., "Gas Price Spikes and Shortages Coming after Fatal Pipeline Blast," *CNN Money*, November 3, 2016, **http://money.cnn.com/2016/11/01/news/colonial-pipeline-explosion-gasoline-price-spike/.**

Lee, H. L., V. Padmanabhan, and S. Whang, "The Bullwhip Effect in Supply Chain," *Sloan Management Review* 38, no. 3 (Spring 1997): 70–77.

Magretta, J., "Fast, Global, and Entrepreneurial: Supply Chain Management, Hong Kong Style," *Harvard Business Review* 76, no. 5 (September–October 1998): 102–109.

Magretta, J., "The Power of Virtual Integration: An Interview with Dell Computer's Michael Dell," *Harvard Business Review* 76, no. 2 (March–April 1998): 72–84.

Paul A. Souders/Corbis/VCG/Getty Images

CHAPTER
twelve

CHAPTER OUTLINE

Managing Production across the Supply Chain

CHAPTER OBJECTIVES

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

- Explain the activities that make up planning and control in a typical manufacturing environment.
- Explain the linkage between sales and operations planning (S&OP) and master scheduling.
- Complete the calculations for the master schedule record and interpret the results.
- Explain the linkage between master scheduling and material requirements planning (MRP).
- Complete the calculations for the MRP record and interpret the results.
- Discuss the role of production activity control and vendor order management and how these functions differ from higher-level planning activities.
- Explain how distribution requirements planning (DRP) helps synchronize the supply chain and complete the calculations for a simple example.

BIGDAWG CUSTOMS, PART 1

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Steve Barr, owner of BigDawg Customs, still wasn't sure whether making the new KZ1 scooter seat was a good business move or a bad one. On the one hand, tapping into the scooter market had definitely boosted sales for BigDawg, which had traditionally made motorcycle accessories. The company was selling over 1,500 KZ1 seats each month and demand was growing. On the other hand, production planning and control for the KZ1 seat was a mess. BigDawg only produced the KZ1 scooter seat in large batches every few weeks, but there were parts inventories all over the place, even in the weeks when BigDawg was not making seats. What was even more worrisome to Steve was that no one had a good handle on how many of the seats being made had already been sold to someone. More than once, a BigDawg salesperson had promised to ship seats to an important customer, only to find out that the inventory in the warehouse was spoken for. Steve worried that if this kept up, his customers would take their business elsewhere. Steve realized it was time to have a meeting with two of his key managers, Traci Griggs, vice president of marketing, and Brad Ashbaugh, vice president of production.

"Folks, as you know the KZ1 has been a big success in the marketplace, and I can see us offering more scooter seats over the next year. I appreciate your efforts to get us to this point, but we've got some issues to resolve. First, we need some way to match up production with the actual orders we have coming in. We just can't tell customers that we will ship them something in a couple of weeks—we have to *know* when seats are available and when we can ship them. Also, it seems to me that we can do a better job managing our parts inventories. We have stacks of saddles, hardware kits, and seat covers out on the plant floor, but we aren't going to be making another batch of seats for another week. There's got to be a way to do it. Let's meet again next week and you can show me what you've got."

INTRODUCTION

The purpose of this chapter is to introduce you to some of the systems manufacturers use to manage production and to coordinate these activities with their supply chain partners. While the focus here is on physical goods, bear in mind that many service firms also depend on the information generated by these efforts. For instance, distributors and transportation carriers all use information generated by manufacturers to plan their own activities.

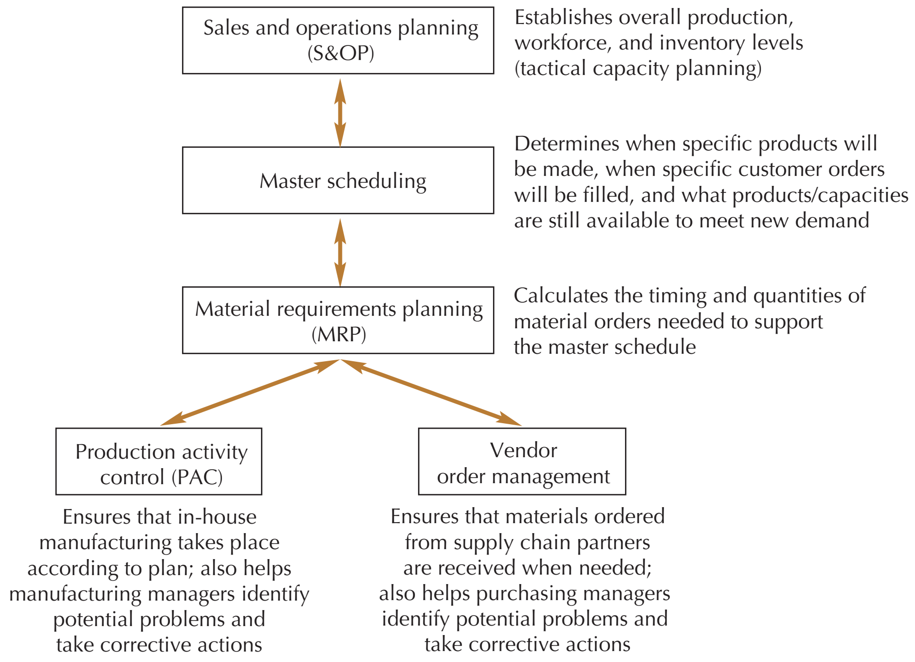
Planning and control
A set of tactical and execution-level business activities that includes master scheduling, material requirements planning, and some form of production activity control and vendor order management.

Planning and control can be thought of as a set of tactical and execution-level business processes that include master scheduling, material requirements planning, and some form of production activity control and vendor order management. Planning and control begins where sales and operations planning (S&OP) ends, as Figure 12.1 shows. The first step in planning and control is master scheduling, in which the overall resource levels established by S&OP begin to be fleshed out with specifics. The master schedule states exactly when and in what quantities specific products will be made. It also links production with specific customer orders, allowing the firm to tell the customer exactly when an order will be filled. Finally, master scheduling informs the operations manager what inventory or resources are still available to meet new demand. As we shall see, the concept of *available to promise* is an important function of master scheduling.

Material requirements planning (MRP) takes the process one step further: It translates the master schedule for final products into detailed material requirements. For example, if the master schedule indicates that 500 chairs will be finished and ready to sell in week 5, MRP determines when the individual pieces—seats, legs, back spindles, and so on—need to be made or purchased.

At the lowest level in the hierarchy are two systems: production activity control (PAC) and vendor order management. At this point, all the plans have been made; the primary task

FIGURE 12.1
A Top-Down Model of Manufacturing Planning and Control Systems



remaining is to make sure they are executed properly. Because materials ultimately come either from in-house manufacturing or from outside suppliers, two distinct types of control systems have sprung up to handle those different environments.

Our description of planning and control seems to suggest a top-down process, with higher-level plans feeding into more detailed lower-level systems. Why, then, do the arrows in Figure 12.1 run in both directions? The reason is simple: Changes in the business environment or other conditions may become apparent at lower levels, requiring the organization to adjust its plans and actions in real time.

In the rest of this chapter, we describe planning and control tools in more detail, starting with master scheduling and ending with PAC and vendor order management systems. We also discuss distribution requirements planning (DRP), one tool for synchronizing planning and control across the supply chain. As thorough as this chapter is, it cannot begin to cover all the choices manufacturers face in designing their planning and control systems. Our intent, rather, is to give you an appreciation of both the advantages of and the effort needed to run these systems.

12.1 MASTER SCHEDULING

Master scheduling
A detailed planning process that tracks production output and matches this output to actual customer orders.

Master scheduling is a detailed planning process that tracks production output and matches this output to actual customer orders. We have already said that master scheduling picks up where S&OP leaves off. Figure 12.2 gives an example of this linkage. The top of the figure shows four months of a sales and operations plan for a fictional manufacturer of lawn equipment. Note that management has established *overall* targets for demand, production, and ending inventory. These targets will guide the firm's tactical decisions, including planned workforce levels, storage space requirements, and cash flow needs. The bottom half of the figure shows the monthly master schedules for the three products the company produces. For every week in March, it shows what the expected demand is, how many of each product will be produced, and what the projected ending inventory is.

If we add up the numbers for production and demand across the three master schedules, we see that they match the figures in the sales and operations plan. Similarly, if we add up the ending inventory figures in week 4 of the master schedules, we see that they, too, match the figures in the plan. As long as the sales and operations planning values (for instance, the number of

FIGURE 12.2
The Link between the Sales and Operations Plan and the Master Schedule

Partial sales and operations plan

Month	Demand	Production	Ending Inventory
January	1,500	1,500	700
February	2,500	2,500	700
March	**4,000**	**5,000**	**1,700**
April	5,000	6,000	2,700

Master schedules for March

			Week 1	Week 2	Week 3	Week 4
Push mowers	Demand		200	250	300	350
	Production		650	0	650	0
	Ending inventory	**200**	650	400	750	**400**
Power mowers	Demand		400	500	600	700
	Production		0	1,350	0	1350
	Ending inventory	**400**	0	850	250	**900**
Lawn tractors	Demand		100	150	200	250
	Production		250	250	250	250
	Ending inventory	**100**	250	350	400	**400**

Beginning inventory =	**700**
Total monthly production =	+5,000
Total monthly demand =	−4,000
Ending inventory =	**1,700**

labor hours required per unit) are correct, the company should have enough capacity to implement these master schedules. In reality, however, the demand and production numbers in the master schedule are unlikely to match the sales and operations plan exactly. Furthermore, the actual capacity requirements might not match the planning values. For example, the plan may state that the average product needs an estimated 4.5 hours of labor, but the actual figure may turn out to be 4.7 hours. In such cases, firms may need to dip into their safety stock, schedule overtime, or take other measures to make up the difference between the plan and reality. As long as the numbers in the sales and operations plan are *close* to those in the master schedule, firms will be able to manage the differences.

The Master Schedule Record

Now that we understand the linkage between the sales and operations plan and the master schedule, let's look at the master schedule record in more detail. Because firms tailor the master schedule record to their manufacturing environment and the characteristics of their product, generalizing about its precise form is difficult. Nevertheless, most master schedule records track several key pieces of information:

- Forecasted demand
- Booked orders
- Projected inventory levels
- Production quantities
- Units still available to meet customer needs (*available to promise*)

To illustrate how the master schedule works, let's look at the master schedule record for Sandy-Built, a company that makes snowblowers (Figure 12.3).

Forecasted Demand versus Booked Orders. At the beginning of November (week 45), Sandy-Built's management is reviewing the master schedule for the company's newest model,

FIGURE 12.3
Partial Master Schedule Record for the MeltoMatic Snowblower

MeltoMatic snowblower								
Month	************November************				************December************			
Week	45	46	47	48	49	50	51	52
Forecasted demand	150	150	150	150	175	175	175	175
Booked orders	170	165	140	120	85	42	20	0
Master production schedule	300	0	300	0	350	0	350	0

Forecasted demand
In the context of master scheduling, a company's best estimate of the demand in any period.

Booked orders
In the context of master scheduling, confirmed demand for products.

Master production schedule (*MPS*)
The amount of product that will be finished and available for sale at the beginning of each week. The master production schedule drives more detailed planning activities, such as material requirements planning.

Projected ending inventory
A field in the master schedule record that indicates estimated inventory level at the end of each time period.

the MeltoMatic. The master schedule record in Figure 12.3 shows the **forecasted demand**—the company's best estimate of the demand in any period—for the months of November and December. It also shows **booked orders,** which represent confirmed demand for products. At this point, forecasted demand is running behind booked orders. In week 45, for instance, the forecasted demand for snowblowers is 150, yet Sandy-Built already has confirmed orders for 170.

Now look at the forecasts and booked orders for December. In that month, booked orders appear to be lagging behind forecasted demand. Perhaps more orders will materialize as December draws nearer. But if booked orders do not increase, managers may need to take action, either by cutting back production or by lowering the price of the MeltoMatic to move more units. One of the benefits of master scheduling is that it allows managers to see ahead and take corrective action when needed.

Another line on the master schedule record, called the **master production schedule (*MPS*),** shows how many products will be finished and available for sale at the beginning of each week. In our example, Sandy-Built seems to be producing enough snowblowers every other week to meet the forecasted demand.

Ending Inventory. With the basic numbers we have so far, we can start to get a picture of what overall inventory levels should look like and, more importantly, how many more snowblowers we can sell. Figure 12.4 contains a new row called **projected ending inventory,** which is simply our best estimate of what inventory levels will look like at the end of each week, based on current information.

Projected ending inventory is calculated as follows:

$$EI_t = EI_{t-1} + MPS_t - \text{maximum}\,(F_t, OB_t) \tag{12.1}$$

where:

EI_t = ending inventory in time period t
MPS_t = master production schedule quantity available in time period t
F_t = forecasted demand for time period t
OB_t = orders booked for time period t

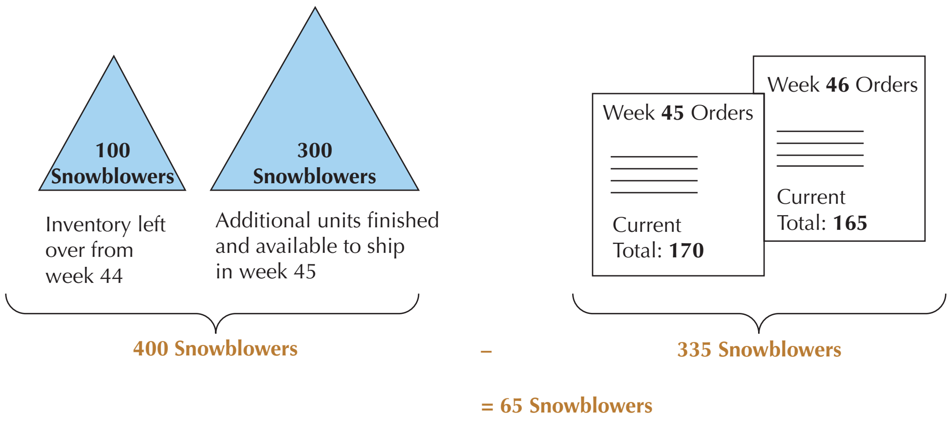
Note that projected ending inventory is a *conservative* estimate of the inventory position at the end of each week. In our example, the inventory at the end of week 44 is 100. Therefore, the projected inventory at the end of week 45 is $100 + 300 - 170 = 230$, and the same calculation for week 46 is $230 + 0 - 165 = 65$. In each case, we use booked orders because this number is higher than the forecasted demand. This makes sense because using the lower forecasted demand numbers would overestimate inventory levels.

But what about other weeks, such as week 47, in which the forecasted demand is *higher* than booked orders? In this case, the assumption is that the booked orders (140) probably do

FIGURE 12.4
Partial Master Schedule Record for the MeltoMatic Snowblower

On-hand inventory at end of week 44	100							
MeltoMatic snowblower								
Month	************November************				************December************			
Week	45	46	47	48	49	50	51	52
Forecasted demand	150	150	150	150	175	175	175	175
Booked orders	170	165	140	120	85	42	20	0
Projected ending inventory	**230**	**65**	**215**	**65**	**240**	**65**	**240**	**65**
Master production schedule	300	0	300	0	350	0	350	0

FIGURE 12.5
Calculating Available to Promise (*ATP*) for Week 45



not reflect all the demand that will eventually occur in that week (150). To be conservative, we subtract the higher number in calculating ending inventory: $65 + 300 - 150 = 215$.

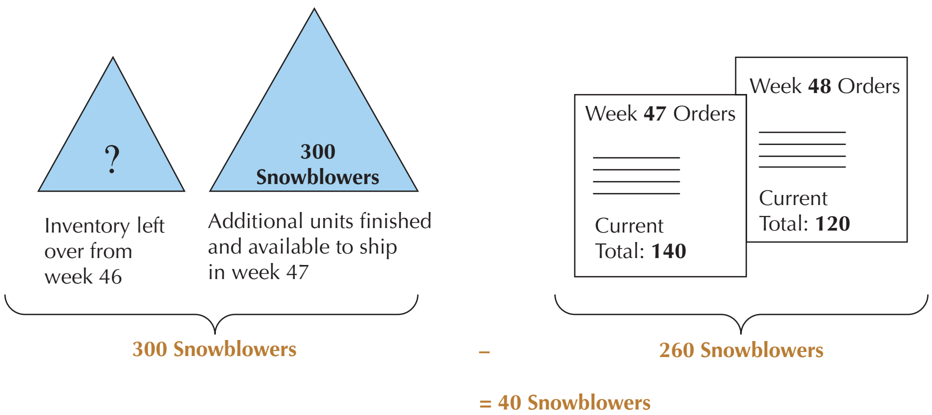
Available to Promise. Now suppose you work for Sandy-Built's sales department and it is the beginning of week 45. You have the information shown in Figure 12.4 sitting in front of you. A customer calls and asks how many snowblowers you can sell to him at the beginning of week 45 and at the beginning of week 47. To answer this question, you need to know how many of the snowblowers in inventory have not been sold and are therefore available to promise. **Available to promise (*ATP*)** indicates the number of units that are available for sale each week, given those that have already been promised to customers.

Available to promise (*ATP*)
A field in the master schedule record that indicates the number of units that are available for sale each week, given those that have already been promised to customers.

To illustrate how *ATP* is calculated, consider Figure 12.5, which represents MeltoMatic's master schedule at the beginning of week 45. On the supply side, there are 100 snowblowers left over from the previous week. Another 300 snowblowers are scheduled to be finished in week 45. As a result, there will be a total supply of 400 snowblowers. On the demand side, Sandy-Built has already booked orders for 170 and 165 snowblowers in weeks 45 and 46, respectively. (We need to consider orders through week 46 because no more snowblowers are expected to be completed until week 47.) When we take the difference between the supply (400) and the demand ($170 + 165 = 335$) shown in Figure 12.5, we get a value of 65. This figure represents the number of additional units we can sell—that is, available to promise—until the next *MPS* quantity comes in.

Figure 12.5 tells us the available to promise quantity for the next two weeks, but what about for week 47, which corresponds with the next *MPS* quantity? Figure 12.6 shows the logic. Since week 47 is still two weeks away (remember, we're in the beginning of week 45), we can't be sure how many snowblowers will be left over from week 46. Therefore, the only supply we can count on is the 300 units being completed in week 47. On the demand side, whatever supply we have in week 47 must carry us through weeks 47 and 48. Total booked orders for these weeks equals $(140 + 120) = 260$. Therefore, the available to promise for week 47 is $(300 - 260) = 40$ snowblowers.

FIGURE 12.6
Calculating Available to Promise (*ATP*) for Week 47



Now that you understand the logic behind *ATP*, let's state it more formally. The formula for *ATP* for the *first week* of the master schedule record is:

$$ATP_t = EI_{t-1} + MPS_t - \sum_{i=t}^{z-1} OB_i \quad \textbf{(12.2)}$$

For any subsequent week in which $MPS > 0$, it is:

$$ATP_t = MPS_t - \sum_{i=t}^{z-1} OB_i \quad \textbf{(12.3)}$$

where:

ATP_t = available to promise in week t
EI_{t-1} = ending inventory in week $t - 1$
MPS_t = master production schedule quantity in week t
$\sum_{i=t}^{z-1} OB_i$ = sum of all orders booked from week t until week z (when the next positive *MPS* quantity is due)

Because week 45 is the first week of the master schedule record, we use Equation (12.2) to calculate the available-to-promise numbers:

$$ATP_t = EI_{t-1} + MPS_t - \sum_{i=t}^{z-1} OB_i$$

$$ATP_{45} = EI_{44} + MPS_{45} - \sum_{i=45}^{46} OB_i$$

$$= 100 + 300 - (170 + 165) = 65 \text{ snowblowers}$$

Note that an *ATP* number must *always* be calculated for the first week in the record, regardless of whether any units are finished that week. Look at Figure 12.7. The *ATP* calculation for week 47 follows Equation (12.3), which assumes that there is no holdover inventory:

$$ATP_t = MPS_t - \sum_{i=t}^{z-1} OB_i$$

$$ATP_{47} = MPS_{47} - \sum_{i=47}^{48} OB_i$$

$$= 300 - (140 + 120) = 40 \text{ snowblowers}$$

Looking at it another way, total booked orders for November are 170 + 165 + 140 + 120 = 595 snowblowers, while the total units that we can sell are 100 + 300 + 300 = 700. The difference between these two totals is 700 − 595 = 105 snowblowers: 65 in the first two weeks of November and 40 in the last two weeks.

To summarize, Equation (12.2) is used to calculate the *ATP* for the first week of the master schedule record; Equation (12.3) is used for subsequent periods in which the *MPS* is positive. In calculating the *ATP*, managers must look ahead to see how many periods will go by before the next batch of finished products is ready.

FIGURE 12.7
Complete Master Schedule Record for the MeltoMatic Snowblower

On-hand inventory at end of week 44	**100**							
MeltoMatic snowblower								
Month	************November************				************December************			
Week	45	46	47	48	49	50	51	52
Forecasted demand	150	150	150	150	175	175	175	175
Booked orders	170	165	140	120	85	42	20	0
Projected ending inventory	**230**	**65**	**215**	**65**	**240**	**65**	**240**	**65**
Master production schedule	300	0	300	0	350	0	350	0
Available to promise	**65**		**40**		**223**		**330**	

EXAMPLE 12.1

Completing the Master Schedule Record for Karam's Alpine Hiking Gear

Galyna Andrushko/Shutterstock

Lisa Karam is the owner of Karam's Alpine Hiking Gear. Lisa has set up the following master schedule record for one of her most popular products, the Eiger1 backpack. She needs to complete the projected ending inventory and available-to-promise calculations (Figure 12.8).

Using Equation (12.1), the projected ending inventory values for weeks 37 through 39 are calculated as follows:

$$EI_t = EI_{t-1} + MPS_t - \text{maximum}\ (F_t, OB_t)$$
$$EI_{37} = 2{,}000 + 0 - \text{maximum}\ (1500, 1422) = 500 \text{ backpacks}$$
$$EI_{38} = 500 + 4{,}500 - \text{maximum}\ (1500, 1505) = 3{,}495 \text{ backpacks}$$
$$EI_{39} = 3{,}495 + 0 - \text{maximum}\ (1500, 1471) = 1{,}995 \text{ backpacks}$$

The remaining projected ending inventory values are calculated in a similar fashion. The master schedule record will also have *four ATP* calculations: one for the first week (week 37) and one for each week in which the *MPS* is positive (weeks 38, 41, and 44):

$$ATP_{37} = 2{,}000 + 0 - 1{,}422 = 578 \text{ backpacks}$$
$$ATP_{38} = 4{,}500 - (1{,}500 + 1{,}471 + 1{,}260) = 264 \text{ backpacks}$$
$$ATP_{41} = 4{,}000 - (980 + 853 + 534) = 1{,}633 \text{ backpacks}$$
$$ATP_{44} = 3{,}700 - 209 = 3{,}491 \text{ backpacks}$$

The completed master schedule record is shown in Figure 12.9. Interpreting the results, Lisa would expect the inventory to drop no lower than about 500 backpacks (week 37). In addition, Lisa has 578 backpacks left to sell in the current week. If she enters week 38 with no inventory, she will have only an additional 264 backpacks to sell over the following three weeks. Because of this, Lisa might try to get customers who aren't in a hurry to book orders in October, when the *ATP* quantities are much higher.

On-hand inventory at end of week 36		**2,000**						
Eiger1 backpack								
Month	************September************				*************October*************			
Week	37	38	39	40	41	42	43	44
Forecasted demand	1,500	1,500	1,500	1,400	1,400	1,250	1,250	1,250
Booked orders	1,422	1,505	1,471	1,260	980	853	534	209
Projected ending inventory								
Master production schedule		4,500			4,000			3,700
Available to promise								

FIGURE 12.8 **Incomplete Master Production Schedule Record for Eiger1 Backpack**

On-hand inventory at end of week 36	**2,000**							
Eiger1 backpack								
Month	************September************				************October************			
Week	37	38	39	40	41	42	43	44
Forecasted demand	1,500	1,500	1,500	1,400	1,400	1,250	1,250	1,250
Booked orders	1,422	1,505	1,471	1,260	980	853	534	209
Projected ending inventory	**500**	**3,495**	**1,995**	**595**	**3,195**	**1,945**	**695**	**3,145**
Master production schedule		4,500			4,000			3,700
Available to promise	**578**	**264**			**1,633**			**3,491**

FIGURE 12.9 Completed Master Production Schedule Record for Eiger1 Backpack

Planning horizon
The amount of time the master schedule record or *MRP* record extends into the future. In general, the longer the production and supplier lead times, the longer the planning horizon must be.

The Planning Horizon. The master schedule records we have shown so far happen to extend eight weeks into the future. In reality, the appropriate **planning horizon** will depend on the lead time a firm needs to source parts and build a product. Products with very short lead times may have planning horizons that are just a few weeks long, but more complex products may need horizons of several months or more.

As the weeks go by, a firm will need to revise the numbers in the master schedule record, a task that is referred to as "rolling through" the planning horizon. For example, the current week in Figure 12.7 is week 45. At the end of week 45, the master schedule record will roll forward, and the new current week will be week 46.

Using the Master Schedule

We have shown how to calculate the master schedule numbers, but how do real firms use the results of these calculations? Look again at Figure 12.7. Imagine that Sandy-Built receives a call from a large retail chain that the company has never dealt with before. The buyer needs 150 snowblowers "as soon as possible." Sandy-Built would like to do business with this customer, but management had not anticipated such a huge order. When can Sandy-Built ship the snowblowers, and what will be the impact on production?

With a formal master schedule, managers can quickly answer these questions. According to the *ATP* figures in Figure 12.7, Sandy-Built can ship 65 snowblowers now, 40 more in week 47, and the remaining 45 in week 49 ($65 + 40 + 45 = 150$). If Sandy-Built decides to accept this order, however, managers will need to recalculate the ending inventory and *ATP* numbers. Figure 12.10 shows the updated master schedule record.

Booked orders in weeks 45, 47, and 49 are now 235, 180, and 130. Because the new order is so large, projected ending inventories drop dramatically. In fact, the calculations suggest that inventories will drop to zero on a regular basis *unless* management alters production levels to increase the safety stock. Finally, the retailer's large order will use up all the *ATP* for November. Unless another order is canceled, Sandy-Built cannot accept new orders until December—a change the sales force should be made aware of.

The master schedule calculations might seem complicated at first, but imagine what could go wrong if a business did not have this information available. Salespeople wouldn't be sure if and when they could fill customer orders. Production managers might not become aware of the impact of new demand on inventory levels in time to do something about it. Worse still, salespeople might continue to promise products to customers, unaware that all output has already

On-hand inventory at end of week 44	**100**							
MeltoMatic snowblower								
Month	************November************				************December************			
Week	45	46	47	48	49	50	51	52
Forecasted demand	150	150	150	150	175	175	175	175
Booked orders	**235**	165	**180**	120	**130**	42	20	0
Projected ending inventory	165	0	120	0	175	0	175	0
Master production schedule	300	0	300	0	350	0	350	0
Available to promise	**0**		**0**		**178**		**330**	

FIGURE 12.10 Updated Master Schedule Record for the MeltoMatic Snowblower

been spoken for. In short, chaos would result. When master scheduling works well, it allows organizations to avoid these problems by closely matching demand with supply, anticipating customers' needs, and adjusting the organization's plans accordingly.

EXAMPLE 12.2

Booking More Orders at Karam's Alpine Hiking Gear

After completing the master schedule record in Figure 12.9, Lisa receives a call from a hiking outfitter in Montana. The customer would like Lisa to send 50 of the Eiger1 backpacks in the third week of September (week 39). Can Lisa do it? Lisa updates the master schedule record to reflect the change. The results are shown in Figure 12.11.

When Lisa compares the updated master schedule record to the old one in Figure 12.9, she sees that booking the new order increases orders booked in week 39 by 50 backpacks and reduces the *ATP* for week 38 by 50. The projected ending inventory for week 39 also falls but not by 50 backpacks, as one might expect. Rather, it falls by just 21 backpacks—the difference between new orders booked and forecasted demand (1,521 − 1,500).

On-hand inventory at end of week 36	**2,000**							
Eiger1 backpack								
Month	************September************				*************October*************			
Week	37	38	39	40	41	42	43	44
Forecasted demand	1,500	1,500	1,500	1,400	1,400	1,250	1,250	1,250
Booked orders	1,422	1,505	**1,521**	1,260	980	853	534	209
Projected ending inventory	500	3,495	**1,974**	**574**	**3,174**	**1,924**	**674**	**3,124**
Master production schedule		4,500			4,000			3,700
Available to promise	578	**214**			1,633			3,491

FIGURE 12.11 **Updated Master Production Schedule Record for Eiger1 Backpack**

12.2 MATERIAL REQUIREMENTS PLANNING

Rough-cut capacity planning
A capacity planning technique that uses the master production schedule to monitor key resource requirements.

Material requirements planning (MRP)
A planning process that translates the master production schedule into planned orders for the actual parts and components needed to produce the master schedule items.

Dependent demand inventory
Inventory items whose demand levels are tied directly to the production of another item.

With strategic capacity planning (Chapter 6), S&OP (Chapter 10), and master scheduling, we have a comprehensive set of high-level planning tools. Master scheduling, as we have seen, is particularly valuable because it allows managers to match production figures to actual customer demand. In addition, some firms use the master production schedule to monitor key resource requirements, an activity called **rough-cut capacity planning.** For instance, Sandy-Built's managers, seeing that 350 snowblowers are scheduled to be completed in week 49, might check to make sure the company has the capacity to meet that production goal. Rough-cut capacity planning verifies the feasibility of the master schedule.

Material requirements planning, more commonly known as **MRP,** takes planning one step further by translating the master production schedule into planned orders for the actual parts and components needed to produce the master schedule items. The logic of the MRP approach to inventory management is *completely different* from the independent inventory approaches described in Chapter 11. This is because MRP is used to manage **dependent demand inventory,** or inventory items whose demand levels are tied directly to the production of another item. Suppose, for instance, that each MeltoMatic snowblower Sandy-Built produces requires three wheels. Once managers know how many snowblowers they are going to make, they can calculate exactly how many wheels they will need and when they will need them. The demand for wheels is completely dependent on the number of snowblowers made. Unlike independent demand items, then, there is no mystery about how many dependent demand items a firm will need and when. MRP takes advantage of this fact to manage inventory quite differently—and more efficiently—than an *EOQ*-based system.

MRP is based on three related concepts:

1. The bill of material (BOM)
2. Backward scheduling
3. Explosion of the bill of material

We will illustrate these concepts using a simple example, the assembly of a furniture piece called the King Philip chair.

EXAMPLE 12.3

The Bill of Material (BOM) for the King Philip Chair

Bill of material (BOM) According to APICS, "a listing of all the subassemblies, intermediates, parts, and raw materials that go into a parent assembly showing the quantity of each required to make an assembly."

The **bill of material (BOM)** is "a listing of all the subassemblies, intermediates, parts, and raw materials that go into a parent assembly, showing the quantity of each required to make an assembly."[1] The bill of material for the King Philip chair has 10 different components, shown in Figure 12.12.

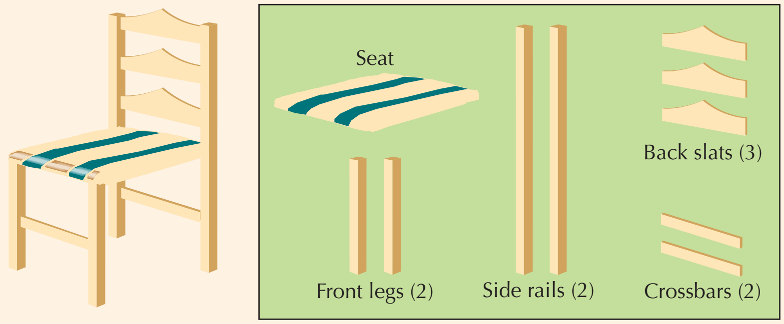


FIGURE 12.12 Bill of Material (BOM) for the King Philip Chair

Product structure tree A record or graphical rendering that shows how the components in the BOM are put together to make the level 0 item.

The **product structure tree** in Figure 12.13 shows how the components in the BOM are put together to make the chair. The chair is assembled using a leg assembly, a back assembly, and a seat; the leg and back assemblies, in turn, are assembled from individual components such as legs, back slats, and crossbars. In MRP jargon, the complete chair is a level 0 item; the leg assembly, back assembly, and seat are level 1 items; and the remaining components are level 2 items. In practice, product assemblies can be dozens of levels deep.

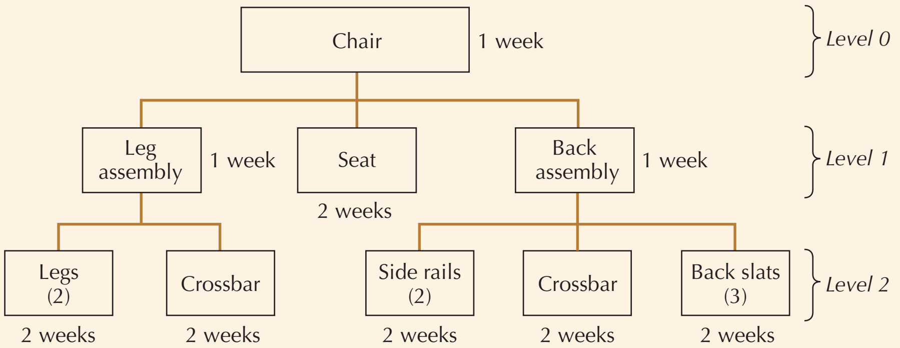


FIGURE 12.13 Product Structure Tree for the King Philip Chair

Planning lead time In the context of MRP, the time from when a component is ordered until it arrives and is ready to use.

The product structure tree also shows the planning lead time for each component. The **planning lead time** is the time from when a component or material is ordered until it arrives and is ready to use. For instance, the finished chair has a planning lead time of one week, the amount of time workers need to assemble a typical batch of chairs using the level 1 items. Seats have a planning lead time of two weeks, which may reflect the time an outside supplier takes to fill an order for seats. We will discuss planning lead times in more detail later in this chapter.

EXAMPLE 12.4

Backward Scheduling (Exploding the BOM) for the King Philip Chair

We can now show how backward scheduling (exploding the BOM) is used in MRP. The master schedule record in Figure 12.14 shows that 500 finished chairs should be ready to sell at the beginning of week 5. How do managers ensure that this commitment is met?

To complete the manufacture of 500 chairs by the beginning of week 5, workers must start assembling the chairs at the beginning of week 4. (Recall from Figure 12.13 that the planning lead time for the assembled chair is one week.) This deadline can be met only

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

On-hand inventory at end of December		600						
King Philip chair								
Month	************January************				************February************			
Week	1	2	3	4	5	6	7	8
Forecasted demand	100	100	100	100	100	100	100	100
Booked orders	100	90	85	80	70	85	80	90
Projected ending inventory	500	400	300	200	600	500	400	300
Master production schedule	0	0	0	0	**500**	0	0	0
Available to promise	245				175			

FIGURE 12.14 **Master Schedule Record for the King Philip Chair**

if the back assemblies, leg assemblies, and seats are available at the beginning of week 4. Continuing to work backward in time, we see that workers must start the back and leg assemblies at the beginning of week 3 in order to have them ready by the beginning of week 4. Seats have a two-week lead time, so they must be ordered no later than the beginning of week 2. Back slats, crossbars, side rails, and legs must be ordered at the beginning of week 1—*right now!*—if managers want to have 500 chairs ready to go in week 5.

The time line in Figure 12.15 shows the logic behind backward scheduling. From a single order for 500 chairs in week 5, we worked backward, first through the level 1 items and then through the level 2 items. This process is called **exploding the BOM.**

Exploding the BOM
The process of working backward from the master production schedule for a level 0 item to determine the quantity and timing of orders for the various subassemblies and components. Exploding the BOM is the underlying logic used by MRP.

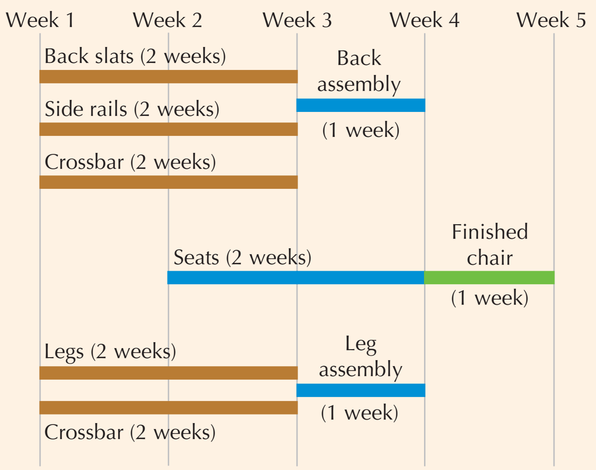


FIGURE 12.15 **Exploding the BOM for the King Philip Chair**

The MRP Record

The simple MRP record builds on the backward scheduling logic but provides some additional information. Like the master schedule record, the format of the MRP record may differ slightly from one firm to the next, but the basic principle—working backward from the planned completion date for the final item—is the same.

Figure 12.16 shows an example of how the MRP record is calculated. Looking at point A in the top row of Figure 12.16, we see that management has committed to having 500 chairs ready at the beginning of week 5. Given the planning lead time from Figure 12.13, workers need to start assembling the chairs in week 4 (point B). This assembly task triggers the need for level 1 components such as seats.

The bottom half of Figure 12.16 shows the MRP record for the seat. The top row shows *gross requirements*—that is, how many seats are needed each week. Because no chairs are being assembled in weeks 1 through 3, the gross requirement for seats in those weeks is zero (point C). In week 4, the gross requirement for seats is 500 (point D). This number is drawn directly from the "Start assembly" quantity at point B.

Gross requirements can be met by drawing from three sources: inventory carried over from the previous week, or the projected ending inventory; units already on order, referred to as

FIGURE 12.16
Calculating the MRP Record for Seats (King Philip Chair)

			WEEK						
			1	2	3	4	5	6	7
King Philip chair LT (weeks) = 1	MPS due date		0	0	0	0	A **500**	400	300
	Start assembly	0	0	0	0	B **500**	400	300	0

C

			WEEK						
			1	2	3	4	5	6	7
Seat	Gross requirements		0	0	0	D **500**	400	300	0
LT (weeks) = 2	Scheduled receipts		0	0	0	0	0	0	0
	Projected ending inventory	0	0	0	0	0 H	0	0	0
	Net requirements		0	0	0	E **500**	400	300	0
Min. order = 1	Planned receipts		0	0	0	F **500**	400	300	0
	Planned orders		0	G **500**	400	300	0	0	0

scheduled receipts; and new orders, termed *planned receipts*. To determine whether any new orders need to be placed, we must first calculate *net requirements*:

$$NR_t = \text{maximum}\ (0; GR_t - EI_{t-1} - SR_t) \qquad \textbf{(12.4)}$$

where:

NR_t = net requirement in time period t
GR_t = gross requirement in time period t
EI_{t-1} = ending inventory from time period $t - 1$
SR_t = scheduled receipts in time period t

In lay terms, if enough seats can be obtained from inventory and scheduled receipts to cover the gross requirements, then managers don't need to order any more seats (i.e., the net requirement equals zero). Otherwise, they have a net requirement that must be met with new planned receipts.

In our chair example, the projected inventory at the end of week 3 is zero, and there are no scheduled receipts in week 4. Therefore, the net requirement for seats in week 4 is:

$$\begin{aligned} NR_4 &= \text{maximum}\ (0; GR_4 - EI_3 - SR_4) \\ &= \text{maximum}\ (0; 500 - 0 - 0) = 500 \end{aligned}$$

This result is shown in Figure 12.16 as point E. If you look in the lower-left corner of Figure 12.16, you will see that the minimum order size for seats is 1. In general, a business would not want to order more units than necessary as doing so would increase inventory levels and costs. Therefore, managers should plan on ordering just enough seats to meet the net requirement (point F). If they plan to receive 500 seats in week 4, they must release the order no later than week 2 (point G) because of the two-week planning lead time for seats. Finally, the ending inventory for week 4 (point H) is calculated using Equation (12.5):

$$EI_t = EI_{t-1} + SR_t + PR_t - GR_t \qquad \textbf{(12.5)}$$

where:

EI_t = ending inventory from time period t
EI_{t-1} = ending inventory from time period $t - 1$
SR_t = scheduled receipts in time period t
PR_t = planned receipts in time period t
GR_t = gross requirements in time period t

$$\begin{aligned} EI_4 &= EI_3 + SR_4 + PR_4 - GR_4 \\ &= 0 + 0 + 500 - 500 = 0 \text{ seats} \end{aligned}$$

To test your understanding of the MRP record, try tracing the calculations through weeks 5 and 6. Figure 12.17 shows the complete MRP record for all the level 1 items, including the leg assembly and the back assembly. The logic behind the calculations is the same, but a couple of things should be noted. First, the factory begins week 1 with 25 leg assemblies in inventory (point I). Because there are no gross requirements in the first three weeks, these assemblies

FIGURE 12.17
MRP Records for the Level 1 Components

			WEEK 1	2	3	4	5	6	7
King Philip chair	MPS due date		0	0	0	0	**500**	400	300
LT (weeks) = 1	Start assembly	0	0	0	0	**500**	400	300	0

			WEEK 1	2	3	4	5	6	7
Seat	Gross requirements		0	0	0	500	400	300	0
LT (weeks) = 2	Scheduled receipts		0	0	0	0	0	0	0
	Projected ending inventory	0	0	0	0	0	0	0	0
	Net requirements		0	0	0	500	400	300	0
Min. order = 1	Planned receipts		0	0	0	500	400	300	0
	Planned orders		0	500	400	300	0	0	0

			WEEK 1	2	3	4	5	6	7
Leg asm	Gross requirements		0	0	0	500	400	300	0
LT (weeks) = 1	Scheduled receipts	I	0	0	0	0	0	0	0
	Projected ending inventory	25	25	25	25	525	125	825	825
	Net requirements		0	0	0	475	0	175	0
Min. order = 1,000	Planned receipts		0	0	0	1,000	0	1,000	0
	Planned orders		0	0	1,000 J	0 K	1,000	0	0

			WEEK 1	2	3	4	5	6	7
Back asm	Gross requirements		0	0	0	500	400	300	0
LT (weeks) = 1	Scheduled receipts		250 L	0	0	0	0	0	0
	Projected ending inventory	0	250	250	250	0	0	0	0
	Net requirements		0	0	0	250	400	300	0
Min. order = 250	Planned receipts		0	0	0	250	400	300	0
	Planned orders		0	0	250	400	300	0	0

gather dust until they are needed in week 4. Though the net requirement in week 4 is only 475, managers place an order for 1,000 (point J) because that is the minimum order size. The result is excess inventory at the end of week 4.

In week 5, the factory has more than enough leg assemblies (525) in beginning inventory to meet the gross requirement (400). As a result, managers do not place any additional orders (point K). Finally, for the back assemblies, the factory has a scheduled receipt of 250 units in week 1 (point L). These units will sit in inventory until week 4, when they are needed.

Just as the gross requirements for level 1 items are determined by the number of finished chairs (level 0) to be manufactured, the gross requirements for level 2 items depend on the *planned orders* for level 1 items.

Figure 12.18 shows the complete MRP calculations for all components in the King Philip chair. Notice that managers want to put together 1,000 leg assemblies in week 3 (planned orders = 1,000). Because each leg assembly requires two legs (Figure 12.13), the gross requirement for legs in week 3 is 2,000 (point M). Similarly, each back assembly requires two side rails. Therefore, a planned order for 300 back assemblies in week 5 results in a gross requirement of 600 side rails in the same week (point N).

Now for a *real* test. Where do the crossbar's gross requirements in Figure 12.18 come from? Because the crossbar is used in two different level 1 items, we must calculate gross requirements based on planned orders for *both* the leg assemblies and the back assemblies. Therefore:

$$\begin{aligned}\text{Gross requirements for crossbars} &= \text{leg assembly planned orders}\\ &\quad + \text{back assembly planned orders}\end{aligned}$$

$$\begin{aligned}\text{Week 3;}&\quad 1{,}000 + 250 = 1{,}250\\ \text{Week 4:}&\quad 0 + 400 = 400\\ \text{Week 5:}&\quad 1{,}000 + 300 = 1{,}300\end{aligned}$$

Once we have calculated the gross requirements, filling out the rest of the MRP records is a matter of following the rules outlined earlier.

FIGURE 12.18 Complete MRP Records for the King Philip Chair

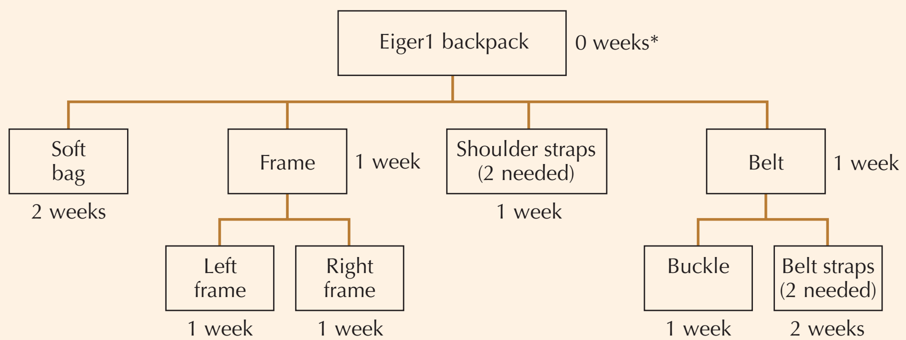
MyLab Operations Management Animation

Item			WEEK 1	2	3	4	5	6	7
** Chair kit**	MPS due date						500	400	300
LT (weeks) = 1	Start assembly					500	400	300	
** Seat **	Gross requirements					500	400	300	
LT (weeks) = 2	Scheduled receipts								
	Projected ending inventory	0	0	0	0	0	0	0	0
	Net requirements					500	400	300	
Min. order = 1	Planned receipts					500	400	300	
	Planned orders			500	400	300			
** Leg asm **	Gross requirements					500	400	300	
LT (weeks) = 1	Scheduled receipts								
	Projected ending inventory	25	25	25	25	525	125	825	825
	Net requirements					475		175	
Min. order = 1,000	Planned receipts					1,000		1,000	
	Planned orders				**1,000**		**1,000**		
** Back asm **	Gross requirements					500	400	300	
LT (weeks) = 1	Scheduled receipts		250						
	Projected ending inventory	0	250	250	250	0	0	0	0
	Net requirements					250	400	300	
Min. order = 250	Planned receipts					250	400	300	
	Planned orders				**250**	**400**	**300**		
** Legs **	Gross requirements				**2,000**		**2,000**		
LT (weeks) = 2	Scheduled receipts								
	Projected ending inventory	25	25	25	0	0	0	0	0
	Net requirements				1,975		2,000		
Min. order = 1	Planned receipts				1,975		2,000		
	Planned orders		1,975		2,000				
** Side rails **	Gross requirements				**500**	**800**	**600**		
LT (weeks) = 2	Scheduled receipts		500						
	Projected ending inventory	100	600	600	100	0	0	0	0
	Net requirements					700	600		
Min. order = 500	Planned receipts					700	600		
	Planned orders			700	600				
** Back slats **	Gross requirements				750	1,200	900		
LT (weeks) = 2	Scheduled receipts					75			
	Projected ending inventory	0	0	0	0	0	0	0	0
	Net requirements				750	1,125	900		
Min. order = 1	Planned receipts				750	1,125	900		
	Planned orders		750	1,125	900				
** Crossbars **	Gross requirements				1,250	400	1,300		
LT (weeks) = 2	Scheduled receipts								
	Projected ending inventory	0	0	0	0	600	300	300	300
	Net requirements				1,250	400	700		
Min. order = 1,000	Planned receipts				1,250	1,000	1,000		
	Planned orders		1,250	1,000	1,000				

EXAMPLE 12.5

Using MRP at Karam's Alpine Hiking Gear

The BOM and associated planning lead times for the Eiger1 backpack are shown in Figure 12.19.



*To save on shipping and assembly costs, the Eiger1 backpack is sold unassembled. The dealer takes the level 1 components and puts them together at the shop.

FIGURE 12.19 BOM for the Eiger1 Backpack

Lisa Karam has asked you to set up the MRP records for all the components for the next six weeks. Lisa also tells you the following:

- According to the master production schedule, Karam is planning on having 850 new backpacks ready to sell at the beginning of each of weeks 4, 5, and 6.
- Currently, there is no component inventory of any kind in the plant.
- The soft bag, shoulder straps, and belt straps all have minimum order quantities of 1,500 units. All of the other components have no minimum order quantity.

			WEEK					
			1	2	3	4	5	6
Eiger1 packs	MPS due date					850	850	850
LT (weeks) = 0	Start assembly					850	850	850
** Soft bag **	Gross requirements		0	0	0	850	850	850
LT (weeks) = 2	Scheduled receipts							
	Projected ending inventory	0	0	0	0	650	1,300	450
	Net requirements					850	200	
Min. order = 1,500	Planned receipts					1,500	1,500	
	Planned orders			1,500	1,500			
** Frame **	Gross requirements		0	0	0	850	850	850
LT (weeks) = 1	Scheduled receipts							
	Projected ending inventory	0	0	0	0	0	0	0
	Net requirements					850	850	850
Min. order = 1	Planned receipts					850	850	850
	Planned orders				850	850	850	
** Shoulder straps **	Gross requirements		0	0	0	1,700	1,700	1,700
LT (weeks) = 1	Scheduled receipts							
	Projected ending inventory	0	0	0	0	0	0	0
	Net requirements					1,700	1,700	1,700
Min. order = 1,500	Planned receipts					1,700	1,700	1,700
	Planned orders				1,700	1,700	1,700	
** Belt **	Gross requirements		0	0	0	850	850	850
LT (weeks) = 1	Scheduled receipts							
	Projected ending inventory	0	0	0	0	0	0	0
	Net requirements					850	850	850
Min. order = 1	Planned receipts					850	850	850
	Planned orders				850	850	850	
** Left frame **	Gross requirements		0	0	850	850	850	0
LT (weeks) = 1	Scheduled receipts		50					
	Projected ending inventory	0	50	50	0	0	0	0
	Net requirements				800	850	850	
Min. order = 1	Planned receipts				800	850	850	
	Planned orders			800	850	850		
** Right frame **	Gross requirements		0	0	850	850	850	0
LT (weeks) = 1	Scheduled receipts							
	Projected ending inventory	0	0	0	0	0	0	0
	Net requirements				850	850	850	
Min. order = 1	Planned receipts				850	850	850	
	Planned orders			850	850	850		
** Buckle **	Gross requirements		0	0	850	850	850	0
LT (weeks) = 1	Scheduled receipts							
	Projected ending inventory	0	0	0	0	0	0	0
	Net requirements				850	850	850	
Min. order = 1	Planned receipts				850	850	850	
	Planned orders			850	850	850		
* Belt straps *	Gross requirements		0	0	1,700	1,700	1,700	0
LT (weeks) = 2	Scheduled receipts							
	Projected ending inventory	0	0	0	0	0	0	0
	Net requirements				1,700	1,700	1,700	
Min. order = 1,500	Planned receipts				1,700	1,700	1,700	
	Planned orders		1,700	1,700	1,700			

FIGURE 12.20 MRP Records for the Eiger1 Backpack

- At present, the only scheduled receipt is for 50 left frames in week 1 (the result of an earlier partial shipment on the part of a vendor).

The completed MRP records are shown in Figure 12.20. There are a couple of interesting points to note:

1. In the current week, the *only* action that needs to be taken is to release an order for 1,700 belt straps.
2. Because the Eiger1 backpacks do not have to be assembled, the final assembly planning lead time is zero.
3. The gross requirements for the shoulder straps are twice those of any other level 1 item. This is because each backpack requires two shoulder straps.
4. The MRP record for the left frame is nearly identical to that for the right frame. The difference is due to the 50 "extra" left frames arriving in week 1. These extra left frames reduce the planned order release in week 2 by 50 units.

The Advantages of MRP

Just as in master scheduling, getting lost in the calculations is easy to do with MRP. Figure 12.16 and Figure 12.18 showed all the MRP records for two *very* simple products. Imagine what the MRP records must look like in a firm that produces hundreds of products, with dozens of BOM levels and thousands of components!

So now is a good time to pull back and consider the benefits of MRP:

1. MRP is *directly tied* to the master production schedule and indicates the *exact* timing and quantity of orders for *all* components. By eliminating a lot of the guesswork associated with the management of dependent demand inventory, MRP simultaneously lowers inventory levels and helps firms meet their master schedule commitments.
2. MRP allows managers to trace every order for lower-level items through all the levels of the BOM, up to the master production schedule. This logical linkage between higher and lower levels in the BOM is sometimes called the **parent/child relationship.** If for some reason the supply of a lower-level item is interrupted, a manager can quickly check the BOM to see the impact of the shortage on production.
3. MRP tells a firm and its suppliers precisely what needs to be made when. This information can be invaluable in scheduling work or shipments, or even in planning budgets and cash flows. In fact, MRP logic is often called the "engine" of planning and control systems. MRP plays a big part in many enterprise resource planning (ERP) systems, described in the supplement.

Parent/child relationship
The logical linkage between higher- and lower-level items in the BOM.

Special Considerations in MRP

The complexity of MRP demands that these systems be computerized. But even with the help of computers, MRP requires *organizational discipline*. Like the calendar function on your smartphone, MRP provides little benefit to those who do not understand and exploit the system.

For an MRP system to work properly, it must have *accurate information*. Key data include the master production schedule, the BOM, inventory levels, and planning lead times. If any of this information is inaccurate, components will not be ordered at the right time or in the right quantities. In some cases, the correct components won't be ordered at all. As a result, most firms that want to implement MRP find that they must first ensure accurate planning information.

MRP systems must also accommodate *uncertainty* about a host of factors, including the possibility of variable lead times, shipment quantities and quality levels, and even changes to the quantities in the master production schedule. In general, firms deal with this uncertainty by lengthening the planning lead times or by holding additional units as safety stock. Of course, such buffers increase the amount of inventory in the system. As a result, many firms make a conscious effort to *eliminate* uncertainty. They do so by choosing suppliers and processes that offer reliable lead times and high quality levels and by keeping the quantities on the master

MRP nervousness
A term used to refer to the observation that any change, even a small one, in the requirements for items at the top of the bill of material can have drastic effects on items further down the bill of material.

production schedule firm. Reducing uncertainty requires a high degree of organizational discipline, but the rewards can be great.

A final consideration in implementing an MRP system is a phenomenon called **MRP nervousness.** Because higher-level items drive the requirements for lower-level items in an MRP system, any change, even a small one, in the requirements for upper-level items can have drastic effects on items listed further down the bill of material. Example 12.6 shows how such changes can affect the MRP records.

EXAMPLE 12.6

MRP Nervousness for the King Philip Chair

After completing the MRP records for the King Philip chair (Figure 12.18), management decides to change the number of chairs to be completed in week 7 from 300 to 125. Figure 12.21 shows the impact of this change on the MRP records. As you can see, no MRP record is left untouched.

			WEEK						
			1	2	3	4	5	6	7
** Chair kit**	MPS due date						500	400	**125**
LT (weeks) = 1	Start assembly					500	400	**125**	
** Seat **	Gross requirements					500	400	**125**	
LT (weeks) = 2	Scheduled receipts								
	Projected ending inventory	0	0	0	0	0	0	0	0
	Net requirements					500	400	**125**	
Min. order = 1	Planned receipts					500	400	**125**	
	Planned orders			500	400	**125**			
** Leg asm **	Gross requirements					500	400	**125**	
LT (weeks) = 1	Scheduled receipts								
	Projected ending inventory	25	25	25	25	525	**125**	0	0
	Net requirements					475			
Min. order = 1,000	Planned receipts					1,000			
	Planned orders				1,000				
** Back asm **	Gross requirements					500	400	**125**	
LT (weeks) = 1	Scheduled receipts		250	0					
	Projected ending inventory	0	250	250	250	0	0	0	0
	Net requirements					250	400	**125**	
Min. order = 250	Planned receipts					250	400	**125**	
	Planned orders				250	400	**125**		
** Legs **	Gross requirements				**2,000**				
LT (weeks) = 2	Scheduled receipts								
	Projected ending inventory	25	25	25	0	0	0	0	0
	Net requirements				1,975				
Min. order = 1	Planned receipts				1,975				
	Planned orders		1,975						
** Side rails **	Gross requirements				500	800	**250**		
LT (weeks) = 2	Scheduled receipts		500						
	Projected ending inventory	100	600	600	100	0	**250**	**250**	**250**
	Net requirements					700	**250**		
Min. order = 500	Planned receipts					700	**500**		
	Planned orders			700	**500**				
** Back slats **	Gross requirements				750	1,200	375		
LT (weeks) = 2	Scheduled receipts					75			
	Projected ending inventory	0	0	0	0	0	0	0	0
	Net requirements				750	1,125	**375**		
Min. order = 1	Planned receipts				750	1,125	**375**		
	Planned orders		750	1,125	**375**				
** Crossbars **	Gross requirements				1,250	400	125		
LT (weeks) = 2	Scheduled receipts								
	Projected ending inventory	0	0	0	0	600	**475**	**475**	**475**
	Net requirements				1,250	400			
Min. order = 1,000	Planned receipts				1,250	1,000			
	Planned orders		1,250	1,000					

FIGURE 12.21 **MRP Nervousness for the King Philip Chair**

Compared to Figure 12.18, the change eliminates the need for a second planned order of 1,000 leg assemblies in week 5. This, in turn, affects the gross requirements for legs and crossbars. The change in planned production also spills over to the records for seats, back assemblies, side rails, and back slats, although the impact is not quite as pronounced.

The point is that a minor change at the top can cause huge changes at lower levels. Planners must take MRP nervousness into consideration when making changes, especially with higher-level items. They must also choose their minimum order quantities with care. Notice the impact of the minimum order, or *lot size*, for leg assemblies: The firm went from ordering 1,000 leg assemblies in week 5 to ordering none at all that week. Because large lot sizes make MRP systems more nervous, firms that take this approach to inventory management usually try to keep their minimum order quantities as small as possible, especially for higher-level items that have the potential to disrupt lower-level requirements.

12.3 PRODUCTION ACTIVITY CONTROL AND VENDOR ORDER MANAGEMENT SYSTEMS

To this point, we have been discussing planning tools: S&OP for planning overall resource levels, master scheduling for planning the production and shipment of end items, and MRP for planning orders for manufacturing components. With production activity control (PAC) and vendor order management systems, the emphasis shifts from planning to *execution*. Besides their many other capabilities, these systems can:

1. Route and prioritize jobs going through the supply chain
2. Coordinate the flow of goods and materials between a facility and other supply chain partners
3. Provide supply chain partners with performance data on operations and supply chain activities

Job Sequencing

Job sequencing rules
Rules used to determine the order in which jobs should be processed when resources are limited and multiple jobs are waiting to be done.

The tools and techniques used to perform PAC and vendor order management are as varied as the operational environments in which they are used. They can be as simple as the rules for deciding which manufacturing job should be processed next or as complex as high-tech software or hardware solutions for tracking the flow of materials among supply chain partners. **Job sequencing rules** have been used for decades to determine the order in which jobs should be processed when resources are limited and multiple jobs are waiting to be done. And as Example 12.7 shows, job sequencing is just as valid in a services environment as it is in manufacturing.

EXAMPLE 12.7

Job Sequencing at Carlos's Restoration Services

Carlos's Restoration Services restores antique paintings. The process consists of three steps. Each of these steps must be completed prior to moving on to the next step. Furthermore, Carlos's can work on only one job at a time at each step.

Carlos's has four jobs waiting to be started. Information on these jobs, shown in the order in which they arrived, is contained in Table 12.1.

TABLE 12.1 Job Requirements for Carlos's Restoration Services

	Estimated Days					
JOB	STEP 1	STEP 2	STEP 3	TOTAL TASK TIME	DAYS UNTIL DUE	CRITICAL RATIO
Uptown Gallery	3	2	3.5	8.5	21	2.47
High Museum	5	2	1	8	20	2.50
Chester College	3	2	5	10	10	1.00
Smith	6	4	1	11	15	1.36

Total task times range from 8 to 11 days. Chester College has requested that its job be completed in 10 days, while Uptown Gallery is willing to wait 21 days. One way to determine the order in which jobs should be sequenced is based on the critical ratio. The *critical ratio* is calculated as follows:

$$\text{Critical ratio} = \frac{\text{days until due}}{\text{total task time remaining}} \tag{12.6}$$

A critical ratio of 1 indicates that the amount of task time equals the amount of time left; hence, any time spent waiting will make the job late. A critical ratio less than 1 indicates that the job is going to be late unless something changes. When the critical ratio is used to sequence work, the jobs with the lowest critical ratio are scheduled to go first. Carlos's decides to test three common job sequencing rules—first come, first served (FCFS), earliest due date (EDD), and the critical ratio—to see which one performs best. The results are shown in Table 12.2.

TABLE 12.2 Testing Three Common Job Sequencing Rules at Carlos's Restoration Services

First come, first served	*Step 1*		*Step 2*		*Step 3*		
JOB	START	END	START	END	START	END	DAYS LATE
Uptown Gallery	0	3	3	5	5	8.5	0
High Museum	3	8	8	10	10	11	0
Chester College	8	11	11	13	13	18	8
Smith	11	17	17	21	21	22	7
					Average lateness:		**3.75** days

Earliest due date	*Step 1*		*Step 2*		*Step 3*		
JOB	START	END	START	END	START	END	DAYS LATE
Chester College	0	3	3	5	5	10	0
Smith	3	9	9	13	13	14	0
High Museum	9	14	14	16	16	17	0
Uptown Gallery	14	17	17	19	19	22.5	1.5
					Average lateness:		**0.375** days

Critical ratio	*Step 1*		*Step 2*		*Step 3*		
JOB	START	END	START	END	START	END	DAYS LATE
Chester College	0	3	3	5	5	10	0
Smith	3	9	9	13	13	14	0
Uptown Gallery	9	12	13	15	15	18.5	0
High Museum	12	17	17	19	19	20	0
					Average lateness:		**0** days

Processing the jobs on a first-come, first-served basis might seem the fairest, but in this case, the result is that two jobs are finished long before they're due, while two jobs are considerably late. Sequencing the jobs according to the earliest due date results in somewhat better results: Only the Uptown Gallery job is late (1.5 days), for an average lateness of 0.375 days.

Carlos's then sequences the jobs from highest to lowest critical ratio value. In this case, all the jobs are completed prior to the due date. Based on these results, Carlos's decides to use the critical ratio to set the sequence.

Monitoring and Tracking Technologies

Radio-frequency identification (RFID), bar coding, and online order tracking systems have been developed to trace the movement and location of materials in the supply chain and report on the progress of specific jobs. Such systems depend on computer hardware and software that can interpret the information gathered by the system. Herman Miller, a designer and manufacturer of high-end office furniture, incorporates PAC and vendor order management tools. Besides helping the company to control its operations and supply chain activities, these systems also alert managers to potential problems. For example, computer displays located throughout Herman Miller's plant provide users with real-time information about the status of manufacturing jobs and required materials. If a shortage of materials threatens to delay a job, the system flags the problem and indicates which jobs will be affected. Managers at Herman Miller or at supply chain partners' facilities can then take corrective action.[2]

12.4 SYNCHRONIZING PLANNING AND CONTROL ACROSS THE SUPPLY CHAIN

Throughout this book, we have emphasized the need to synchronize decisions across the supply chain. This need is especially critical in planning and control activities. In this section, we introduce one technique for synchronizing planning and control decisions: distribution requirements planning (DRP). In Chapter 13, we will talk about another technique, called *kanban*. DRP helps to synchronize supply chain partners at the *master schedule level*, while kanban systems help to synchronize them at the PAC and vendor order management levels (Figure 12.22).

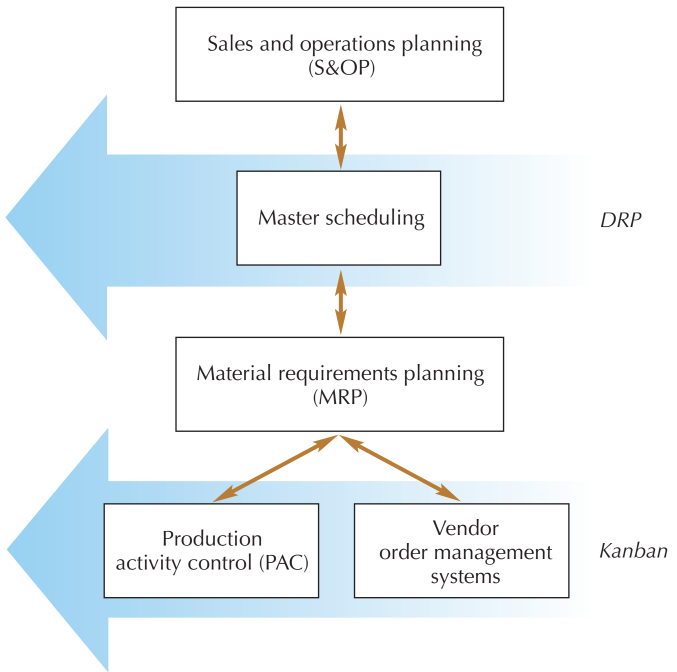
Distribution Requirements Planning

Distribution requirements planning (DRP) A time-phased planning approach similar to MRP that uses planned orders at the point of demand (customer, warehouse, etc.) to determine forecasted demand at the source level (often a plant).

Distribution requirements planning (DRP) is a time-phased planning approach similar to MRP that uses planned orders at the point of demand (customer, warehouse, etc.) to determine forecasted demand at the source level (often a plant). DRP is one of many ways in which supply chain partners can synchronize their planning efforts at the master schedule level. These forecasted demand numbers then become input to the master scheduling process.

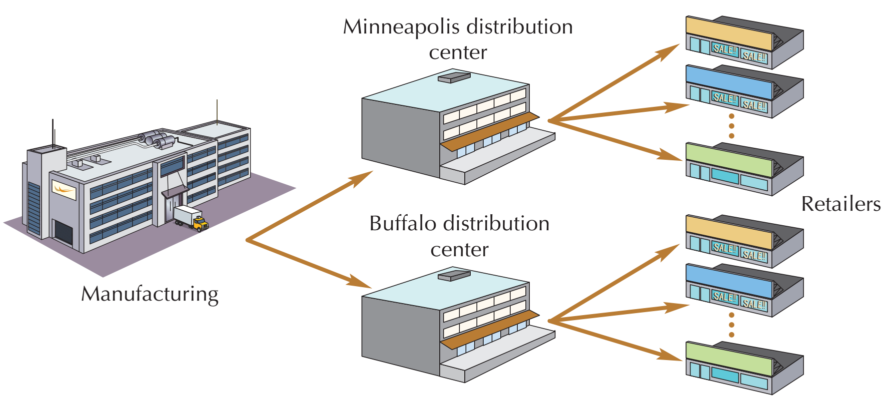
To illustrate how DRP works, let's return to the example of Sandy-Built's MeltoMatic snowblower. When you first looked at the master schedule record shown in Figure 12.7, you may have wondered where the forecasted demand numbers came from. After all, much of the value of master scheduling hinges on the accuracy of forecasts. Managers typically base their forecasts on past history or educated guesses, but DRP forecasts are calculated directly from downstream supply partners' requirements. That is, DRP uses MRP-style logic to feed accurate demand information into the master schedule.

FIGURE 12.22
Synchronized Planning and Control



[2]W. Bundy, "Miller SQA: Leveraging Technology for Speed and Reliability," *Supply Chain Management Review* 3, no. 2 (Spring 1999): 62–69.

FIGURE 12.23 Downstream Supply Chain for MeltoMatic Snowblowers



Suppose the MeltoMatic is sold through two regional distribution centers, one in Minneapolis, Minnesota, and the other in Buffalo, New York. These distribution centers, in turn, sell directly to retailers. Figure 12.23 shows the structure of this downstream supply chain.

Each distribution center has its own weekly demand forecasts, inventory data, order lead times, and minimum order quantities. Both centers use this information to estimate when they will need to place orders with the main plant.

The two sections at the top of Figure 12.24 show the DRP records for the two distribution centers. Note that these records are almost identical to MRP records, with one exception: Instead of gross requirements, they show forecasted demand. Here, the term *forecasted demand* refers to the number of snowblowers each center expects to ship to retail customers each week. By substituting forecasted demand for gross requirements, managers at the distribution centers can calculate net requirements, planned receipts, and planned orders. Finally, activities at these two distribution centers are synchronized when their total weekly planned orders become forecasted demand in the factory's master schedule (see the third section of Figure 12.24). Master scheduling occurs as usual, except that the forecasted demand is tied explicitly to planned orders at the distribution centers.

Now look at what happens when forecasted demand changes at the distribution centers (Figure 12.25). Starting in week 49, the forecasted demand at the Minneapolis distribution center has increased dramatically. What is the impact of this change on the master schedule? Logic suggests that in order to meet the increased demand, Sandy-Built's managers will need to increase

Minneapolis distribution center		Month	********November********				********December********				********January********			
		Week	45	46	47	48	49	50	51	52	1	2	3	4
	Forecasted demand		60	60	60	60	75	75	75	75	90	90	120	120
LT (weeks) = 2	Scheduled receipts			120										
	Projected ending inventory	75	15	75	15	75	0	45	90	15	45	75	75	75
	Net requirements		0	0	0	45	0	75	30	0	75	45	45	45
Min. order = 120	Planned receipts		0	0	0	120	0	120	120	0	120	120	120	120
	Planned orders		0	120	0	120	120	0	120	120	120	120	0	0

Buffalo distribution center		Month	********November********				********December********				********January********			
		Week	45	46	47	48	49	50	51	52	1	2	3	4
	Forecasted demand		80	80	85	85	90	90	95	95	100	100	105	105
LT (weeks) = 1	Scheduled receipts		100											
	Projected ending inventory	25	45	65	80	95	5	15	20	25	25	25	20	15
	Net requirements		0	35	20	5	0	85	80	75	75	75	80	85
Min. order = 100	Planned receipts		0	100	100	100	0	100	100	100	100	100	100	100
	Planned orders		100	100	100	0	100	100	100	100	100	100	100	0

Master schedule, MeltoMatic snowblowers		Month	********November********				********December********			
		Week	45	46	47	48	49	50	51	52
	Forecasted demand		**100**	**220**	**100**	**120**	**220**	**100**	**220**	**220**
	Booked orders		100	0	0	0	0	0	0	0
	Projected ending inventory	37	257	37	157	37	137	37	257	37
	Master production schedule		320		220		320		440	0
	Available to promise		257		220		320		440	

FIGURE 12.24 DRP Records for the MeltoMatic Snowblower

	Month		********November********				********December********				********January********			
Minneapolis distribution center	Week		45	46	47	48	49	50	51	52	1	2	3	4
	Forecasted demand		60	60	60	60	**90**	**90**	**90**	**90**	**110**	**110**	**130**	**130**
LT (weeks) = 2	Scheduled receipts			120			0							
	Projected ending inventory	75	15	75	15	75	105	15	45	75	85	95	85	75
	Net requirements		0	0	0	45	15	0	75	45	35	25	35	45
Min. order = 120	Planned receipts		0	0	0	120	120	0	120	120	120	120	120	120
	Planned orders		**0**	**120**	**120**	**0**	**120**	**120**	**120**	**120**	**120**	**120**	**0**	**0**

	Month		********November********				********December********				********January********			
Buffalo distribution center	Week		45	46	47	48	49	50	51	52	1	2	3	4
	Forecasted demand		80	80	85	85	90	90	95	95	100	100	105	105
LT (weeks) = 1	Scheduled receipts		100											
	Projected ending inventory	25	45	65	80	95	5	15	20	25	25	25	20	15
	Net requirements		0	35	20	5	0	85	80	75	75	75	80	85
Min. order = 100	Planned receipts		0	100	100	100	0	100	100	100	100	100	100	100
	Planned orders		100	100	100	0	100	100	100	100	100	100	100	0

	Month		********November********				********December********			
Master schedule, MeltoMatic snowblowers	Week		45	46	47	48	49	50	51	52
	Forecasted demand		**100**	**220**	**220**	**0**	**220**	**220**	**220**	**220**
	Booked orders		100	0	0	0	**0**	0	0	0
	Projected ending inventory	37	257	37	37	37	**257**	37	257	37
	Master production schedule		320		220		**440**		440	
	Available to promise		257		220		**440**		440	

FIGURE 12.25 The Impact of Forecast Changes on DRP Records

the master production schedule to 440 snowblowers in week 49. The point is that DRP quickly translates downstream demand into upstream production decisions.

Figure 12.26 provides a final, high-level view of how DRP helps synchronize Sandy-Built's supply chain. Retailer orders drive not only Sandy-Built's plans but also those of upstream suppliers who plan their activity based on Sandy-Built's material orders. In effect, every *MPS* quantity or MRP planned order can be traced back to demand from the retailers.

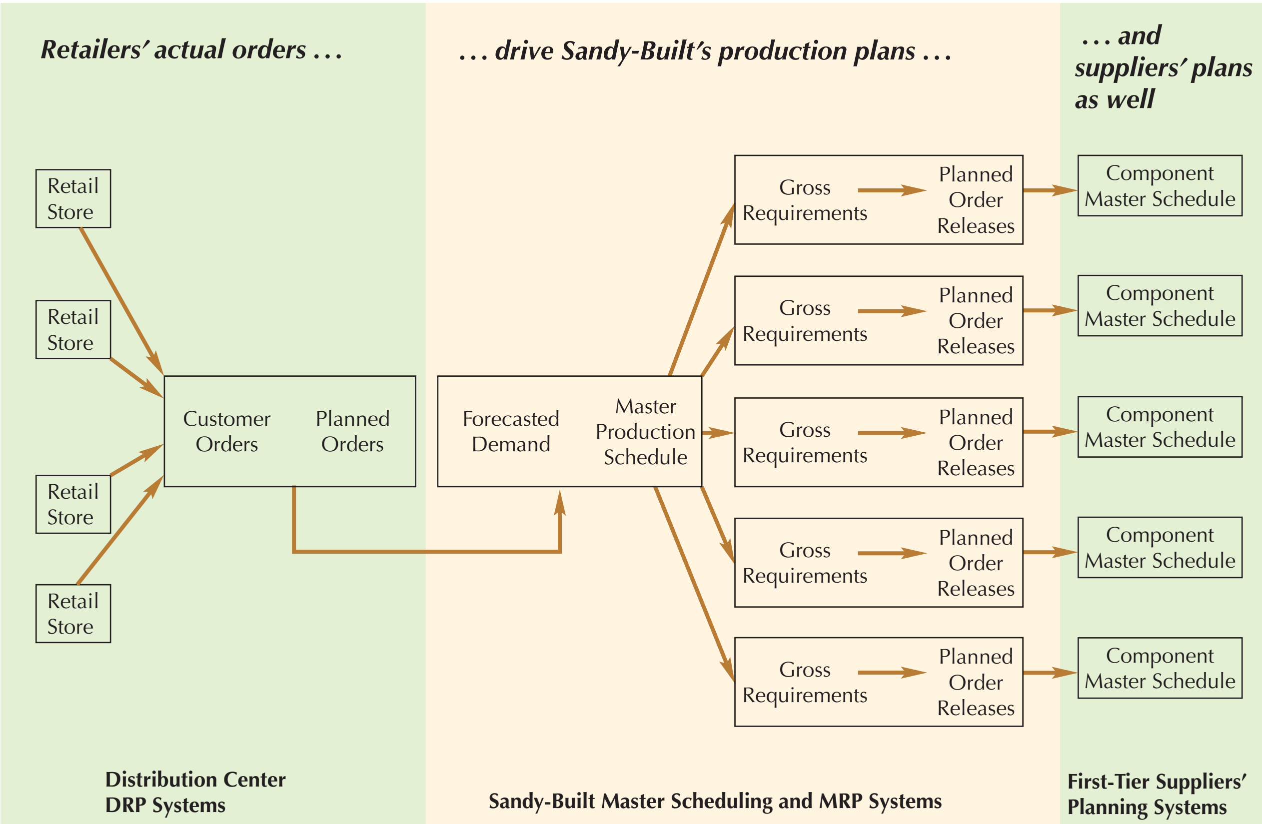


FIGURE 12.26 Synchronizing Plans across the Supply Chain

CHAPTER SUMMARY

This chapter has provided a comprehensive overview of the various tools companies use to manage production, starting with master scheduling, then MRP and job sequencing, and ending with DRP. Planning and control systems aid manufacturers and service firms alike by helping them to determine the quantities and timing of their activities. Put another way, production management should be of interest not only to manufacturing firms but to virtually all firms involved in the flow of physical products.

Today, advances in information technology are radically changing planning and control systems in two fundamental ways. First, faster computers and extensive communications networks are expanding the depth and breadth of planning and control activities. Firms can replan and share new information with their supply chain partners almost instantaneously. Second, planning and control software tools are becoming more sophisticated. Some firms even have advanced decision support tools that allow them to quickly evaluate multiple plans or even to generate an optimal plan.

That said, the usefulness of planning and control systems still depends on people who understand how they work and how to use them correctly. This fundamental requirement will never change.

EXAMPLE 12.8

BigDawg Customs Revisited

"OK, so what should we do?" asked Steve Barr, owner of BigDawg Customs.

Traci Griggs, vice president of marketing, spoke up. "One of the problems you mentioned was that currently we really didn't have a way to match up production of KZ1 seats with actual customer orders. So I've worked with Brad in manufacturing to develop a master production schedule for the KZ1. Brad, show Steve how it works."

Brad Ashbaugh handed Steve a preliminary master schedule for the KZ1 (Figure 12.27). "The master schedule really does several things. First, it allows us to compare the weekly forecasts Traci has developed against our planned production levels. Second, it allows us to . . ."

KZ1 inventory at end of March =			252					
Month	***************April***************				***************May***************			
Week	14	15	16	17	18	19	20	21
Forecast demand	**300**	**300**	**400**	**450**	**500**	**500**	**500**	**500**
Orders booked	**240**	**295**	**170**	**150**	**90**	**0**	**0**	**0**
Projected ending inventory	–48	852	452	2	1,002	502	2	1,002
Master production schedule	**0**	**1,200**	**0**	**0**	**1,500**	**0**	**0**	**1,500**
Available-to-promise	12	585			1,410			1,500

FIGURE 12.27 Master Schedule for KZ1 Scooter Seat

"Woah!" Steve Barr interjected. "What does that negative inventory number in week 14 mean? Have we overpromised again?"

Brad replied, "Good question. No, we haven't overpromised yet. In fact, the 'available-to-promise' line for week 14 tells us we still have another 12 seats that we can sell this week before we make more seats next week. The –48 means that, given what we've already promised and what we have available, we expect that we'll have to turn away orders for 48 seats this week. This is not great and we want to avoid this in the future, but not meeting demand is still better than promising something we can't deliver."

"OK, I think I get it. So how will this master schedule work as time goes on?" asked Steve. Traci answered, "Every week, Brad and I will get together and roll the schedule forward one week. We will update the forecast numbers and see what adjustments if any should be made to the master production schedule. Also—and this is key—every time a salesperson makes a sale, he or she will first need to check to see whether inventory is available, and then make sure the master schedule is updated every time there is a change to the orders booked. This way we can make sure we don't promise something we can't deliver."

Steve replied, "OK, that sounds good, but what about our parts inventory problem?" Brad spoke up, "The KZ1 seat is assembled from three components we order from vendors: the saddle, the cover, and a hardware kit. We can use material requirements planning to tell us when we need to order stuff so that we don't order too earlier and we don't order too much. Brad then handed Steve a preliminary copy of the MRP for the KZ1 seat (Figure 12.28).

		WEEK							
KZ1 Seat		14	15	16	17	18	19	20	21
LT (weeks) = 1	MPS due date	0	1,200	0	0	1,500	0	0	1,500
	Start assembly	1,200	0	0	1,500	0	0	1,500	0

			WEEK							
			14	15	16	17	18	19	20	21
Saddle	Gross requirements		1,200	0	0	1,500	0	0	1,500	0
LT (weeks) = 2	Scheduled receipts		0	0	0	0	0	0	0	0
	Projected ending inventory	1,650	450	450	450	0	0	0	0	0
$30	Net requirements		0	0	0	1,050	0	0	1,500	0
	Planned receipts		0	0	0	1,050	0	0	1,500	0
Min. order = 1	Planned orders	0	0	1,050	0	0	1,500	0	0	0

			WEEK							
			14	15	16	17	18	19	20	21
Hardware Kit	Gross requirements		1,200	0	0	1,500	0	0	1,500	0
LT (weeks) = 1	Scheduled receipts		0	0	0	0	0	0	0	0
$20	Projected ending inventory	2,200	1,000	1,000	1,000	500	500	500	0	0
	Net requirements		0	0	0	500	0	0	1,000	0
Min. order = 1,000	Planned receipts		0	0	0	1,000	0	0	1,000	0
	Planned orders	0	0	0	1,000	0	0	1,000	0	0

			WEEK							
			14	15	16	17	18	19	20	21
Cover	Gross requirements		1,200	0	0	1,500	0	0	1,500	0
LT (weeks) = 2	Scheduled receipts		0	250	0	0	0	0	0	0
$10	Projected ending inventory	1,200	0	250	250	0	0	0	0	0
	Net requirements		0	0	0	1,250	0	0	1,500	0
Min. order = 250	Planned receipts		0	0	0	1,250	0	0	1,500	0
	Planned orders	0	0	1,250	0	0	1,500	0	0	0

FIGURE 12.28 MRP Record for KZ1 Scooter Seat

Brad continued, "We are about to go into week 14 of the year, and we currently have 1,650 saddles, 2,200 hardware kits, and 1,200 covers sitting in inventory. At current costs, this inventory is worth:

$$\begin{aligned} &1{,}650 \text{ saddles} * (\$30 \text{ each}) + 2{,}200 \text{ hardware kits} * (\$20 \text{ each}) \\ &\qquad + \$1{,}200 * (\$10 \text{ each}) = \$105{,}500 \end{aligned}$$

"Ugh! And most of that stuff has been sitting around for a couple weeks," interjected Steve. "Exactly," Brad continues, "but if we use MRP to plan the timing and quantities of orders, we can reduce component inventories to zero by the end of week 21."

Steve, Traci, and Brad discuss the master schedule and MRP records for a while longer until Steve is satisfied and has a basic understanding of how the planning tools work. Finally he says:

"This looks like a really good start, and I'll be interested to see how this works in practice. I guess I have a couple of questions. First, what do we need to do to help make sure everyone follows the rules—that is, placing customer orders through the master schedule, and keeping accurate inventory records? Also, once we get this system working for the KZ1 seats, how might we apply it to other areas of our business?"

KEY FORMULAS

Projected ending inventory for the master schedule record (page 368):

$$EI_t = EI_{t-1} + MPS_t - \text{maximum}\,(F_t, OB_t) \qquad \textbf{(12.1)}$$

where:

EI_t = ending inventory in time period t
MPS_t = master production schedule quantity available in time period t
F_t = forecasted demand for time period t
OB_t = orders booked for time period t

Available to promise for the master schedule record (page 370):

For the *first week* of the master schedule record:

$$ATP_t = EI_{t-1} + MPS_t - \sum_{i=t}^{z-1} OB_i \qquad \textbf{(12.2)}$$

For any subsequent week in which $MPS > 0$:

$$ATP_t = MPS_t - \sum_{i=t}^{z-1} OB_i \qquad \textbf{(12.3)}$$

where:

ATP_t = available to promise in week t
EI_{t-1} = ending inventory in week $t - 1$
MPS_t = master production schedule quantity in week t
$\sum_{i=t}^{z-1} OB_i$ = sum of all orders booked from week t until week z (when the next positive MPS quantity is due)

Net requirements for the MRP record (page 376):

$$NR_t = \text{maximum}\,(0; GR_t - EI_{t-1} - SR_t) \qquad \textbf{(12.4)}$$

where:

NR_t = net requirement in time period t
GR_t = gross requirement in time period t
EI_{t-1} = ending inventory from time period $t - 1$
SR_t = scheduled receipts in time period t

Projected ending inventory for the MRP record (page 376):

$$EI_t = EI_{t-1} + SR_t + PR_t - GR_t \qquad \textbf{(12.5)}$$

where:

EI_t = ending inventory from time period t
EI_{t-1} = ending inventory from time period $t - 1$
SR_t = scheduled receipts in time period t
PR_t = planned receipts in time period t
GR_t = gross requirements in time period t

Critical ratio (page 383):

$$\text{Critical ratio} = \frac{\text{days until due}}{\text{total task time remaining}} \qquad \textbf{(12.6)}$$

KEY TERMS

SOLVED PROBLEM

PROBLEM

Completing a Master Schedule Record

Complete the projected ending inventory and available to promise calculations for the following master schedule record. Interpret the results.

On-hand inventory at end of week 15: 222								
Week	16	17	18	19	20	21	22	23
Forecasted demand	220	220	215	215	210	210	205	205
Booked orders	192	189	233	96	135	67	85	40
Projected ending inventory								
Master production schedule		450		430		415		400
Available to promise								

Solution

The projected ending inventory values can be found using Equation (12.1):

$$EI_t = EI_{t-1} + MPS_t - \text{maximum}\,(F_t, OB_t) \tag{12.1}$$

For weeks 16 through 18, the projected ending inventories are:

$$EI_{16} = 222 + 0 - \text{maximum}\,(220, 192) = 2$$
$$EI_{17} = 2 + 450 - \text{maximum}\,(220, 189) = 232$$
$$EI_{18} = 232 + 0 - \text{maximum}\,(215, 233) = -1$$

Weeks 19 through 23 are calculated in a similar manner. In the projected ending inventory in week 18, the negative value suggests that there is not enough inventory to meet the forecasted demand. But has the company overpromised yet? To see, we need to calculate the *ATP* numbers:

$$ATP_{16} = 222 + 0 - 192 = 30$$
$$ATP_{17} = 450 - (189 + 233) = 28$$
$$ATP_{19} = 430 - (96 + 135) = 199$$
$$ATP_{21} = 415 - (67 + 85) = 263$$
$$ATP_{23} = 400 - 40 = 360$$

The completed master schedule record is as follows:

On-hand inventory at end of week 15: 222								
Week	16	17	18	19	20	21	22	23
Forecasted demand	220	220	215	215	210	210	205	205
Booked orders	192	189	233	96	135	67	85	40
Projected ending inventory	**2**	**232**	**–1**	**214**	**4**	**209**	**4**	**199**
Master production schedule		450		430		415		400
Available to promise	**30**	**28**		**199**		**263**		**360**

The master schedule record suggests that, as of right now, the company has not overpromised. However, if the company wants to meet all the forecasted demand (or keep some safety stock available, just in case), it should consider taking steps to bump up its master production schedule quantities.

DISCUSSION QUESTIONS

1. Someone says to you, "If a company is already using sales and operations planning to coordinate marketing and operations, then it doesn't need master scheduling as well." Is this true? How are S&OP and master scheduling similar? How are they different? What information does master scheduling provide that S&OP does not? How difficult would it be to develop successful master schedules without doing S&OP first?
2. Can a company complete its material requirements plans before it does master scheduling? Explain.
3. Discuss the importance of accurate forecasting to planning and control systems. What happens if an organization's planning efforts are strong, except for forecasting?
4. What is MRP nervousness? Can this condition affect DRP systems as well?

5. Master scheduling, MRP, and DRP have been around for a long time, but too many companies still do an inadequate job of using these tools. How can this be? In particular, what role do you think organizational discipline plays in making these tools work?
6. What are the benefits of having a formal master scheduling process? What could happen to firms that don't follow some of the basic rules of master scheduling?
7. Explain in your own words how tools such as master scheduling, MRP, and DRP can be used to coordinate activity up and down a supply chain. For example, what information might we share with our customers? Our suppliers? What information might we want from them to do master scheduling, MRP, and DRP effectively?

PROBLEMS

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

Problems for Section 12.1: Master Scheduling

1. (*) Complete the following master schedule record:

On-hand inventory at end of week 1: 65								
Week	2	3	4	5	6	7	8	9
Forecasted demand	45	50	55	60	65	70	75	80
Booked orders	15	100	48	25	72	22	67	10
Projected ending inventory								
Master production schedule	150			200			150	
Available to promise							**73**	

2. (**) Consider the master schedule record shown in problem 1. Suppose marketing books an order for an additional 10 units in week 4. Recalculate the projected ending inventory and available-to-promise numbers. How low does the projected ending inventory get? What actions might the company take as a result?
3. (**) Complete the following master schedule record:

On-hand inventory at end of week 1: 100								
Week	2	3	4	5	6	7	8	9
Forecasted demand	250	250	300	300	350	350	250	250
Booked orders	265	255	270	245	260	235	180	100
Projected ending inventory								
Master production schedule	500		600		700		500	
Available to promise							**220**	

4. (**) Consider the master schedule record shown in problem 3. Suppose the production manager calls and says that only 600 units will be finished in week 6, not the 700 units originally called for. Recalculate the projected ending inventory and available-to-promise numbers. What does a negative projected ending inventory value mean? How does it differ from a negative available-to-promise number? As a manager, which would be easier to deal with—a negative projected inventory value or a negative *ATP*?
5. Consider the following partially completed master schedule record:

On-hand inventory at end of April: 40								
Month	************May************				************June************			
Week	19	20	21	22	23	24	25	26
Forecasted demand	200	200	200	225	225	225	200	200
Booked orders	205	203	201	195	193	190	182	178
Projected ending inventory								
Master production schedule	600	0	0	675	0	0	600	0
Available to promise							**240**	

a. (*) Complete the projected on-hand inventory calculations and the available-to-promise calculations.

b. (**) Suppose that a customer calls and cancels an order for 50 units in week 25. Which of the following statements are *true*?

- The *ATP* for week 25 will increase by 50 units.
- The projected ending inventory for week 25 will increase by 50 units.
- The *ATP* for weeks 19 and 22 will be unaffected.

Problems for Section 12.2: Material Requirements Planning

6. (*) Complete the following MRP record. All gross requirements, beginning inventory levels, and scheduled receipts are shown.

WEEK		1	2	3	4	5	6
A2	Gross requirements	200	200	200	300	300	300
LT (weeks) = 2	Scheduled receipts		200				
	Projected ending inventory: 260						
	Net requirements						
Min. order = 1	Planned receipts						
Planned orders							

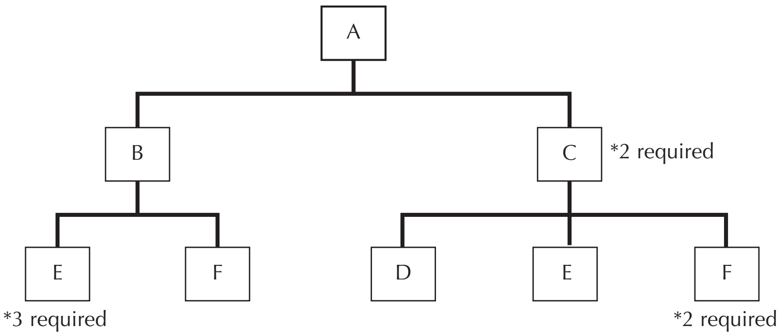
7. (**) Now suppose the lead time for item A2, shown in problem 6, is three weeks rather than two weeks. Based on this information, can the company support the current gross requirements for the A2? Why? What are the implications of having reliable supplier and manufacturing lead times in an MRP environment?

8. (**) Complete the following MRP record. Note that the minimum order quantity is 900. What is the average ending inventory over the six weeks?

WEEK		1	2	3	4	5	6
B3	Gross requirements	0	400	400	400	0	400
LT (weeks) = 1	Scheduled receipts						
	Projected ending inventory: 0						
	Net requirements						
Min. order = 900	Planned receipts						
	Planned orders						

9. (**) Now suppose the minimum order quantity for item B3 in problem 8 is reduced to 300 units. Redo the MRP record. What is the new average ending inventory level over the six weeks? What are the implications for setting order quantities in an MRP environment?

10. (**) The following figure shows the bill of material (BOM) for the Acme PolyBob, a product that has proven unsuccessful in capturing roadrunners. Complete the MRP records. All the information you need is shown in the BOM and on the MRP records.



Item B: Lead time = 1 week; Minimum order quantity = 1

WEEK	1	2	3	4	5	6
Gross requirements		250	300	300	300	200
Scheduled receipts						
Projected ending inventory: 0						
Net requirements						
Planned receipts						
Planned orders						

Item C: Lead time = 3 weeks; Minimum order quantity = 500

WEEK	1	2	3	4	5	6
Gross requirements						
Scheduled receipts		500	600			
Projected ending inventory: 0						
Net requirements						
Planned receipts						
Planned orders						

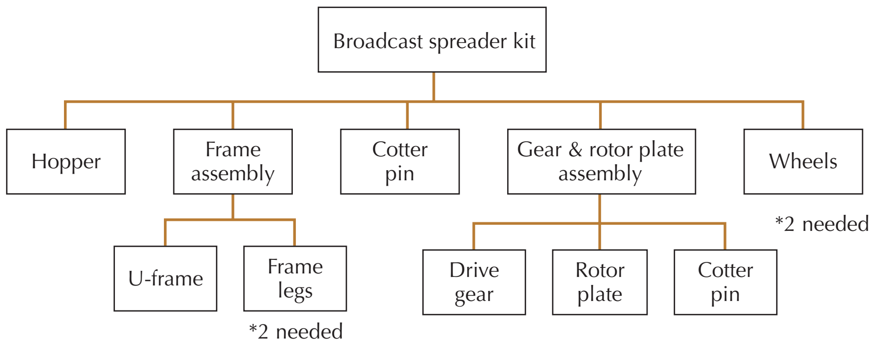
Item E: Lead time = 4 weeks; Minimum order quantity = 5,000

WEEK	1	2	3	4	5	6
Gross requirements						
Scheduled receipts						
Projected ending inventory: 5,750						
Net requirements						
Planned receipts						
Planned orders						

Item F: Lead time = 5 weeks; Minimum order quantity = 750

WEEK	1	2	3	4	5	6
Gross requirements						
Scheduled receipts						
Projected ending inventory: 4,750						
Net requirements						
Planned receipts						
Planned orders						

11. (**) Republic Tool and Manufacturing Company of Carlsbad, California, makes a wide variety of lawn care products. One of Republic's products is the Model Number 540 Broadcast Spreader:



Complete the following MRP records. Note the following:

- Republic intends to start assembling 2,000 broadcast spreader kits in weeks 2, 4, and 6.
- The gross requirements for the gear and rotor plate assembly have already been given to you. For the remaining items, you will need to figure out the gross requirements.
- All scheduled receipts, lead times, and beginning inventory levels are shown.
- Note that cotter pins appear *twice* in the bill of material.

Gear and rotor plate assembly: Lead time = 1 week; Minimum order quantity = 2,500

WEEK	1	2	3	4	5	6
Gross requirements		2,000		2,000		2,000
Scheduled receipts						
Projected ending inventory: 1,000						
Net requirements						
Planned receipts						
Planned orders						

Wheels: Lead time = 1 week; Minimum order quantity = 1

WEEK	1	2	3	4	5	6
Gross requirements						
Scheduled receipts						
Projected ending inventory: 0						
Net requirements						
Planned receipts						
Planned orders						

Cotter pins: Lead time = 3 weeks; Minimum order quantity = 15,000

WEEK	1	2	3	4	5	6
Gross requirements						
Scheduled receipts						
Projected ending inventory: 11,000						
Net requirements						
Planned receipts						
Planned orders						

12. (**) Each Triam Deluxe gamer computer system consists of *two* speakers, a monitor, a system unit, a keyboard, and an installation kit. These pieces are packed together and shipped as a complete kit. In MRP terms, all of these items are level 1 items that make the level 0 kits. Complete the MRP records, using the following information:

- Production plans for complete kits are as follows:

  Start assembling 2,500 kits in week 2
  Start assembling 3,000 kits in weeks 3, 4, and 5
  Start assembling 2,000 kits in week 6
- The gross requirements for the system unit have already been given to you. For the remaining items, you will need to figure out the gross requirements.
- All scheduled receipts, lead times, and beginning inventory levels are shown.

System unit: Lead time = 1 week; Minimum order quantity = 1

WEEK	1	2	3	4	5	6
Gross requirements		2,500	3,000	3,000	3,000	2,000
Scheduled receipts						
Projected ending inventory: 0						
Net requirements						
Planned receipts						
Planned orders						

Speakers: Lead time = 1 week; Minimum order quantity = 5,000

WEEK	1	2	3	4	5	6
Gross requirements						
Scheduled receipts	5,000					
Projected ending inventory: 0						
Net requirements						
Planned receipts						
Planned orders						

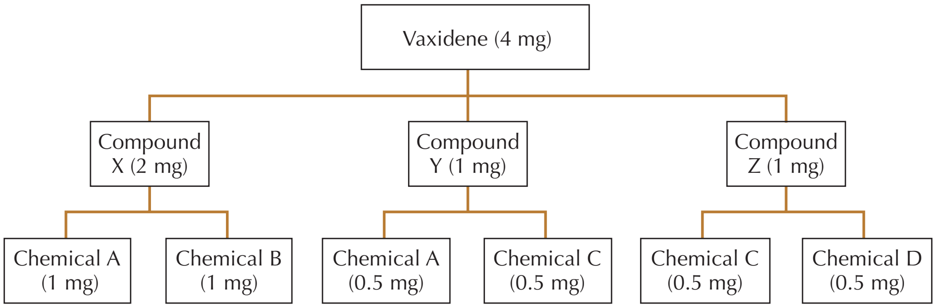
CD-ROM drives: Lead time = 6 weeks; Minimum order quantity = 5,000

WEEK	1	2	3	4	5	6
Gross requirements						
Scheduled receipts						
Projected ending inventory: 13,500						
Net requirements						
Planned receipts						
Planned orders						

Vaxidene (Problems 13 and 14)

After graduating from college, you take a job with Baxter Pharmaceuticals. You are made the product manager for Vaxidene, a new vaccine used to fight bacterial meningitis. The bill of material (BOM) for a *single 4-milligram dose* of Vaxidene follows:

Each dose is actually a mixture of three proprietary compounds, called compounds X, Y, and Z. It takes one week to mix them together to make doses of Vaxidene. You also have the following information:



- Compound X is made up of two chemicals (A and B) and takes one week to synthesize (i.e., lead time = 1 week).
- Compound Y is made up of two chemicals (A and C) and takes one week to synthesize.
- Compound Z is made up of two chemicals (C and D) and takes one week to synthesize.
- The lead times for chemicals A through D are all one week.

13. Consider the following master schedule record for Vaxidene:

On-hand inventory at end of December: 916 doses								
Month	**********January**********				********February********			
Week	6	7	8	9	10	11	12	13
Forecast demand	1,000	1,000	1,250	1,250	1,500	1,500	1,750	1,750
Orders booked	1,095	950	1,100	963	1,125	1,095	1,243	1,208
Projected on-hand inventory								
Master schedule	3,250	0	0	4,250	0	0	3,500	0
Available-to-promise								

a. (*) Complete the master schedule record.

b. (**) Suppose a hospital in the Tucson area calls and says it is facing an epidemic of bacterial meningitis. It needs 2,000 doses as soon as possible. Assuming that Baxter can make no changes to the master production schedule quantities or orders booked, how quickly can it get the hospital the 2,000 doses? Be specific with regard to what quantities Baxter can ship and when.

c. (**) Suppose the hospital says it needs the doses now, not in three weeks. What steps could Baxter Pharmaceuticals take to deal with this emergency? Who would Baxter need to talk to? (*Hint:* Consider the current booked orders and their sources.)

14. (***) Complete the following MRP records for the Vaxidene drug. Note the following:

- Doses have been converted into milligrams to facilitate material planning (4,250 doses = 17,000 milligrams).
- Make sure that you calculate the correct requirements for each compound and drug. For instance, each 4-milligram dose requires 2 milligrams of compound X (2 to 1). Therefore, to start mixing 17,000 milligrams of Vaxidene, Baxter Pharmaceuticals will need 8,500 milligrams of compound X.

Vaxidene

		WEEK						
		1	2	3	4	5	6	7
LT (weeks) = 1 start mixing	MPS due date		0	0	17,000	0	0	14,000
				17,000			14,000	
Compound X	Gross requirements							
LT (weeks) =	Scheduled receipts							
	Projected ending inventory: 1,500							
	Net requirements							
Minimum order (mg) 20,000	Planned receipts							
	Planned orders							
Compound Y	Gross requirements							
LT (weeks) =	Scheduled receipts							
	Projected ending inventory: 1,000							
	Net requirements							
Minimum order (mg) 5,000	Planned receipts							
	Planned orders							
Compound Z	Gross requirements	200						
LT (weeks) =	Scheduled receipts							
	Projected ending inventory: 0							
	Net requirements							
Minimum order (mg) 1	Planned receipts							
	Planned orders							
Chemical A	Gross requirements							
LT (weeks) =	Scheduled receipts							
	Projected ending inventory: 500							
	Net requirements							
Minimum order (mg) 9,500	Planned receipts							
	Planned orders							
Chemical B	Gross requirements							
LT (weeks) =	Scheduled receipts							
	Projected ending inventory: 0							
	Net requirements							
Minimum order (mg) 4,000	Planned receipts							
	Planned orders							
Chemical C	Gross requirements							
LT (weeks) =	Scheduled receipts							
	Projected ending inventory: 0							
	Net requirements							
Minimum order (mg) 2,000	Planned receipts							
	Planned orders							
Chemical D	Gross requirements							
LT (weeks) =	Scheduled receipts							
	Projected ending inventory: 3,000							
	Net requirements							
Minimum order (mg) 1	Planned receipts							
	Planned orders							

Problems for Section 12.3: Production Activity Control and Vendor Order Management Systems

15. (**) Consider the following job information. Each job must proceed sequentially through the different work areas, and each area can work on only one job at a time. Sequence the jobs according to the (1) first-come, first-served rule, (2) earliest due date, and (3) critical ratio. Calculate the average lateness under each rule. Which rule performs best? Are any of the results completely satisfactory? What are the implications?

	Estimated Days				
JOB	**PAINTING**	**ASSEMBLY**	**PACKING**	**TOTAL TASK TIME**	**DAYS UNTIL DUE**
A	1.5	2	0.5	4	15
B	4	3	1	8	16
C	3	2	0.5	5.5	8
D	6	4	1	11	20

16. (**) Recall Example 12.7, where Carlos's Restoration Services wanted to determine the best sequence for four jobs. According to Table 12.2, the critical ratio was the only rule tested that resulted in an estimated average lateness value of 0 days.

Now suppose a representative of Chester College calls and says the college won't need the restored art piece for 14 days. At the same time, the High Museum leaves a message saying it would really like its job completed in 15 days.

How would these requests change the suggested sequence, based on the critical ratio rule? If Carlos's uses the critical ratio rule to sequence the jobs, will they all be done on time?

Problems for Section 12.4: Synchronizing Planning and Control across the Supply Chain

17. (***) Due to unusual weather conditions in Minneapolis and Buffalo, Sandy-Built has changed the forecasted demand numbers for MeltoMatic snowblowers at its two distribution centers. Using Figures 12.24 and 12.25 as guides, complete the following DRP records and master schedule record.

Minneapolis Distribution Center

	Month	***November***				***December***				***January***			
	WEEK	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**1**	**2**	**3**	**4**
LT (weeks) = 2	Forecasted demand	80	80	80	80	90	90	100	100	120	120	140	140
	Scheduled receipts												
	Projected ending inventory: 160												
	Net requirements												
Minimum order = 120	Planned receipts												
	Planned orders												

Buffalo Distribution Center

	Month	***November***				***December***				***January***			
	WEEK	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**1**	**2**	**3**	**4**
LT (weeks) = 1	Forecasted demand	60	60	70	70	80	80	80	80	90	90	95	95
	Scheduled receipts	100											
	Projected ending inventory: 25												
	Net requirements												
Minimum order = 100	Planned receipts												
	Planned orders												

Master Schedule

Month	***November***				***December***			
WEEK	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**
Total planned orders								
Booked orders	120	0	0	0	0	0	0	0
Projected ending inventory: 37								
Master production schedule	340		320		340		440	
Available to promise								

CASE STUDY

The Realco Breadmaster

Two years ago, Johnny Chang's company, Realco, introduced a new breadmaker, which, due to its competitive pricing and features, was a big success across the United States. While delighted to have the business, Johnny felt uneasy about the lack of formal planning surrounding the product. He found himself constantly wondering, "Do we have enough breadmakers to meet the orders we've already accepted? Even if we do, will we have enough to meet expected future demands? Should I be doing something *right now* to plan for all this?"

To get a handle on the situation, Johnny decided to talk to various folks in the organization. He started with his inventory manager and found out that inventory at the end of last week was 7,000 units. Johnny thought this was awfully high.

Johnny also knew that production had been completing 40,000 breadmakers every other week for the last year. In fact, another batch was due this week. The production numbers were based on the assumption that demand was roughly 20,000 breadmakers a week. In over a year, no one had questioned whether the forecast or production levels should be readjusted.

Johnny then paid a visit to his marketing manager to see what current orders looked like. "No problem," said Jack Jones, "I have the numbers right here."

WEEK	PROMISED SHIPMENTS
1	23,500
2	23,000
3	21,500
4	15,050
5	13,600
6	11,500
7	5,400
8	1,800

Johnny looked at the numbers for a moment and then asked, "When a customer calls, how do you know if you can meet the order?" "Easy," said Jack. "We've found from experience that nearly all orders can be filled within two weeks, so we promise them three weeks. That gives us a cushion, just in case. Now look at weeks 1 and 2. The numbers look a little high, but between inventory and the additional 40,000 units coming in this week, there shouldn't be a problem."

Questions

1. Develop a master production schedule for the breadmaker. What do the projected ending inventory and available-to-promise numbers look like? Has Realco overpromised? In your view, should Realco update either the forecast or the production numbers?
2. Comment on Jack's approach to order promising. What are the advantages? The disadvantages? How would formal master scheduling improve this process? What organizational changes would be required?
3. Following up on question 2, which do you think is worse: refusing a customer's order up front because you don't have the units available or accepting the order and then failing to deliver? What are the implications for master scheduling?
4. Suppose Realco produces 20,000 breadmakers every week rather than 40,000 every other week. According to the master schedule record, what impact would this have on average inventory levels?

REFERENCES

Books and Articles

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

Bundy, W. "Miller SQA: Leveraging Technology for Speed and Reliability," *Supply Chain Management Review* 3, no. 2 (Spring 1999): 62–69.

SUPPLEMENT

Paul A. Souders/Corbis/VCG/Getty Images

CHAPTER
twelve

Supply Chain Information Systems

SUPPLEMENT OUTLINE

SUPPLEMENT OBJECTIVES

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

- Explain why information flows are a necessary part of any supply chain.
- Describe in detail how supply chain information needs vary according to the organizational level and the direction of the linkages (upstream or downstream).
- Describe and differentiate among ERP, DSS, CRM, SRM, and logistics applications.
- Describe what business process management (BPM) tools and cloud computing are and how they might impact future operations and supply chain activities.

IBM'S WATSON SUPPLY CHAIN

Imagine that you are the supply chain manager for a new product being launched by your company. Marketing has promised eager customers that the product will start shipping in two weeks. Unfortunately, weather reports indicate that a major snowstorm is about to strike one of your key European suppliers. Some of the questions you might have:

- Will delivery from our European supplier be delayed due to the snowstorm? If so, for how long?
- What will the impact be, if any, on our ability to ship product on time? What will be the ultimate impact on revenues?
- Are there any alternative suppliers who can help us? Do they have the production capacity? What would be the impact on production schedules and costs?

Supply chain information systems, the topic of this supplement, support everything from day-to-day production activities to long-term strategic planning. And as the above example suggests, managers depend on supply chain information systems to help them quickly *replan* based on changing events.

This is where solutions like IBM's Watson Supply Chain come into play. Watson Supply Chain is one example of a technology platform known as cognitive computing. *Cognitive computing* "refers to systems that learn at scale, reason with purpose and interact with humans naturally. Rather than being explicitly programmed, they learn and reason from their interactions with us and from their experiences with their environment." As Alex Zhuong, senior marketing manager, IBM Watson Supply Chain, suggests: "Cognitive technology will shape the future, creating a more intelligent, predictive and agile supply chain." For instance, in response to your concerns about the European supplier, Watson Supply Chain might inform you that:

- There is an 80% chance that supplier deliveries will be delayed approximately 96 hours.
- If unresolved, your company will be three days late getting product, resulting in lost revenues of $3 million.
- Fortunately, there are three suppliers with the capacity to meet your short-term needs.

Alex goes on to note, "The focus of the cognitive supply chain is to compare and understand both structured data, such as traditional enterprise records, and unstructured data, including images, natural language, and social media, to provide real time and deep insights with the ultimate goal of allowing professionals to optimize decision making across the supply chain."

Source: J. Kelly, "Computing, Cognition and the Future of Knowing," *IBM Research: Cognitive Computing*, IBM Corporation, 2015, **www.research.ibm.com/software/IBMResearch/multimedia/Computing_Cognition_WhitePaper.pdf.**

INTRODUCTION

Whether we are talking about purchasing or forecasting, master scheduling or project planning, information is an essential part of managing operations and supply chains. Imagine, for example, trying to decide how much capacity your organization needs or how much of a product to make if you don't have a clear idea of what the demand will be or what the relevant costs are.

The importance of information is reflected in the APICS definition of a *supply chain*: "The global network used to deliver products and services from raw materials to end customers through an engineered flow of information, physical distribution, and cash."[1] In fact, one could argue that neither physical nor monetary flows could take place without information flows.

Information system (IS) According to Laudon and Laudon, "a set of interrelated components that collect (or retrieve), process, store, and distribute information to support decision making, coordination, and control in an organization."

In this supplement, we look at supply chain information flows and the types of information systems firms use to carry them out. Laudon and Laudon define an **information system (IS)** as "a set of interrelated components that collect (or retrieve), process, store, and distribute information to support decision making, coordination, and control in an organization."[2] We should note that not all information systems are computer-based. Nevertheless, much of the growth and interest in supply chain information systems lies in computer-based applications.

[1]J. H. Blackstone, ed., *APICS Dictionary*, 15th ed. (Chicago IL: APICS, 2016).
[2]K. Laudon and J. Laudon, *Management Information Systems: Managing the Digital Firm*, 13th ed. (Upper Saddle River, NJ: Prentice Hall, 2013).

This chapter is divided into two parts. In the first part, we discuss the critical role information flows play in the supply chain. Our purpose here is to give you an understanding of the different ways in which information is used. The second section shifts the focus away from information *flows* to information *systems*. In particular, we discuss some of the major categories of supply chain information systems, including enterprise resource planning (ERP) systems.

12S.1 UNDERSTANDING SUPPLY CHAIN INFORMATION NEEDS

Companies use information to help do everything from handling customers' orders to developing new business strategies. It makes sense, then, to start our discussion of supply chain information flows by describing the different ways in which information supports supply chain activities. Common sense tells us that if we understand what the information needs are, we will be in a better position to identify possible solutions later on.

Differences across Organizational Levels

Some of the supply chain activities we have described in this book are particularly information intensive. These include:

1. Execution and transaction processing (e.g., vendor order management systems);
2. Routine decision making (e.g., master scheduling and supplier evaluation systems);
3. Tactical planning (e.g., S&OP); and
4. Strategic decision making (e.g., location modeling, qualitative forecasting, capacity decisions).

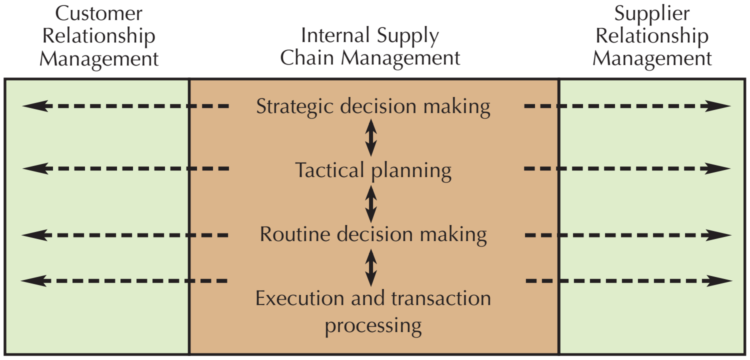
Table 12S.1 arranges these categories vertically, with longer-term strategic decision making at the top and day-to-day, routine activities at the bottom. By looking at supply chain activities in this way, we can begin to see how supply chain information needs differ at various levels of the organization.

At the lowest levels, supply chain information flows record and retrieve necessary data and execute and control physical and monetary flows. This is referred to as *execution and transaction processing*. Information flows at this level tend to be highly automated, with a great deal of emphasis on performing the activity the same way each time. The best execution and transaction processing flows require little or no user intervention and are very accurate and fast.

TABLE 12S.1 Supply Chain Information Needs

SUPPLY CHAIN ACTIVITY	PURPOSE	CHARACTERISTICS	KEY PERFORMANCE DIMENSIONS FOR INFORMATION FLOWS
Strategic decision making	Develop long-range strategic plans for meeting the organization's mission	• Focus is on long-term decisions, such as new products or markets and brick-and-mortar capacity decisions • Least structured of all; information needs can change dramatically from one effort to the next • Greatest user discretion	• Flexibility
Tactical planning	Develop plans that coordinate the actions of key supply chain areas, customers, and suppliers across the tactical time horizon	• Focus is on tactical decisions, such as inventory or workforce levels • Plans, but does not carry out, physical flows • Greater user discretion	• Form • Flexibility
Routine decision making/Replanning	Support rule-based decision making	• Fairly short time frames • User discretion	• Accuracy • Timeliness • Limited flexibility
Execution and transaction processing	Record and retrieve data and execute and control physical and monetary flows	• Very short time frames, very high volumes • Highly automated • Standardized business practices • Ideally no user intervention	• Accuracy • Timeliness

FIGURE 12S.1
Supply Chain Information Flows



At a somewhat higher level, information flows are used to support routine decision making and replanning. Here, users often must have some flexibility to handle exceptions. For example, a retailer might use an inventory management system to forecast, calculate order quantities, establish reorder points, and release orders for the vast majority of items. But the retailer may still want the ability to override the software when the situation warrants. Our opening case study on IBM's Watson Supply Chain is a sophisticated state-of-the-art example of this capability.

The next level up is tactical planning. Here managers are responsible for developing plans that coordinate the actions of key supply chain areas, customers, and suppliers across some tactical time horizon, usually a few months to a year out. Information requirements at this level differ from those at lower levels in a number of ways. First, the information must support *planning* activities, *not* actual execution. Therefore, the time frames are somewhat longer and accuracy is important, but not to the same degree as at lower levels. Second, the information must be widely available and in a form that can be interpreted, manipulated, and used by parties with very different perspectives. A classic example is sales and operations planning (S&OP), which we described in Chapter 10.

Finally, information is needed to support strategic decision making. Here sophisticated analytical tools are often used to search for patterns or relationships in data. Examples include customer segment analysis, product life cycle forecasting, and what-if analyses regarding long-term product or capacity decisions. An excellent example of this is the simulation model we developed for Luc's Deluxe Car Wash in the Chapter 6 supplement. Information systems at the strategic level must be highly flexible in how they manipulate and present the data because the strategic question of interest may change from one situation to the next. Later in this chapter, we talk about decision support systems (DSS), which are specifically geared to support strategic decision making. Notice how the name emphasizes the fact that these systems *support*, but do not *make*, decisions for top managers.

Customer relationship management (CRM)
A term that broadly refers to planning and control activities and information systems that link a firm with its downstream customers.

Supplier relationship management (SRM)
A term that broadly refers to planning and control activities and information systems that link a firm with its upstream suppliers.

Internal supply chain management
A term that refers to the information flows between higher and lower levels of planning and control systems within an organization.

Direction of Linkages

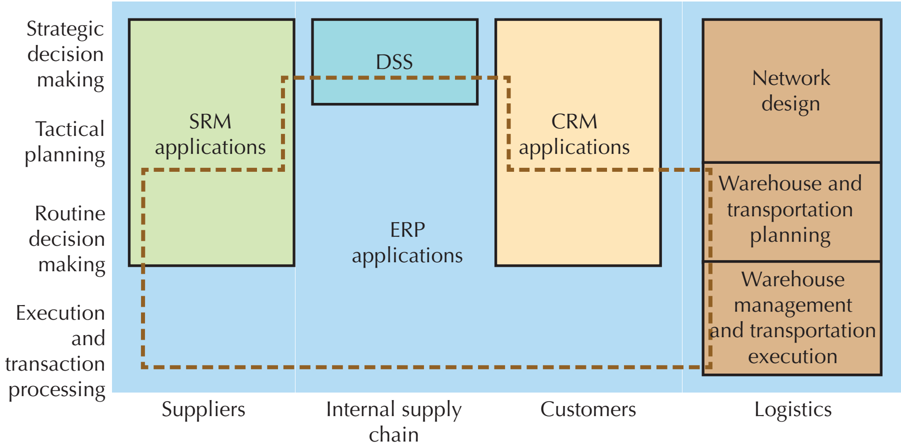
In addition to the organizational level, we need to consider the direction of the linkages. For example, there are planning and control activities that link a firm with its downstream customers, broadly referred to as **customer relationship management (CRM)** activities, and those that link a firm with its upstream suppliers, known as **supplier relationship management (SRM)** activities (Figure 12S.1). There are also flows that link higher-level planning and decision making with lower-level activities *within* the firm (dubbed **internal supply chain management** by Chopra and Meindl[3]).

12S.2 SUPPLY CHAIN INFORMATION SYSTEMS

In this section, we shift our focus from a general discussion of supply chain information flows to a description of the different *solutions* currently being offered. The basis of our map was first laid out more than a decade ago by Steven Kahl,[4] then a software industry analyst. Kahl's map

[3]S. Chopra and P. Meindl, *Supply Chain Management: Strategy, Planning and Operation*, 5th ed. (Upper Saddle River, NJ: Prentice Hall, 2012).
[4]S. Kahl, "What's the 'Value' of Supply Chain Software?" *Supply Chain Management Review* 2, no. 4 (Winter 1999): 59–67.

FIGURE 12S.2
A Map of Supply Chain Management Information Systems



was later refined by Chopra and Meindl,[5] who applied the labels CRM, SRM, and internal supply chain management (ISCM) to various areas of the map.

Our map (Figure 12S.2) parallels Figure 12S.1 in that it distinguishes the various applications by organizational level and the direction of linkages. We add an additional column labeled "Logistics." Logistics applications deal with facilities and transportation issues, such as determining facility locations, optimizing transportation systems, and controlling the movement of materials between supply chain partners.

Enterprise resource planning (ERP) systems Large, integrated, computer-based business transaction processing and reporting systems. ERP systems pull together all of the classic business functions such as accounting, finance, sales, and operations into a single, tightly integrated package that uses a common database.

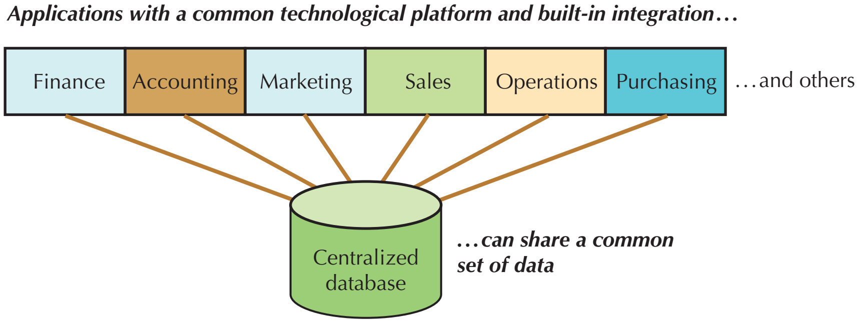
Enterprise resource planning (ERP) systems are large, integrated, computer-based business transaction processing and reporting systems. The primary advantage of ERP systems is that they pull together all of the classic business functions, such as accounting, finance, sales, and operations, into a single, tightly integrated package that uses a common database (Figure 12S.3).

To understand why this is such a big deal, imagine what the information systems for a typical company looked like before ERP. First, every functional area had its own set of software applications, often running on completely different systems. Sharing information (e.g., forecasts, customer information) between systems was a nightmare. To make matters worse, the same information often had to be entered multiple times in different ways. ERP pulled all of these disparate systems into a single integrated system. In practice, few companies use ERP systems to serve all of their information requirements. Rather, companies use ERP systems to meet the bulk of their needs and "plug in" preexisting legacy systems and best-in-class applications to tailor the system to their exact needs. Figure 12S.4 illustrates the idea. As you can imagine, making ERP systems integrate with other applications presents a significant technological challenge.

Decision support systems (DSS) Computer-based information systems that allow users to analyze, manipulate, and present data in a manner that aids higher-level decision making.

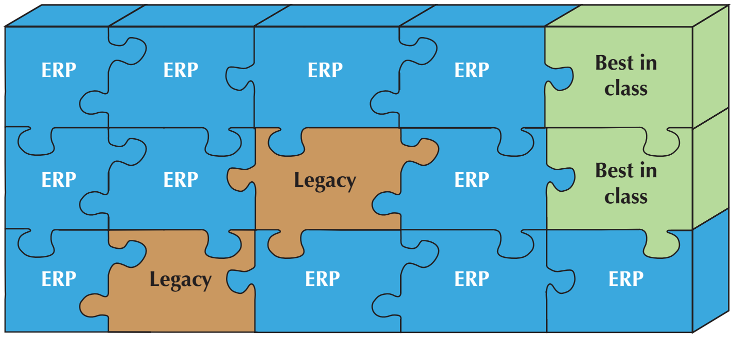
ERP's traditional strengths lie in routine decision making and in execution and transaction processing. To the extent that ERP systems support higher-level planning and decision making, the focus is on the internal supply chain. ERP systems also capture much of the raw data needed to support higher-level decision support systems. **Decision support systems (DSS)**

FIGURE 12S.3
ERP Systems



[5] Chopra and Meindl, *Supply Chain Management*.

FIGURE 12S.4
Integrating ERP Systems with Legacy and Best-in-Class Applications



are computer-based information systems that allow users to analyze, manipulate, and present data in a manner that aids higher-level decision making.

SRM and CRM applications, in contrast, are computer-based information systems specifically designed to help plan and manage the firm's external linkages with its suppliers and customers, respectively. Table 12S.2 gives examples of the types of functionality provided by SRM and CRM applications.

Vendors specializing in CRM and SRM applications tend to provide greater functionality in their chosen areas than do ERP vendors. As a result, many firms choose a standard ERP package for routine decision making and for execution and transaction processing and use best-in-class CRM and SRM applications to manage external relationships. However, this situation has changed in recent years, as ERP vendors, such as SAP and Oracle, increase the CRM and SRM functionality of their own systems.

Network design applications Logistics information systems that address such long-term strategic questions as facility location and sizing, as well as transportation networks. These applications often make use of simulation and optimization modeling.

The last set of supply chain IS applications we will discuss deals directly with logistics decisions. These applications can be divided into three main categories: network design applications, warehouse and transportation planning systems, and warehouse management and transportation execution systems. **Network design applications** address such long-term strategic questions as facility location and sizing, as well as transportation networks. These applications often make use of simulation and optimization modeling.

Warehouse and transportation planning systems Logistics information systems that support tactical planning efforts by allocating "fixed" logistics capacity in the best possible way, given business requirements.

Warehouse management and transportation execution systems Logistics information systems that initiate and control the movement of materials between supply chain partners.

Warehouse and transportation planning systems support tactical planning efforts by allocating "fixed" logistics capacity in the best possible way, given business requirements. These IS applications can also use optimization modeling and simulation. The warehouse assignment problem in Chapter 8, where we had to decide how many units to ship from each warehouse to each demand point, is a classic example of a warehouse and transportation planning system. To find the optimal answer, we built an optimization model that used data on fixed warehouse capacities, demand levels, and shipping costs to generate the lowest-cost solution.

Finally, **warehouse management and transportation execution systems** initiate and control the movement of materials between supply chain partners. Within a warehouse, for example, sophisticated execution systems tell workers where to store items, where to go to pick them up, and how many to pick. Similarly, bar-code systems and global positioning systems (GPSs) have dramatically changed the ability of businesses to manage actual movements in the distribution system. Not too long ago, the only thing most transportation firms could tell you was that your shipment was "on the way" and "should be there in a day or two." Now carriers can tell their customers the exact location of a shipment and the arrival time within minutes.

TABLE 12S.2 Examples of SRM and CRM Applications

SRM APPLICATIONS	CRM APPLICATIONS
Design collaboration	Market analysis
Sourcing decisions	Sell process
Negotiations	Order management
Buy process	Call/service center management
Supply collaboration	

Source: Chopra, S., and Meindl, P., *Supply Chain Management: Strategy, Planning, and Operation*, 5th Edition, pp. 491–494. © 2012. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ.

12S.3 TRENDS TO WATCH

Of course, operations and supply chain information systems continue to evolve. Three trends of particular interest to operations and supply chain professionals are (1) the emergence of sophisticated business process management (BPM) tools, (2) cloud computing, and (3) the Internet of Things (IoT).

BPM Tools

As we noted earlier, there may be times when a prepackaged software solution does not meet an organization's needs. This is especially true when an organization wants to implement its own unique business processes. In his book, *Business Process Change: A Guide for Business Managers and Six Sigma Professionals*, Harmon describes a number of software tools aimed at business process analysis and design. He highlights two key tools:

Business process modeling tools
According to Harmon, "software tools that aid business teams in the analysis, modeling, and redesign of business processes."

Business process management systems (BPMS) products
According to Harmon, "software tools that allow analysts to model processes and . . . then automate the execution of the process at run time."

- **Business process modeling tools** are "software tools that aid business teams in the analysis, modeling, and redesign of business processes."[6] BP modeling tools do more than just chart work flows; they allow users to graphically define a process and simulate the performance of the new process to gain insights into how it might work in the real world. BP modeling tools can also help users develop cost estimates based on the sequence of activities in a process and save defined processes in a database so that they can be reused again in other parts of the business.
- **Business process management systems (BPMS) products** are state-of-the-art software tools for developing and implementing business processes. As Harmon puts it, BPMS products are "software tools that allow analysts to model processes and… then automate the execution of the process at run time."[7] Imagine how this would work: Experts use a BPMS product to develop a process map of how they want a process to work. They then define business rules to manage the flow of work through process (e.g., "If an order is scheduled to be finished late by X or more days, initiate the defined expedited shipping process"). When the users are satisfied that the new process works the way they want it to, the BPMS product can be used to automatically carry out future business activity, without requiring developers to write new software code.

Cloud Computing

Prior to the Internet, the vast majority of computer systems were isolated from one another, requiring their own hardware, software, and databases. Even when organizations put in place private networks to link these systems, sharing software applications and data was a relatively difficult task. The Internet has changed all that and has led to the advent of what is broadly called **cloud computing.** Peter Mell and Timothy Grance of the National Institute of Standards and Technology (NIST) define cloud computing as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction."[8] According to Mell and Grance, the cloud model has five essential characteristics:

Cloud computing
According to a National Institute of Standards and Technology (NIST) report "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction."

1. **On-demand self-service.** Users can automatically access applications and storage space whenever they need them.
2. **Broad network access.** Capabilities are available over the network and accessed through standard mechanisms that promote use by a wide range of platforms, including mobile phones, laptops, and PDAs.
3. **Resource pooling.** The provider's computing resources are pooled to serve multiple consumers, with different physical and virtual resources dynamically assigned and reassigned according to consumer demand.

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[6]P. Harmon, *Business Process Change: A Business Process Management Guide for Managers and Process Professionals*, 3rd ed. (Waltham, MA: Morgan Kaumann Publishers, 2014), p. 382.
[7]Ibid., p. 384.
[8]P. Mell and T. Grance, *The NIST Definition of Cloud Computing (Draft): Recommendations of the National Institute of Standards and Technology*, NIST Special Publication 800–145, **http://csrc.nist.gov/publications/nistpubs/800-145/SP800-145.pdf.**

4. **Rapid elasticity.** Capabilities can be rapidly and elastically provisioned, in some cases automatically, to quickly scale out, and they can be rapidly released to quickly scale in. To the consumer, the capabilities available for provisioning often appear to be unlimited and can be purchased in any quantity at any time.
5. **Measured service.** Resource usage can be monitored, controlled, and reported, providing transparency for both the provider and consumer of the utilized service.

So what does cloud computing mean for operations and supply chain management? Consider two quick examples. First, cloud computing makes it much easier for firms to outsource key portions of their business process information flows (e.g., credit checking, satellite tracking) to outside firms. Second, broad network access allows individual or computer systems to upload and retrieve information through a wide range of devices and virtually anywhere. In a nutshell, cloud computing will make supply chain information flows faster, more flexible, and cheaper than ever. How organizations take advantage of these breakthroughs to improve their existing operations or provide new products and services remains to be seen.

Internet of Things (IoT)

Internet of Things (IoT) According to *Business Insider*, "a network of internet-connected objects able to collect and exchange data using embedded sensors."

Business Insider defines the **Internet of Things (IoT)** as "a network of internet-connected objects able to collect and exchange data using embedded sensors."[9] Unlike cloud computing, the IoT includes not only computer resources, but any physical device that can be monitored and controlled from a remote location via the Internet. A simple example you may be familiar with is using your smartphone to lock the doors or turn off the lights in your house. In an industrial setting, IoT devices tend to be more advanced in terms of functionality, security, and reliability.[10] With more than 2.4 billion IoT devices expected to be in place by 2020,[11] the implications of and challenges for operations and supply chain management are endless.

SUPPLEMENT SUMMARY

In this supplement, we discussed the critical role information flows play in the supply chain and laid out a map of supply chain information systems. To conclude, we will consider the various ways in which information adds value and how breakthroughs in technology will affect supply chain management activities over time. A number of years ago, Jeffrey Rayport and John Sviokla wrote an article in which they talked about three ways information adds value.[12] These ways were, in order of increasing value added:

1. Visibility;
2. Mirroring; and
3. Creation of new customer relationships.

Visibility represents the most basic function of information in the supply chain. Here information allows managers to "see" the physical and monetary flows in the supply chain and, as a result, better manage them. Classic examples include forecasts and point-of-sales data, as well as information regarding inventory levels and the status of jobs in the production system.

Mirroring takes visibility a step further and seeks to *replace* certain physical processes with virtual ones. For example, Rayport and Sviokla describe Boeing's efforts to design new engine housings. In the past, Boeing had to create physical mock-ups of the housings and test them in a wind tunnel in order to evaluate their performance. This was a time-consuming and expensive process. But with the advent of powerful computers, Boeing was able to replace this physical process altogether:

> *Boeing engineers developed the prototype as a virtual product that incorporated relevant laws of physical and material sciences and enabled the company to test an evolving computer-simulated model in a virtual wind tunnel. As a result, engineers could test many more designs at dramatically lower costs and with much greater speed.*[13]

The third stage, creation of new customer relationships, involves taking raw information and organizing, selecting, synthesizing, and distributing it in a manner that creates whole new sources of value. Creating virtual, customized textbooks with access to instructor-led videos and online quizzes is one example. Other examples include taking raw supply chain data and turning

[9]A. Meola, "What Is the Internet of Things (IoT)?," *Business Insider*, December 19, 2016, **www.businessinsider.com/what-is-the-internet-of-things-definition-2016-8.**

[10]J. Thatcher, "Leveraging the Internet of Things (IOT) and the Industrial Internet of Things (IIOT)," *APICS Blog*, March 13, 2017, **www.apics.org/sites/apics-blog/think-supply-chain-landing-page/thinking-supply-chain/2017/03/13/leveraging-the-internet-of-things.**

[11]Meola, A., "What Is the Internet of Things (IoT)?"

[12]J. Rayport and J. Sviokla, "Exploiting the Virtual Value Chain," *Harvard Business Review* 73, no. 6 (November–December 1995): 75–85.

[13]Ibid., p. 79.

them into graphical executive "dashboards" that allow managers to see, at a glance, how the overall business is performing.

So how has all this played out? Visibility systems continue to improve and provide more real-time data, especially as more organizations take advantage of cloud computing. In fact, many managers find themselves making decisions more often to take advantage of the increased availability of timely information. Second, more mirroring is occurring as many physical flows are replaced with virtual ones. Of course, mirroring will be limited to those physical flows whose mission is to create or disseminate information. It is highly unlikely that physical goods will be transformed and moved over the electronic superhighway anytime soon!

Finally, we can expect to see more information-based products aimed at the creation of new customer relationships. Because raw data can be used repeatedly and the variable costs of rearranging and organizing information are so low, this area is limited only by the imagination and needs of businesses.

KEY TERMS

Business process management systems (BPMS) products 405
Business process modeling tools 405
Cloud computing 405
Customer relationship management (CRM) 402
Decision support systems (DSS) 403
Enterprise resource planning (ERP) systems 403
Information system (IS) 400
Internal supply chain management 402
Internet of Things (IoT) 406
Network design applications 404
Supplier relationship management (SRM) 402
Warehouse and transportation planning systems 404
Warehouse management and transportation execution systems 404

DISCUSSION QUESTIONS

1. What is the difference between an information *flow* and an information *system*? Do information systems always have to be computerized? Why?
2. Consider Figure 12S.1. Some people have argued that companies need to put in place information systems that address routine decision making and transactional requirements *prior to* tackling higher-level planning and decision making. Others strongly disagree, pointing out that the higher-level functions are a prerequisite to good tactical planning and execution. What do you think?
3. SAP, the world leader in ERP systems software, has developed tailored ERP systems for different industries. Go to **www.sap.com/solution.html** and examine the solutions for (1) a service industry and (2) a manufacturing industry of your choice. How are they similar? How are they different?

REFERENCES

Books and Articles

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

Chopra, S., and P. Meindl, *Supply Chain Management: Strategy, Planning, and Operation*, 5th ed. (Upper Saddle River, NJ: Prentice Hall, 2012).

Harmon, P., *Business Process Change: A Business Process Management Guide for Managers and Process Professionals*, 3rd ed. (Waltham, MA: Morgan Kaufmann Publishers, 2014).

Kahl, S., "What's the 'Value' of Supply Chain Software?" *Supply Chain Management Review* 2, no. 4 (Winter 1999): 59–67.

Laudon, K., and Laudon, J., *Management Information Systems: Managing the Digital Firm*, 13th ed. (Upper Saddle River, NJ: Prentice Hall, 2013).

Rayport, J., and Sviokla, J., "Exploiting the Virtual Value Chain," *Harvard Business Review* 73, no. 6 (November–December 1995): 75–85.

Internet

Kelly, J., "Computing, Cognition and the Future of Knowing," *IBM Research: Cognitive Computing*, IBM Corporation, 2015, **www.research.ibm.com/software/IBMResearch/multimedia/Computing_Cognition_WhitePaper.pdf.**

Mell, P., and Grance, T., *The NIST Definition of Cloud Computing (Draft): Recommendations of the National Institute of Standards and Technology*, NIST Special Publication 800-145. **http://csrc.nist.gov/publications/nistpubs/800-145/SP800-145.pdf.**

Meola, A, "What Is the Internet of Things (IoT)?," *Business Insider*, December 19, 2016, **www.businessinsider.com/what-is-the-internet-of-things-definition-2016-8.**

Thatcher, J., "Leveraging the Internet of Things (IOT) and the Industrial Internet of Things (IIOT)," *APICS Blog*, March 13, 2017, **www.apics.org/sites/apics-blog/think-supply-chain-landing-page/thinking-supply-chain/2017/03/13/leveraging-the-internet-of-things.**

Paul A. Souders/Corbis/VCG/Getty Images

CHAPTER
thirteen

JIT/Lean Production

CHAPTER OUTLINE

CHAPTER OBJECTIVES

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

- Describe JIT/Lean and differentiate between the Lean philosophy and kanban systems.
- Discuss the Lean perspective on waste and describe the eight major forms of waste, or *muda*, in an organization.
- Discuss the Lean perspective on inventory and describe how a kanban system helps control inventory levels and synchronize the flow of goods and material across a supply chain.
- Describe how the concepts of the Lean supply chain and Lean Six Sigma represent natural extensions of the Lean philosophy.
- Explain how a two-card kanban system works.
- Calculate the number of kanban cards needed in a simple production environment.
- Show how MRP and kanban can be linked together and illustrate the process using a numerical example.

PORSCHE'S "SHOCK THERAPY" PAYS OFF

Ben Smith/Shutterstock

Porsche Badge

If imitation is the sincerest form of flattery, Porsche—a perennial winner in the J.D. Power and Associates annual quality study and the firm whose profit margins are among the highest in the auto industry—is prepared to make the most of it with its thriving Lean consulting business.

The luxury carmaker is already well known to its European competitors as the manufacturer that carries the smallest material inventories. In fact, it keeps a current inventory level of only 0.8 workdays. Porsche has mastered the just-in-time (JIT) method, assembling only the parts it needs and only when it needs them. It smoothes progress every step of the way with sophisticated time- and labor-saving techniques. Working closely with its many suppliers and transportation providers, the company manages a components flow so precisely tuned to its assembly process that car and engine parts can be delivered right to the factory floor and can be installed moments later in the individual cars for which they were ordered. Porsche virtually eliminated warehousing in 2009, freeing up space and capital in the process of improving efficiency, scheduling, waste reduction, and the accuracy of its delivery dates.

These benefits have flowed to its suppliers as well, since only the most disciplined and committed can live up to Porsche's high standards. With lower inventories and minimal fallback levels, these suppliers enjoy increased efficiency and shorter response times. Customers benefit in several ways, too, from lower prices for Porsche's cars to precise product delivery schedules that ensure customer satisfaction at the dealership.

Where does the imitation come in? With such enviable and lucrative results from its well-planned JIT processes, Porsche soon realized it could also profit by selling advice about how to streamline operations and reduce waste. Thus, in 1994, the Porsche Consulting subsidiary was born, with offices in Italy and Brazil to begin with and, by 2014, additional sites in Atlanta, Georgia, and Shangai, China.

Customers of the consulting subsidiary include such manufacturing giants as Deutsche Lufthansa AG, Volkswagen AG, and Meyer Werft GmbH. They and about 150 other corporate clients stand to learn much from Porsche's run-in with near-insolvency in 1993. That watershed experience left the company battered by high inventory, excess factory space, weak sales, a legacy of inefficient and labor-intensive work processes, and a net loss of $162 million. The company had no alternative, says a former Porsche executive, but to resort to "shock therapy" to turn itself around.

So Porsche looked to Toyota, the pioneer in implementing JIT and Lean production techniques. Toyota already had a consulting wing, and from its trainers, Porsche learned how to fine-tune its manufacturing processes and develop new relationships with its suppliers that made JIT operations a feasible remedy. Its embrace of JIT and continuous improvement was soon complete, and every production step is now carefully defined and perfectly orchestrated to maximize resources and minimize waste. For example, Porsche uses small, standardized containers for shipments of its parts orders and loads the empty containers on the same trucks that deliver full ones so they can make a closed transportation circuit. The height of the tow trains in its manufacturing plants is calibrated to match that of the racks in its order-picking departments, so workers can simply slide containers full of parts onto the driverless transport system that takes them to the engine assembly line.

JIT has now been widely adopted in the auto industry, and thanks in part to Porsche Consulting, it is transforming many other industries, including not only auto parts suppliers but also airplane and furniture manufacturers, airlines, construction companies, and even hospitals. One of Porsche Consulting's recent clients was a German manufacturer of cruise ships that now employs a JIT system to reduce inventory from its 1,800 suppliers and has set up its own in-house training academy to ensure that the improvements take hold permanently. Porsche helped shorten service time for Lufthansa's Airbus 340 planes by 10 days, and the airline's catering division, which produces more than 400 million meals a year for other passenger airlines, is now working with Porsche to improve its own logistics. Shorter highway construction schedules and reduced costs for staff and equipment were the goals of another Porsche client, the biggest construction company in central Europe.

As if happy clients weren't enough, the enviable financial results of Porsche's car manufacturing unit are themselves an advertisement for Porsche Consulting. Its operating margin for one recent quarter was 19% versus 11% for Volkswagen's Audi and 9.5% for Mercedes-Benz.

Says the head of Porsche Consulting, "Many clients come to us and say, 'Please turn us into the Porsches of our industries.' "

Sources: Based on Noah Joseph, "Porsche Consulting Sets Up Shop in Atlanta," Autoblog, July 21, 2011, **www.autoblog.com/2011/07/21/porsche-consulting-sets-up-shop-in-atlanta/;** "Typical Porsche: No Superfluous Parts," *Porsche Consulting*, no. 10, January 2011, **www.porsche-consulting.com/it/stampa/porsche-consulting-the-magazine/detail/issue-10-january-2011-4/;** Andreas Cremar, "Porsche 'Shock Therapy' Spurs VW, Lufthansa Efficiency Drive," *Automotive News Europe*, December 13, 2010, **http://europe.autonews.com/article/20101213/ANE/101209816/porsche-%E2%80%98shock-therapy-spurs-vw-lufthansa-efficiency-drive.**

INTRODUCTION

Just-in-time (JIT)
A philosophy of manufacturing based on planned elimination of all waste and on continuous improvement of productivity. In a broad sense, it applies to all forms of manufacturing and to many service industries as well. Used synonymously with *Lean*.

Lean
A philosophy of production that emphasizes the minimization of the amount of all the resources (including time) used in the various activities of an enterprise. It involves identifying and eliminating non-value-adding activities in design, production, supply chain management, and dealing with customers. Used synonymously with *JIT*.

In Chapter 12, we presented a top-down model of production planning and control and offered detailed discussion of several of the most common techniques, including master scheduling, MRP, and DRP. The focus of this chapter is the **just-in-time (JIT)** or **Lean** philosophy and, in particular, kanban production techniques.

As the following APICS definition suggests, Lean touches on many of the areas we have dealt with throughout this book:

> *Lean is a philosophy of production that emphasizes the minimization of the amount of all the resources (including time) used in the various activities of the enterprise. It involves identifying and eliminating non-value-adding activities in design, production, supply chain management, and dealing with the customers. Lean producers employ teams of multiskilled workers at all levels of the organization and use highly flexible, increasingly automated machines to produce volumes of products in potentially enormous variety. It contains a set of principles and practices to reduce cost through the relentless removal of waste and through the simplification of all manufacturing and support processes.*[1]

The Lean philosophy has extended beyond just manufacturing to include services and essentially all aspects of supply chain management. Firms following a Lean philosophy often experience remarkable improvements in their productivity (outputs/inputs), inventory levels, and quality.

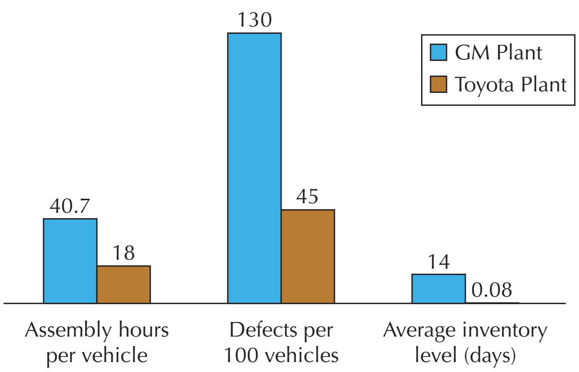
To understand why Lean has made such an impact, consider some eye-opening statistics from 1986, which compared performance at Toyota's Takaoka facility with that at GM's Framingham plant (Figure 13.1). Numbers such as these kicked off what was then called the JIT/Lean production revolution in the U.S. automotive industry during the late 1980s and early 1990s.

Notice how the Toyota plant needed fewer hours and much less inventory to do its job. This ability to do more with less is what first led people to refer to JIT as *Lean production*. Similarly, the phrase *just-in-time* reflected the idea that the timing and level of inventory and production activities are closely matched to demand. With average inventory levels of only two hours, the Toyota plant was clearly receiving parts and materials "just" before they were needed.

Even though we cover Lean production and kanban in a separate chapter from the other production planning techniques, it would be erroneous to assume that companies using traditional planning and control techniques can't adopt a Lean philosophy. For one thing, the underlying emphasis of Lean—to eliminate all forms of waste—is relevant to all organizations, regardless of the specific planning and control tools used. Second, even though some techniques such as kanban are not suitable in all production and service environments, it is entirely possible that an organization can follow the Lean philosophy. To summarize:

- The Lean philosophy can be applied to a wide range of production and service environments. In fact, one could easily argue that there is no environment that wouldn't benefit from adopting its core principles.

FIGURE 13.1
The Performance Advantage of a JIT Plant, Circa 1986
Source: Based on J. Womack, D. Jones, and D. Daniel Roos, *The Machine That Changed the World: The Story of Lean Production* (New York: HarperCollins, 1991).



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

- Companies following the Lean philosophy can and do use a wide range of planning and control techniques, not just kanban.
- The Lean philosophy is entirely consistent with business process improvement (Chapter 4), quality improvement (Chapter 5), and supplier management initiatives (Chapter 7). It's no surprise, then, that the business world has seen the advent of such approaches as *Lean Six Sigma* and *Lean supply chain management*, which we describe in Section 13.3.

With this background, let's look at the historical roots of JIT/Lean, the various forms of waste and uncertainty, the special role of inventory in a Lean environment, and kanban systems in particular.

13.1 THE LEAN PERSPECTIVE ON WASTE

Waste
According to APICS, in the JIT/Lean philosophy, "any activity that does not add value to the good or service in the eyes of the consumer."

Muda
A Japanese term meaning waste.

A key component of the Lean philosophy is a never-ending effort to eliminate **waste,** which is defined as "any activity that does not add value to the good or service in the eyes of the consumer."[2] Starting with Taiichi Ohno, a Toyota engineer, experts have sought to identify the major sources of waste (or **muda** in Japanese). The following are eight commonly recognized sources:[3]

1. **Overproduction.** Inflexible or unreliable processes may cause organizations to produce goods before they are required.
2. **Waiting.** Inefficient layouts or an inability to match demand with output levels may cause waiting.
3. **Unnecessary transportation.** Transporting goods always increases costs and the risk of damage, but it does not necessarily provide value to the final customer.
4. **Inappropriate process.** Companies sometimes use overly complex processes when simpler, more efficient ones would do.
5. **Unnecessary inventory.** Uncertainty with regard to quality levels, delivery lead times, and the like can lead to unnecessary inventory.
6. **Unnecessary/excess motion.** Poorly designed processes can lead to unnecessary motion.
7. **Defects.** Not only do defects create uncertainty in the process, they rob production capacity by creating products or services that require rework or must be scrapped.
8. **Underutilization of employees.** This is the newest form of waste added to the list, and it recognizes that too often companies do not fully utilize the skills and decision-making capabilities of their employees.

To put these forms of waste in context, suppose it takes an inspector at a manufacturing plant 15 minutes to inspect an incoming batch of material. The pre-Lean perspective would be that inspections like these are a necessary and prudent business expense. But according to Lean, this is a waste of *both* time and human resources caused by defects. Services examples abound as well. If you have to wait even *five minutes* at the doctor's office before being seen, then waste has occurred.

If this definition seems harsh, it is meant to be. The point is to get organizations to think critically about the business processes they use to provide products and services, as well as the outcomes of these processes. As far as Lean is concerned, if there is any waste at all, there is room for improvement.

EXAMPLE 13.1

Unnecessary Inventory Caused by Supplier Problems at Riggsbee Boating Supply

For several years, Riggsbee Boating Supply has purchased life vests from the same U.S. supplier. Jermaine Riggsbee, owner of the company, has collected the following information on the life vests:

Weekly demand:	50 vests, with a variance of 9.5 vests
Supplier lead time:	6 weeks, with a variance of 3.2 weeks

[2]Ibid.
[3]J. Womack and D. Jones, *Lean Thinking: Banish Waste and Create Wealth in Your Corporation, Revised and Updated* (New York: Free Press, 2003).

Using Equation (11.8) from Chapter 11, Jermaine calculates the reorder point for the life vests based on a 90% service level ($z = 1.28$):

$$\begin{aligned} ROP_{US} &= \bar{d}\bar{L} + z\sqrt{\bar{L}\sigma_d^2 + \bar{d}^2\sigma_L^2} \\ &= 50 \times 6 + 1.28\sqrt{6 \times 9.5 + 2{,}500 \times 3.2} \\ &= 300 + 114.9 \\ &= 414.9, \text{ or } 415 \text{ life vests} \end{aligned}$$

Looking at the results, Jermaine realizes that the second half of the equation, or about 115 vests, represents safety stock, or extra inventory *he* has to hold (and pay for!).

Jermaine had already been considering switching to a Mexican supplier with similar quality levels and prices but a *constant* lead time of two weeks. Plugging the new numbers into the equation, Jermaine generates the following results:

$$\begin{aligned} ROP_{Mexico} &= \bar{d}\bar{L} + z\sqrt{\bar{L}\sigma_d^2 + \bar{d}^2\sigma_L^2} \\ &= 50 \times 2 + 1.28\sqrt{2 \times 9.5 + 2{,}500 \times 0} \\ &= 100 + 5.6 \\ &= 105.6, \text{ or } 106 \text{ life vests} \end{aligned}$$

With the Mexican supplier, the reorder point drops to about 106 vests. More importantly, the safety stock level falls to just 5.6, or 6 vests. Put another way, supplier problems were causing Jermaine to hold a safety stock of $(115 - 6) = 109$ more vests than he needed, a clear example of unnecessary inventory.

13.2 THE LEAN PERSPECTIVE ON INVENTORY

One hallmark of a Lean environment is the strong emphasis placed on reducing raw material, work-in-process, and finished goods inventories throughout the system. This is not only because inventory is seen as a form of waste in and of itself but also because inventory can *cover up* wasteful business practices. Under the Lean philosophy, lowering inventory levels *forces* firms to address these poor practices.

To illustrate how inventory can hide problems, consider a simple facility consisting of three work centers (A, B, and C), shown in Figure 13.2. The triangles in the diagram represent inventory. In addition, between the work centers is plenty of room for inventory. Take one of the work centers—say, center B—and consider what happens if it has an equipment breakdown that reduces its output. The answer is that, *in the short run*, only center B is affected. Because there is plenty of space for inventory between centers A and B, center A can continue to work. And because inventory exists between centers B and C, center C can continue to work as long as the inventory lasts. Most importantly, the customer can continue to be served. The same result occurs regardless of the reason for any disruption in center B, including worker absenteeism, poor quality levels, and so forth. Whatever the problem, inventory hides it (but at a cost).

Now let's take the same facility after a successful Lean program has been put in place. The work centers have been moved closer together, eliminating wasted movement and space where inventory could pile up. Setup times have also been reduced, allowing the work centers to make only what is needed when it is needed. If we assume that the program has been in place for a while, we can also assume that the inventory levels have been reduced dramatically, giving us a revised picture of the facility (Figure 13.3).

Now inventory has been reduced to the point where it shows up only in the customer facility. Under these conditions, what happens in the short run if the equipment at center B breaks down? The answer this time is that *everything stops*, including shipments to the customer. Center A has to stop because there is no spot for it to put inventory and no demand for it. Center C has to stop because there is no inventory on which to work.

FIGURE 13.2
Inventory Positioned throughout a Supply Chain

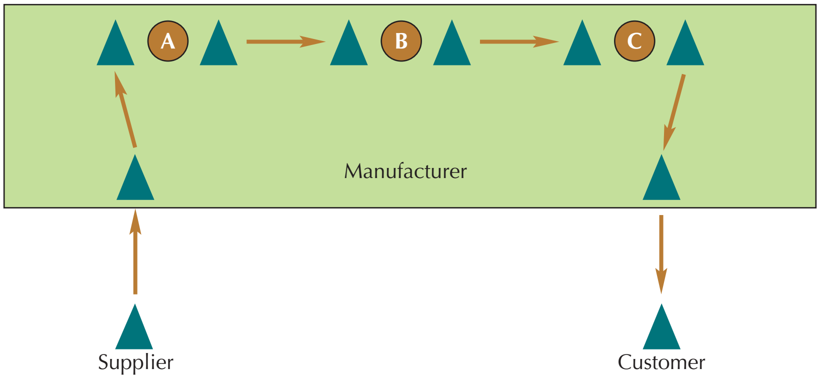


FIGURE 13.3
Supply Chain after the Elimination of Excess Inventories

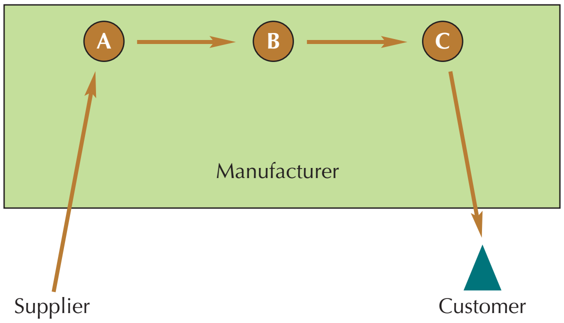
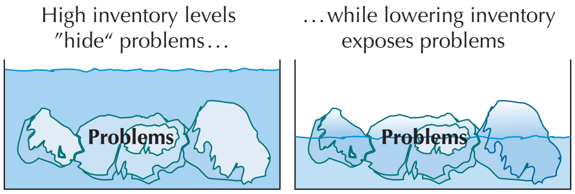


FIGURE 13.4
How Inventory Hides Problems



Inventory in the supply chain is often compared to water in a river. If the "water" is high enough, it will cover all the "rocks" (quality problems, absenteeism, equipment breakdowns, etc.), and everything will appear to be running smoothly.

Under Lean, the approach is to gradually remove the "water" until the first "rock" is exposed, thereby establishing a priority as to the most important obstacle to work on. After resolving this problem, inventory levels are reduced further, until another problem (and opportunity to eliminate waste) appears. This process continues indefinitely, or until all forms of waste and uncertainty have been eliminated (Figure 13.4).

This is not an easy approach to implement. The implication is that every time a process is working smoothly, there may be too much inventory, and more should be removed until the organization hits another "rock." This is certainly not a natural action for most people, and the performance evaluation system needs to be altered to reflect this type of activity.

13.3 RECENT DEVELOPMENTS IN LEAN THINKING

It shouldn't be surprising that businesses have looked for ways to combine the Lean philosophy with other management efforts. One such hybrid is Lean Six Sigma. In Chapter 4, we defined the Six Sigma methodology as "a business improvement methodology that focuses an organization on understanding and managing customer requirements, aligning key business processes to achieve those requirements, utilizing rigorous data analysis to understand and ultimately minimize variation in those processes, and driving rapid and sustainable improvement to business processes."[4]

Lean Six Sigma
A methodology that combines the organizational elements and tools of Six Sigma with Lean's focus on waste reduction.

Lean Six Sigma combines the organizational elements and tools of Six Sigma, with Lean's focus on waste reduction. As Paul Mullenhour and Jamie Flinchbaugh put it, "Lean encourages action along a broad front by empowering people at all levels to contribute. This allows organizations to welcome challenges and implement improvement initiatives. . . . Six Sigma brings the discipline of define, measure, analyze, improve and control, as well as the rigor of statistical analysis, to identify a root cause, sustain improvement and provide the solid measurements that create a balanced scorecard."[5]

The *Supply Chain Connections* feature contains an extended example of how Lean Six Sigma was applied in a hospital setting. Notice how this example combines all the elements of the Six Sigma methodology—black belts and green belts, process mapping, careful use of statistics, and the DMAIC cycle—with Lean's focus on waste reduction—in this case, patient waiting time and unused beds.

Lean supply chain management
An extension of the Lean philosophy to supply chain efforts beyond production. Lean supply chain management seeks to minimize the level of resources required to carry out *all* supply chain activities.

Some practitioners and researchers have moved beyond Lean production to what can be called *Lean supply chain management*. In a nutshell, **Lean supply chain management** seeks to minimize the level of resources required to carry out *all* supply chain activities. Lean principles are applied to eliminate waste in a firm's sourcing and logistics activities, as well as within the firm's internal operations. But it doesn't end there. The Lean philosophy is applied to all relevant flows—physical, informational, and monetary—and, where possible, to supply chain partners. This means that firms might need to work closely with key partners to eliminate waste within *their* operations. Lean supply chain management is certainly consistent with what we have emphasized throughout this book; namely, it is not enough for a firm to manage the activities that occur within its four walls.

13.4 KANBAN SYSTEMS

The first part of this chapter dealt with the philosophical underpinnings of the Lean philosophy. In this section, we take a decidedly more *executional* view, focusing on one particular approach to production control in a Lean environment, known as kanban. But even as you are working through the logic of kanban systems, keep in mind that the focus is still on reducing waste.

Kanban system
A production control approach that uses containers, cards, or visual cues to control the production and movement of goods through the supply chain.

A **kanban system** is a production control approach that uses containers, cards, or visual cues to control the production and movement of goods through the supply chain. These systems have several key characteristics:

1. Kanban systems use simple signaling mechanisms, such as a card or even an empty space or container, to indicate when specific items should be produced or moved. Most kanban systems, in fact, do not require computerization.
2. Kanban systems can be used to synchronize activities either within a plant or between different supply chain partners. Therefore, a kanban system can be an important part of both production activity control (PAC) and vendor order management systems (Chapter 12).
3. Kanban systems are *not* planning tools. Rather, they are control mechanisms that are designed to pull parts or goods through the supply chain, based on downstream demand. As a result, many firms use techniques such as MRP (Chapter 12) to *anticipate* requirements but depend on their kanban systems to control the actual execution of production and movement activities.

Two-card kanban system
A special form of the kanban system that uses one card to control production and another card to control movement of materials.

To illustrate how a kanban system works, we will describe a **two-card kanban system** that links the production and movement of units at two work centers, A and B. Suppose that in

[4]Motorola University, **www.motorolasolutions.com/US-EN/Home.**
[5]P. Mullenhour and J. Flinchbaugh, "Bring Lean Systems Thinking to Six Sigma," *Quality Digest*, March 2005, **www.qualitydigest.com/mar05/articles/05_article.shtml.**

SUPPLY CHAIN CONNECTIONS

CREATING A LEAN SIX SIGMA HOSPITAL DISCHARGE PROCESS[6]

A lengthy, inefficient process for discharging inpatients is a common concern of hospitals. It not only causes frustration for patients and family members but also leads to delays for incoming patients from Admitting, the Post Anesthesia Care Unit, or the Emergency Department.

When Valley Baptist Medical Center in Harlingen, Texas, faced this issue, it decided to apply Lean Six Sigma and change management techniques within one pilot unit. A multidisciplinary project team led by a black belt included nursing staff, case managers, an information technology green belt, and the chief medical officer, also a green belt.

The project was to reduce the time between when a discharge order for a patient is entered into the computer and when the room is ready for the next patient. During the initial scoping of this project, the team divided the process into four components:

1. From discharge order entry to discharge instructions signed
2. From discharge instructions signed to patient leaving
3. From patient leaving to room cleaned
4. From room cleaned to discharge entered in the computer (thus indicating that the bed is ready for another patient)

Because of the hospital's commitment to customer service, the team was asked to concentrate on the first two components. The goal was for this first subprocess to be completed in less than 45 minutes. To minimize the time a bed was empty, the team realized it would also need to address the time between when a patient's room was cleaned and the time a discharge was entered into the computer, or the second subprocess. This would address the problem that arises when Admitting does not have the necessary information to assign a new patient to a clean and empty bed.

Mapping the Process

The team began with a process map to visually understand how the process was currently working. When several nurses were asked to help develop a detailed process map on the discharge process, they initially could not reach consensus since they each followed their own methods for discharging the patient. This lack of standard operating procedures had led to widespread process variation.

Michal Heron/Pearson Prentice Hall-College

[6]Copyright © 2000-2017 iSixSigma, a division of Web X.0 Media LLC—All Rights Reserved Reproduced with Permission of iSixSigma, **https://www.isixsigma.com/uncategorized/creating-lean-six-sigma-hospital-discharge-processan-isixsigma-casestudy/#authors**

The team developed a representative process map, printed a large copy, and placed it in the nurses' lounge. Each staff member was encouraged to review the map and add comments on the flow. After a week, the team retrieved the inputs and revised the "as is" process map accordingly. Elements of Lean thinking were combined with this map to help identify waste (or muda). To understand which steps were not contributing to timely discharge, aspects of the existing process were categorized as value-added, non-value-added, and value-enablers.

Baseline data revealed the "from discharge order entry to patient leaving" subprocess required 184 minutes, with a standard deviation of 128 minutes. The second subprocess, "from patient leaving to discharge in computer" required an average of 36 minutes, with a standard deviation of 36 minutes. When compared against an upper specification limit of 45 minutes, the first subprocess had a yield of 7% (i.e., 7% of the patients were able to leave in 45 minutes or less), and the second subprocess did only slightly better, with a yield of 25% compared to its upper specification of 5 minutes.

Behind the Waste and Variation

The most important tool for determining the critical drivers of waste and variation was the Lean process map. The staff segmented the process into key steps and used the value-added and non-valued-added times to understand the delays and rework involved.

The segments of the process were:

- Secretary processes discharge order entry
- Discharge order processed to nurse begins (delay)
- Nurse begins computer entry (to create discharge instructions)
- Computer entry to patient signature

The team found that three factors were critical drivers of waste and variation:

1. **Clarification.** In 21% of the cases, clarification from the physician was needed before the nurse could enter the information in the computer. The team confirmed that clarification processes added a significant amount of time. The median flow time of the process increased from 12 minutes to 45 minutes when clarification was required.
2. **Handoff.** The current process required a handoff as the charge nurse placed vital signs and other relevant information in the computer system, printed out the discharge instructions, and then placed them in a bin for the primary nurse to pick up. In many cases, the primary nurse would then review the information with the patient and obtain the patient's signature. In a small number of cases, however, the primary nurse completed all tasks without any handoff. The median time increased from 9 minutes when one nurse completed all tasks to 73 minutes when a handoff between nurses was required. Without a signal for the handoff, the patient's paperwork often waited up to an hour before it was acted upon.
3. **Aftercare.** Finally, the team tested the hypothesis that when aftercare was required (for example, ordering equipment), there was an increase in median cycle time from 121 minutes in the current process to 160 minutes.

Improving the Process

Since variations in the "as is" process were contributing greatly to long cycle times and delays, a new six-step standard operating procedure (SOP) was developed:

1. Unit secretary enters discharge order.
2. Unit secretary tells primary nurse via spectra link phone that he or she is next in the process.
3. Primary nurse verifies order and provides assessment.
4. Primary nurse enters information into computer system.
5. Primary nurse prints instructions and information.
6. Primary nurse reviews instructions and obtains patient signature.

Having the primary nurse complete all discharge tasks eliminated the bottlenecks created by time-consuming handoffs, the need for signaling those handoffs, and the fact that the charge nurse, who has many responsibilities, was not always readily available.

With the first subprocess of the deliverable improved—from discharge order entry to patient leaving—the team focused on getting information into the computer so the bed could be filled. A session was conducted with transporters and unit secretaries to determine the best way to improve the computer entry process. It was immediately clear that the current process was not working. Unit secretaries were not always aware when a patient was transferred from the unit. No signal was provided when a transporter moved a patient. Since the secretaries performed numerous activities (not always at the nurses' station), they could easily forget that a patient had been discharged.

A small discharge slip was developed, containing the patient name, room number, and time of call. The transporter would pick up the patient and then go to the nurses' station and ask the secretary to provide the time on the computer. The transporter would write the time and hand the slip to the secretary. This served as a trigger and transferred the process from the transporter to the secretary.

Maintaining Improvement

Two tactics employed simultaneously helped to sustain the improvements. The first was the use of a change acceleration process (CAP) and the second was an ongoing tracking system. Four CAP sessions were guided by the black belt and process owner, increasing understanding about why the initiative was undertaken, providing baseline data, and establishing the rationale for improvements.

Each session also included an exercise to help participants better appreciate Lean and Six Sigma, with a catapult exercise as a learning tool. Participants split into groups and worked to meet customer needs. They then reviewed the process, made adjustments, and developed standard operating procedures. Upon execution, the new plan showed improved performance.

A tracking system included three components:

1. A daily report of the prior day's discharges, including discharge times, primary nurse, and unit secretary responsible for discharging the patient from the computer
2. A performance tracker to ensure individual accountability for primary nurses and unit secretaries in terms of mean, standard deviation, and yield
3. A control chart that tracked the means and standard deviations

Summary: Process in Control

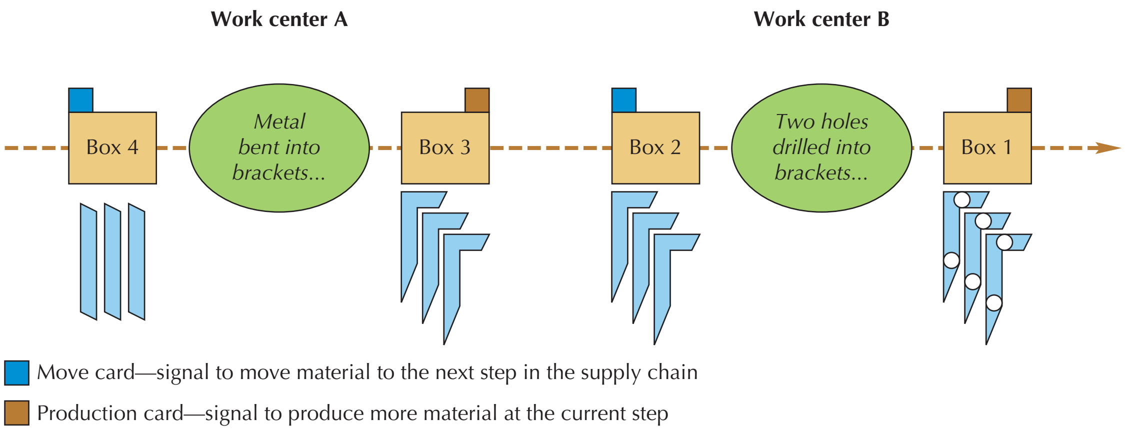
With the process now in control, the components were remeasured (Table 13.1). The "from discharge order entry to patient leaving" subprocess showed a mean improvement of 74%, with a 70% decrease in the standard deviation. The second subprocess, "from patient leaving to discharge in computer," showed an improvement of 90% in the mean and 58% in the standard deviation. With success in this unit, a translation effort would be undertaken for the entire hospital. This will be an ongoing effort requiring change management for the entire hospital and training sessions on the new standard operating procedures.

TABLE 13.1 Results of Lean Six Sigma Effort at Valley Baptist Medical Center

	From Discharge Order Entry to Patient Leaving: Upper Specification Limit = 45 Minutes		*From Patient Leaving to Discharge in Computer: Upper Specification Limit = 5 Minutes*	
	BEFORE	**AFTER**	**BEFORE**	**AFTER**
Mean	184.8 min.	47.8 min.	36.6 min.	3.47 min.
St. Dev.	128.7 min.	37.2 min.	36.1 min.	16.9 min.
Yield	6.9% patients leave within 45 min.	61.7% patients leave within 45 min.	24.6% entered into computer within 5 min.	95.4% entered into computer within 5 min.

work center A, metal rectangles are bent to form a bracket. In work center B, two holes are then drilled into the brackets. Figure 13.5 shows a diagram of the system.

Note that each work center has boxes of raw material in front of the work center and finished material directly after. For work center A, the raw material is unbent metal; the finished material is undrilled brackets. For work center B, the raw material is undrilled brackets and the



MyLab Operations Management Animation

FIGURE 13.5 Kanban System for Two Work Centers

Move card
A kanban card that is used to indicate when a container of parts should be moved to the next process step.

Production card
A kanban card that is used to indicate when another container of parts should be produced.

finished material is drilled brackets. Under kanban system rules, each box of raw material must have a **move card,** while each box of finished material must have a **production card.** These cards are used to precisely control the amount and movement of material in the supply chain. We will see in a moment how the system works.

Now suppose a downstream customer places an order. The effect is to "pull" a box of finished drilled brackets (box 1) out of work center B. Immediately, the production card is removed from the box and placed in a conspicuous location in work center B. The card signals to personnel in work center B that they need to drill more brackets (Figure 13.6).

To drill more brackets, employees in work center B must pull a box of undrilled brackets (box 2) into the production process. As they do so, they remove the move card from box 2 and replace it with the production card that was removed from box 1. The newly freed-up move card then signals to employees that they need to move, or "pull," more materials out of work center A (Figure 13.7).

When the freed-up move card arrives at work center A, it takes the place of a production card on a box of undrilled brackets (box 3), and that box is transferred to work center B (Figure 13.8). The freed-up production card then signals employees in work center A to produce more parts.

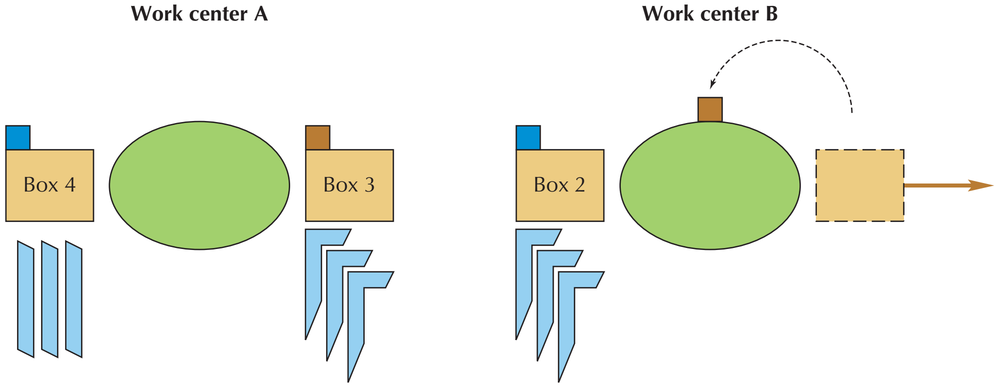
To summarize this system:

- A downstream station pulls finished material out of work center B (Figure 13.6).
- Work center B pulls raw material into production (Figure 13.7).
- Demand for more raw material in work center B pulls finished material out of work center A (Figure 13.8).

The beauty of this system is that all production and movement of materials is controlled by a set of cards. If workers see a freed-up production card, they produce more units; if they

FIGURE 13.6
Release of Finished Materials from Work Center B

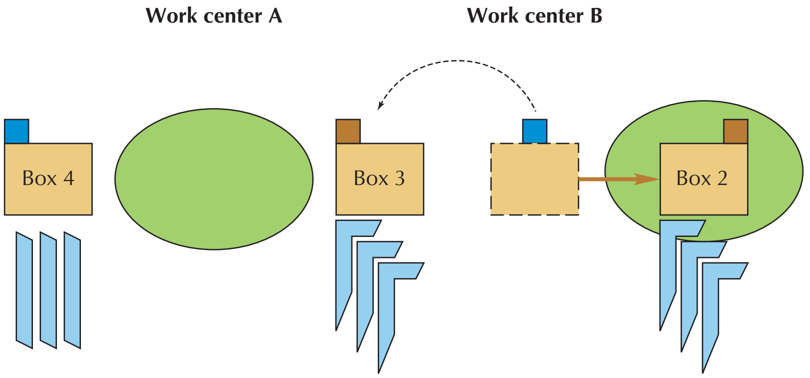
MyLab Operations Management Animation



- Box of drilled brackets (Box 1) is "pulled" out of work center B
- Freed-up production card is signal to produce more

FIGURE 13.7
Pulling of Raw Materials into Production at Work Center B

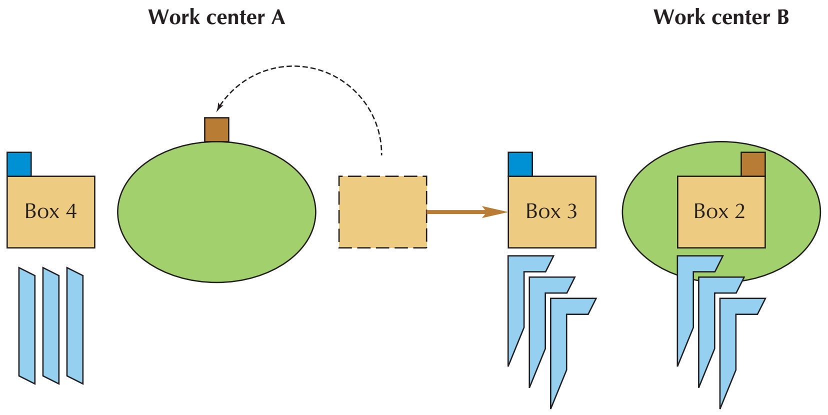
MyLab Operations Management Animation



- Box of undrilled brackets (Box 2) is "pulled" into production at work center B
- Freed-up move card is signal to move more undrilled brackets (Box 3) from work center A into work center B

FIGURE 13.8
Removal of Finished Materials from Work Center A

MyLab Operations Management Animation



- Box of undrilled brackets from work center A (Box 3) is "pulled" into raw material area at work center B
- Freed-up production card is signal to produce more parts at work center A
- And the cycle continues with work center A . . .

Pull system
A production system in which actual downstream demand sets off a chain of events that pulls material through the various process steps.

don't, they stop producing units. Likewise, if they see a move card, they move materials; if not, they leave materials where they are. You can see now why a kanban system is also called a **pull system:** Actual downstream demand sets off a chain of events that pull materials through the various process steps.

As we noted before, cards aren't the only signaling method used in a kanban system. Some other methods include:

- Single-card systems, where the single card is the production card and the empty container serves as the move signal
- Color coding of containers
- Designated storage spaces
- Computerized bar-coding systems

Controlling Inventory Levels Using Kanbans

It is a simple fact that by controlling the number of production kanbans—whether they be cards, containers, or some other signaling mechanism—organizations can control the amount of inventory in the system. Consider our previous example. Work center A could not produce unless it had a freed-up production card. As a result, the number of production cards set precise limits on the amount of inventory between work centers A and B.

While reading the last section, you may have wondered how organizations determine the number of kanbans needed to link together two process steps. The answer depends on several factors, including the lead time between the two steps being linked, the size of the containers that hold the parts, the demand level, and the stability of demand. A general formula for calculating the number of kanbans is:

$$y = \frac{DT(1 + x)}{C} \tag{13.1}$$

where:

y = number of kanbans (cards, containers, etc.)
D = demand per unit of time (from the downstream process)
T = time it takes to produce and move a container of parts to the downstream demand point
x = a safety factor, expressed as a decimal (for example, 0.20 represents a 20% safety factor)
C = container size (the number of parts it will hold)

EXAMPLE 13.2

Determining the Number of Kanbans at Marsica Industries, Part 1

At Marsica Industries, work cell H provides subassemblies directly to final assembly. The production manager for work cell H, Terri O'Prey, is trying to determine how many production cards she needs. Terri has gathered the following information:

D	Final assembly's demand for subassemblies from work cell H	300 assemblies per hour, on average
T	Time it takes to fill and move a container of subassemblies from work cell H to final assembly	2.6 hours, on average
x	Safety factor to account for variations in D or T	15%
C	Container size	45 subassemblies

Using Equation (13.1), the number of production cards needed is:

$$y = \frac{DT(1 + x)}{C}$$

$$= \frac{300*2.6(1 + 0.15)}{45} = 19.93\text{, or 20 production cards}$$

Terri rounds up her answer because there is no such thing as a fractional production card. Evaluating the results, she notes that 20 production cards is the equivalent of 20 containers of subassemblies, or:

$$(20\text{ containers})\ (45\text{ subassemblies per container}) = 900\text{ subassemblies}$$

And in hourly terms, 900 subassemblies equals:

$$\frac{900\text{ subassemblies}}{300\text{ units of demand each hour}} = 3\text{ hours' worth of subassemblies}$$

The fact that there are slightly more subassemblies than needed is due to the safety factor and the rounding up of the number of production cards.

While Equation (13.1) is useful as a starting point, another approach used by many companies is to start with more than enough kanbans. The organization then slowly removes kanbans in an attempt to uncover the "rocks," or problems (similar to Figure 13.4). At the same time, the organization will try to shorten lead times and stabilize demand levels as much as possible, thereby further reducing the need for inventory.

EXAMPLE 13.3

Recalculating the Number of Kanbans at Marsica Industries, Part 2

After nearly a year of continuous improvement efforts in work cell H, Terri O'Prey feels it is time to reevaluate the number of production cards and hence inventory in the work cell. In particular, Terri has made the following changes:

- Production lead time has been cut from 2.6 hours to a constant 1.6 hours.
- Demand from final assembly has been stabilized at 300 subassemblies per hour.
- Smaller, standardized containers that hold just 25 subassemblies are now being used.

Because production lead time (T) and demand rate (D) have been stabilized, Terri feels she can reduce the safety factor to just 4%. She recalculates the number of kanban cards to reflect all of these changes:

$$y = \frac{DT(1 + x)}{C}$$

$$= \frac{300*1.6(1 + 0.04)}{25} = 19.97\text{, or 20 production cards}$$

Since the container size is smaller, Terri is not concerned that the number of cards has not changed. In fact, 20 production cards are now the equivalent of:

$$(20 \text{ containers}) (25 \text{ subassemblies per container}) = 500 \text{ subassemblies}$$

and

$$\frac{500 \text{ subassemblies}}{300 \text{ units of demand each hour}} = 1.67 \text{ hours' worth of subassemblies}$$

Either way she looks at it, by improving the process, Terri has been able to cut inventory significantly.

Synchronizing the Supply Chain Using Kanbans

In Chapter 12, we alluded to the idea that kanban systems can be used to synchronize the supply chain at the PAC and vendor order management levels. Put another way, kanban can be used to link supply chain partners, as well as the work centers in a factory. Suppose, for instance, that work center B in our earlier examples is located in a facility 200 miles from work center A. In this case, electronic requests for more materials would be substituted for the factory's move cards.

Figure 13.9 shows how kanban can be used to synchronize the production and movement of goods among multiple supply chain partners. You might even think of customer demand as a pull on a rope (the kanban system) that ties together all members of the supply chain. One pull at the end of the supply chain triggers movement and production down the chain.

For a kanban system to work properly, however, there must be a *smooth, consistent* pull of material through the links. Consider the supply chain shown in Figure 13.10. As we have seen, the number of kanbans linking work centers A and B is based on an understanding of the demand rate coming from B.

But what happens if the demand rate changes or there is an interruption in the flow of goods? If final assembly demand doubles, work center B may quickly use up all the material linking it with A, and subsequent shipments from B to final assembly may be slowed down as a result.

If there is an *interruption* in the flow of goods—say, within work center B—the result could be even worse: Final assembly may have to stop production, thereby stopping the pull of goods from work centers C and D as well and shutting down the entire supply chain. This is not as far-fetched as it seems; in fact, it is exactly what happened to Toyota in 1997 when the manufacturing plant for Toyota's primary supplier of brake proportioning valves—a $20 part—burned to the ground. Within hours, the Toyota final assembly plant had to shut down due to the lack of

FIGURE 13.9
Using Kanban to Synchronize the Supply Chain

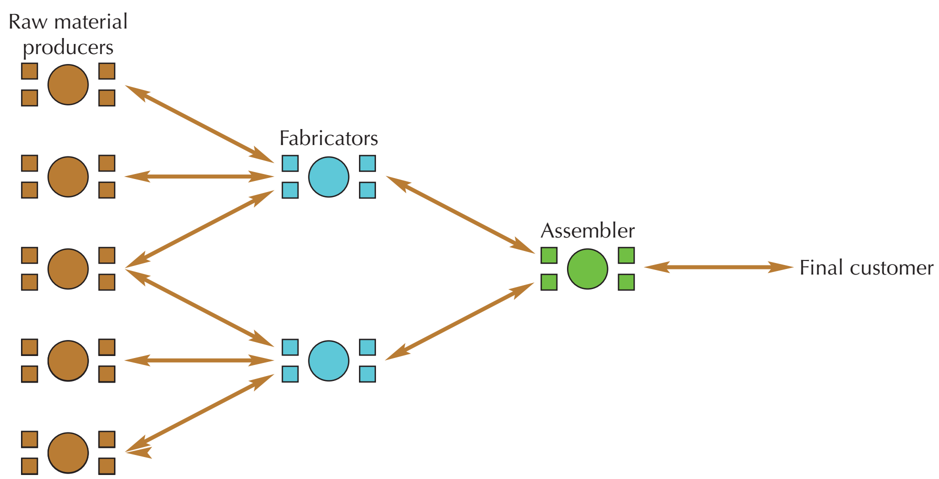
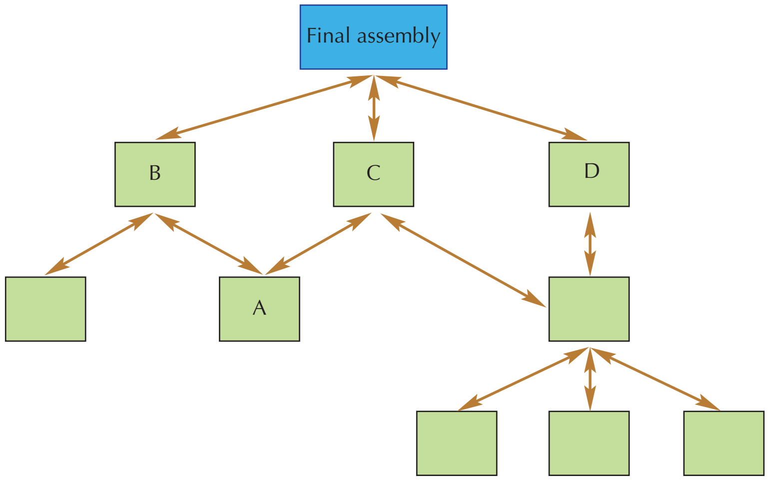


FIGURE 13.10 Work Centers A and B as Part of a Larger Supply Chain



one part. The shutdown reverberated through the rest of Toyota's supply chain, with production resuming only after other Toyota suppliers started producing the missing brake parts. The point is this: For a kanban system to work properly, demand rates must be relatively stable, and interruptions must be minimized or quickly resolved.

Using MRP and Kanban Together

Some companies have found it beneficial to combine the *planning* capabilities of MRP with the *control* capabilities of kanban. In particular, MRP can be used to anticipate changes in planned order quantities over the planning horizon. This information is then used to recalculate the number of production kanbans (containers or cards) needed. Example 13.4 illustrates how the concept works.

EXAMPLE 13.4

Using MRP and Kanban Together at Marsica Industries, Part 3

The past six months have been tumultuous ones for Marsica Industries; demand levels have varied dramatically from one week to the next, as the company has taken on seasonal customers and marketing has used pricing changes to either boost or limit demand. The result for Terri O'Prey, production manager for work cell H, has been that the *D* values underlying her kanban calculations have been all over the place, undercutting the effectiveness of the kanban system. Terri knows that she needs some way to anticipate these changes and adjust the number of kanban production cards accordingly.

Terri also knows that the company uses MRP to estimate planned orders for components, including the subassemblies coming out of work cell H. She finds the MRP record for the subassembly shown in Figure 13.11.

		WEEK							
** Subassembly, work cell H **		1	2	3	4	5	6	7	8
Gross requirements		12,000	12,000	14,000	14,000	14,000	16,000	16,000	16,000
Scheduled receipts									
Projected ending inventory	0	0	0	0	0	0	0	0	0
Net requirements		12,000	12,000	14,000	14,000	14,000	16,000	16,000	16,000
Planned receipts		12,000	12,000	14,000	14,000	14,000	16,000	16,000	16,000
Planned orders		**12,000**	**12,000**	**14,000**	**14,000**	**14,000**	**16,000**	**16,000**	**16,000**

FIGURE 13.11 MRP Record for Work Cell H's Subassembly

Looking at the MRP record, Terri notices a couple of interesting points. First, there is no projected ending inventory. This is consistent with the Lean philosophy of having no more inventory in the system than is needed. Second, the planned orders all occur *in the same week* as the planned receipts. This is because the planning lead time for subassemblies is just 1.6 hours (Example 13.3); therefore, any orders released in a week should be completed in that week.

But the most interesting line for Terri is the planned order quantities. These tell her the total weekly demand for the subassemblies. Assuming that this demand is spread evenly across a 40-hour workweek, Terri can use the planned orders to calculate the D values for the various weeks:

$$D_{\text{weeks } 1\text{–}2} = \frac{12{,}000}{40 \text{ hours per week}} = 300 \text{ subassemblies per hour}$$

$$D_{\text{weeks } 3\text{–}5} = \frac{14{,}000}{40 \text{ hours per week}} = 350 \text{ subassemblies per hour}$$

$$D_{\text{weeks } 6\text{–}8} = \frac{16{,}000}{40 \text{ hours per week}} = 400 \text{ subassemblies per hour}$$

Finally, Terri can use the different demand rates and the other values from Example 13.3 to determine the number of production cards needed each week:

$$y_{\text{weeks } 1\text{–}2} = \frac{300*1.6(1 + 0.04)}{25} = 19.97, \text{ or } 20 \text{ production cards}$$

$$y_{\text{weeks } 3\text{–}5} = \frac{350*1.6(1 + 0.04)}{25} = 23.29, \text{ or } 24 \text{ production cards}$$

$$y_{\text{weeks } 6\text{–}8} = \frac{400*1.6(1 + 0.04)}{25} = 26.62, \text{ or } 27 \text{ production cards}$$

In practice, Terri will adjust the number of production cards by adding new cards when she anticipates that demand will go up and "retiring" freed-up production cards when she anticipates that demand will go down. But the key insight is this: Terri can use the MRP records to help anticipate needs and control production at the work cell level.

CHAPTER SUMMARY

JIT/Lean is both a business philosophy for reducing waste and a specific approach to production control. In this chapter, we reviewed the philosophical elements behind Lean and discussed how these elements fit with many of the other topics covered throughout this book, including quality management and supplier development. Even though it started out in manufacturing, the Lean philosophy has a lot to say to any organization wishing to eliminate waste.

We paid particular attention to the role of inventory in Lean environments and showed how kanban systems can be used to control the flow of materials in a Lean environment and across the supply chain. We also demonstrated why kanban systems may not be appropriate in all environments (particularly ones in which demand "pull" varies greatly) and illustrated how the planning capabilities of MRP can be combined with the control strengths of kanban.

KEY FORMULA

Number of production kanbans required (page 419):

$$y = \frac{DT(1 + x)}{C} \qquad \textbf{(13.1)}$$

where:

y = number of kanbans (cards, containers, etc.)

D = demand per unit of time (from the downstream process)

T = time it takes to produce and move a container of parts to the downstream demand point

x = a safety factor, expressed as a decimal (for example, 0.20 represents a 20% safety factor)

C = container size (the number of parts it will hold)

KEY TERMS

Just-in-time (JIT) 410	Lean supply chain management 414	Pull system 419
Kanban system 414	Move card 418	Two-card kanban system 414
Lean 410	Muda 411	Waste 411
Lean Six Sigma 414	Production card 418	

SOLVED PROBLEM

PROBLEM

Fixing the Kanban System at Work Cell K

Because of her success in setting up a kanban system in work cell H, Terri O'Prey has been brought over to help fix the kanban system at work cell K. According to work cell K's current production manager, Tom Tucker, "We're swimming in inventory here. I thought I calculated the right number of production cards, but something must have changed."

Tom provides Terri with the information he used to determine the number of production cards:

$$\begin{aligned} \text{Assumed demand rate, } D &= 260 \text{ units per hour} \\ \text{Lead time, } T &= 2 \text{ hours} \\ \text{Container size} &= 50 \text{ units} \\ \text{Safety factor, } x &= 5\% \end{aligned}$$

Tom notes, "Of course, there have been a few changes, but they're really no big deal. Demand is off slightly, down to 220 units an hour, and we've increased the container size to 100 units. But I can't see that making much of a difference."

Questions

1. Calculate the number of production cards needed, based on the original set of values given by Tom. According to the results, how many hours' worth of inventory would there be, given the original set of assumptions?
2. Now consider the changes to demand and container sizes noted by Tom. If Tom uses the *old* number of production cards, how many hours' worth of inventory would there be in the system?
3. Recalculate what the *new* number of production cards should be and estimate how many hours' worth of inventory this would equal.

Solution

Based on the old values, the number of production cards needed is:

$$\begin{aligned} y &= \frac{DT(1 + x)}{C} \\ &= \frac{260 * 2(1 + 0.05)}{50} = 10.92, \text{ or } 11 \text{ production cards} \end{aligned}$$

which is equivalent to:

$$(11 \text{ containers})\ (50 \text{ units per container}) = 550 \text{ units}$$

or:

$$\frac{550 \text{ units}}{260 \text{ units of demand each hour}} = 2.12 \text{ hours' worth of units}$$

The problem, however, is that the values behind the production card calculation have changed. With a new container size of 100 units and a new demand rate of 220 units per hour, 11 production cards translates into:

$$(11 \text{ containers})\ (100 \text{ units per container}) = 1{,}100 \text{ units}$$

or:

$$\frac{1{,}100 \text{ units}}{220 \text{ units of demand each hour}} = 5 \text{ hours' worth of units}$$

which is clearly too much inventory. After showing Tom the error of his ways, Terri helps him recalculate the new kanban level:

$$\frac{220 * 2(1 + 0.05)}{100} = 4.62, \text{ or } 5 \text{ production cards}$$

which is equivalent to:

$$(5 \text{ containers})\ (100 \text{ units per container}) = 500 \text{ units}$$

or:

$$\frac{500 \text{ units}}{220 \text{ units of demand each hour}} = 2.27 \text{ hours' worth of units}$$

DISCUSSION QUESTIONS

1. Transportation can create value, as when an ambulance takes a patient to the hospital or a truck delivers fruits and vegetables to the grocery store. How would you differentiate between "necessary" and "unnecessary" transportation?
2. Even though waiting is a form of waste, does it always make sense to eliminate it? (*Hint:* Recall our discussion of waiting line theory in Chapter 6, and the relationship between resource levels and waiting times.)
3. Comment on the relationship between quality management (Chapter 5) and Lean. Are they the same thing, or are there some differences?
4. We noted in the chapter that kanban is not a planning tool but a control mechanism. What did we mean by that? How does the MRP/kanban example in Example 13.4 illustrate the point?
5. In what ways might a firm's suppliers improve or undermine the firm's Lean efforts? Can you think of any examples from the chapter that illustrate this idea?

PROBLEMS

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

Problems for Section 13.4: Kanban Systems

1. (*) Suppose you have the following information:

   Demand rate (D) = 750 units per hour
   Lead time (T) = 40 hours
   Container capacity (C) = 1,000 units
   Safety factor (x) = 10%

   How many kanban production cards are required?

   a. 59 **b.** 28
   c. 30 **d.** 33

2. Consider the following information:

   Demand rate (D) = 200 units per hour
   Lead time (T) = 12 hours
   Container capacity (C) = 144 units
   Safety factor (x) = 15%

   a. (*) How many kanban production cards are needed?
   b. (**) How many hours' worth of demand will these cards represent?
   c. (**) Suppose the container size is cut in half. Will this make any difference in the inventory levels? Show your work.

3. Consider the following information:

   Demand rate (D) = 300 units per hour
   Lead time (T) = 4 hours
   Container capacity (C) = 40 units
   Safety factor (x) = 10%

   a. (*) How many kanban production cards are needed?
   b. (**) How many hours' worth of demand will these cards represent?
   c. (**) Suppose the lead time is reduced to three hours. Will this make any difference in the inventory levels? Show your work.

4. Consider the following information:

   Demand rate (D) = 1,000 units per hour
   Lead time (T) = 2 hours
   Container capacity (C) = 250 units
   Safety factor (x) = 15%

a. (*) How many kanban production cards are needed?
b. (**) How many hours' worth of demand will these cards represent?
c. (**) Suppose the safety factor is eliminated. Will this make any difference in the inventory levels? Would this be a wise thing to do? Show your work.

5. Consider the following information:

Demand rate (D) = 60 units per hour
Lead time (T) = 40 hours
Container capacity (C) = 20 units
Safety factor (x) = 10%

a. (*) How many kanban production cards are needed?
b. (**) How many hours' worth of demand will these cards represent?
c. (**) Suppose the demand rate is doubled but the lead time is cut in half. Will this make any difference in the inventory levels? Show your work.

6. (*Microsoft Excel problem*) (***) The following figure shows a Microsoft Excel spreadsheet that calculates the number of kanban production cards needed, based on the MRP planned orders. **Re-create this spreadsheet in Excel.** Your spreadsheet should calculate new results any time a change is made to any of the highlighted cells. Your formatting does not need to be the same, but your answers should be. To test your spreadsheet, change the production lead time to 2.5 hours and the container size to 144. The number of production cards (not rounded up) for week 1 should be 6.84, and there should be 2.69 hours' worth of inventory. *Note:* To round up the kanban card calculation, use Excel's = ***ROUNDUP*** function.

	A–C	D	E	F	G	H	I	J	K	L
1	**Using MRP Planned Orders to Determine the Number of Kanban Production Cards Needed**									
2										
3	Hours per week:	40								
4	Production lead time (T):	3	hours							
5	Container size (C):	5.0%								
6	Safety factor (x):	300								
7										
8					WEEK					
9		1	2	3	4	5	6	7		
10	Planned orders (from MRP):	15,000	16,000	15,000	15,000	14,500	14,000	13,000		
11										
12										
13	Hourly demand (D):	375	400	375	375	362.5	350	325		
14										
15	# of production cards (not rounded)	3.94	4.20	3.94	3.94	3.81	3.68	3.41		
16	# of production cards (rounded up)	4	5	4	4	4	4	4		
17										
18	Hours' worth of inventory	3.20	3.75	3.20	3.20	3.31	3.43	3.69		

CASE STUDY

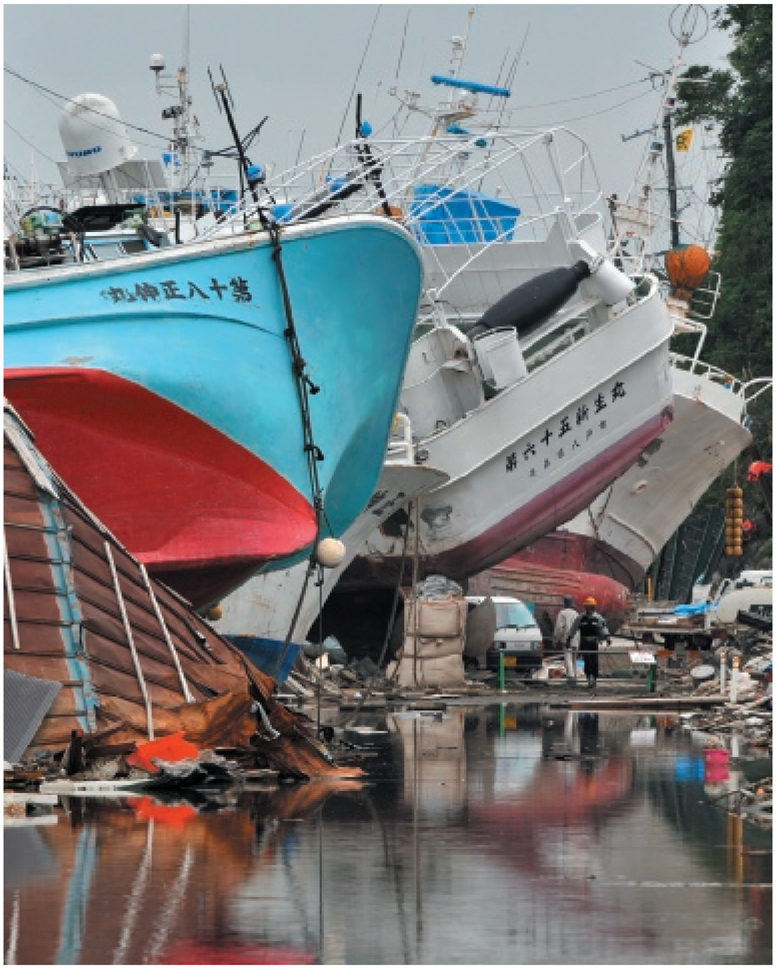
Supply-Chain Challenges in Post-Earthquake Japan

Japanese automakers have long been known for the quality of their products, and especially for the efficiency of their streamlined manufacturing and supply processes. Thus, few people could have predicted how severely the destructive earthquake and tsunami that struck Japan in March 2011 would disrupt the country's entire auto industry. Matters were further complicated by the damage the quake and floodwaters caused to one of Japan's nuclear power plants, interrupting power supplies around the country and creating a dangerous radiation zone for miles around the plant.

Following the quake and ensuing floods, most automotive factories in Japan were closed for at least several weeks, bringing to a halt about 13% of worldwide auto production. Toyota, Honda, and Mazda shut down many of their parts and manufacturing plants in Japan, and Toyota also announced plans to suspend production in at least one North American plant because of parts shortages. The company said it would make plant improvements and run training programs in its other U.S. facilities while the assembly lines were idle or run operations on a part-time basis to conserve its parts inventory. Honda, Nissan, and Subaru also reduced their North American output as they anticipated and tried to deal with expected parts shortages.

Since one of the guiding principles of Lean production is to keep parts inventories as low as possible, it wasn't long before these shortages occurred. "The supply chain in the automotive industry is so fragile," said one legal advisor to the global auto industry. "It's based on just-in-time principles, where you don't have a lot of inventories built up, so you leave yourself without much margin for error when a supply interruption happens."

Industry observers predicted that about half of Japan's auto capacity would remain closed for at least eight weeks after the disaster, which would eventually put about one-third of worldwide production in jeopardy, as the effects of parts



Kazuhiro Nogi/AFP/Getty Images

The disaster zone in Kesennuma, Miyagi prefecture, 100 days after a massive 9.0-magnitude earthquake and tsunami devastated the northeastern coast of Japan.

shortages made themselves increasingly felt in manufacturing facilities far from Japan. One auto industry research firm predicted that about five million cars that the industry had expected to sell in 2011 would never be made.

By spring and summer 2011, in fact, U.S. auto dealers were reporting what one called “a lot of emptiness” in their showrooms. Many logged dwindling sales as supplies fell to as little as one-fifth their normal levels, and popular cars such as the Honda Civic and Accord went out of stock. Without new cars to sell, even trade-in sales were slowing. Honda posted a 27% decline in sales for August 2011, and Toyota anticipated a dramatic 31% profit decline for the year. Although the Japanese auto industry worked hard to quickly return to full capacity, output was still not fully restored some six months after the disaster. The disaster’s long-lasting ripple effects thus motivated industry executives to consider some changes in their vaunted manufacturing and supply operations. Traditionally, Toyota had used a single source for many parts that were common to more than one of its car models. Although the company locally sources about 85% to 90% of parts and materials needed for its North American manufacturing operations, a strategy that should make it less vulnerable to supply interruptions in Japan, it actually builds a larger proportion of its vehicles in Japan than do the other automakers, so the 2011 disaster was a serious blow.

In response to these problems, Toyota’s management began work to “foolproof” the supply chain so that it could recover from major interruptions in as little as two weeks. The plan had three parts. First, Toyota would increase standardization of auto parts so all Japanese carmakers could share the supply. These parts would be made in several locations to ensure uninterrupted supply. Next, the company asked its upstream suppliers of highly specialized parts, or parts that are sourced from only one location, to hold larger inventories than they had been carrying, as and opened up new options for manufacturing such parts to reduce its dependence on single sources. Finally, and perhaps most ambitiously, Toyota took steps to make each of its global regions independent of the others in terms of parts supply, so supply chain disruptions in one area will not spill over into the operations of any other areas.

Questions

1. What are some of the advantages of the supply chain used in the Japanese auto industry before the March 2011 earthquake and tsunami? What were some of its disadvantages?

2. Is Toyota's plan for a "foolproof" supply chain consistent with the Lean production philosophy? Explain.
3. Can you think of any additional ways Toyota (and its competitors in the Japanese auto industry) can improve upon the company's plan to create a "foolproof" supply chain?
4. What impact do you think Toyota's plan will have on the way it handles relationship management in its supply chain?

Sources: Based on Chang-Ran Kim, "Toyota Aims for Quake-Proof Supply Chain," *Huffington Post*, September 6, 2011, **www.huffingtonpost.com/2011/09/06/toyota-aims-for-quake-pro_n_950105.html;** James R. Healey, "Honda Zapped as Nissan, VW Report Strong August Sales," *USA Today*, September 1, 2011, **http://content.usatoday.com/communities/driveon/post/2011/09/vw/1;** Mike Ramsey, "Honda Struggles with Supply," *Wall Street Journal*, August 17, 2011, p. B3; Hiroko Tabushi, "Toyota Expects 31% Profit Slump," *New York Times*, June 11, 2011, **www.nytimes.com/2011/06/11/business/global/11toyota.html?scp=1&sq=toyota%20expects%2031%%20profit%20slump&st=cse;** Jonathan Schultz, "With Supplies Dwindling, Some Honda Dealers Foresee Long, Dry Summer," *New York Times* Wheels blog, May 4, 2011, **http://wheels.blogs.nytimes.com/2011/05/04/with-supplies-dwindling-some-honda-dealers-foresee-long-dry-summer/?scp=1&sq=with%20supplies%20dwindling,%20some%20honda%20dealers&st=cse;** Nick Bunkley, "Toyota Plans to Reduce Production for 6 Weeks," *New York Times*, April 19, 2011, **www.nytimes.com/2011/04/20/business/global/20auto.html;** Nick Bunkley and David Jolly, "Toyota, Struggling with Part Shortages, to Restart Car Lines," *New York Times*, March 24, 2011, **www.nytimes.com/2011/03/25/business/global/25auto.html.**

REFERENCES

Books and Articles

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

Ramsey, M., "Honda Struggles with Supply," *Wall Street Journal*, August 17, 2011, p. B3.

Womack, J., and Jones, D., *Lean Thinking: Banish Waste and Create Wealth in Your Corporation, Revised and Updated* (New York: Free Press, 2003).

Womack, J., Jones, D., and Roos, D., *The Machine That Changed the World: The Story of Lean Production* (New York: HarperCollins, 1991).

Internet

Bunkley, N., "Toyota Plans to Reduce Production for 6 Weeks," *New York Times*, April 19, 2011, **www.nytimes.com/2011/04/20/business/global/20auto.html.**

Bunkley, N., and Jolly, D., "Toyota, Struggling with Part Shortages, to Restart Car Lines," *New York Times*, March 24, 2011, **www.nytimes.com/2011/03/25/business/global/25auto.html.**

Cremar, A., "Porsche 'Shock Therapy' Spurs VW, Lufthansa Efficiency Drive," *Automotive News Europe*, December 13, 2010, **http://europe.autonews.com/article/20101213/ANE/101209816/porsche-%E2%80%98shock-therapy-spurs-vw-lufthansa-efficiency-drive.**

Debusk, C., and Rangel, A., "Creating a Lean Six Sigma Hospital Discharge Process," *iSixSigma.com*, September 15, 2004, **http://issuu.com/desandipan/docs/creating-a-lean-six-sigma-hospital-discharge-proce.**

Healey, J. R., "Honda Zapped as Nissan, VW Report Strong August Sales," *USA Today*, September 1, 2011, **http://content.usatoday.com/communities/driveon/post/2011/09/vw/1.**

Joseph, N., "Porsche Consulting Sets Up Shop in Atlanta," Autoblog, July 21, 2011, **www.autoblog.com/2011/07/21/porsche-consulting-sets-up-shop-in-atlanta/.**

Kim, C. R., "Toyota Aims for Quake-Proof Supply Chain," *Huffington Post*, September 6, 2011, **www.huffingtonpost.com/2011/09/06/toyota-aims-for-quake-pro_n_950105.html.**

Motorola University, **www.motorolasolutions.com/US-EN/Home.**

Mullenhour, P., and Flinchbaugh, J., "Bring Lean Systems Thinking to Six Sigma," *Quality Digest*, March 2005, **www.qualitydigest.com/mar05/articles/05_article.shtml.**

Schultz, J., "With Supplies Dwindling, Some Honda Dealers Foresee Long, Dry Summer," *New York Times* Wheels blog, May 4, 2011, **http://wheels.blogs.nytimes.com/2011/05/04/with-supplies-dwindling-some-honda-dealers-foresee-long-dry-summer/?scp=1&sq=with%20supplies%20dwindling,%20some%20honda%20dealers&st=cse.**

Tabushi, H., "Toyota Expects 31% Profit Slump," *New York Times*, June 11, 2011, **www.nytimes.com/2011/06/11/business/global/11toyota.html?scp=1&sq=toyota%20expects%2031%%20profit%20slump&st=cse.**

"Typical Porsche: No Superfluous Parts," *Porsche Consulting*, no. 10, January 2011, **www.porsche-consulting.com/it/stampa/porsche-consulting-the-magazine/detail/issue-10-january-2011-4/.**

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CHAPTER fourteen

Managing Projects

CHAPTER OUTLINE

CHAPTER OBJECTIVES

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

- Explain the difference between routine business activities and projects.
- Describe the five major phases of a project.
- Construct a Gantt chart or project network diagram, and use these tools to manage a project.
- Describe some of the key features and advantages of project management software.
- Describe what the Project Management Institute is, and what type of information can be found in the Institute's Project Management Body of Knowledge (PMBOK®)

HARNESSING THE NEW ZEALAND WINDS

David Wall Danita Delimont Photography/Newscom

Te Apiti Wind Farm, North Island, New Zealand

THE first wind farm to supply electricity to New Zealand's national grid, the Te Apiti wind farm produces enough clean and sustainable power for about 39,000 homes. The site was well chosen; the turbines' 115-foot-long blades take full advantage of a natural high-speed wind tunnel created by nearby Manawatu Gorge.

Te Apiti's 55 turbines, 230 feet tall, are electronically controlled and help conserve water and reduce pollution and greenhouse gas emissions by replacing the use of fossil fuels such as gas and coal for generating electricity. They also provide additional income for the farmers whose land they occupy and they even add one other benefit to the local economy: They attract some 400 groups of sightseers every week.

Despite the need to construct over 13 miles of extra-wide new roads at its remote location and install almost 25 miles of cable while adhering to the requirements of several landowners at the site, the Te Apiti facility was up and running five days ahead of schedule and within its budget of NZ$200 million, just 11 months after construction started. Its planners relied on effective project management tools and techniques to overcome challenges such as unstable terrain, streams, drop-offs in the level of the land, consistently bad weather, and a major gas pipeline running through the construction site. Perhaps most challenging of all were two unexpected rainstorms of historic proportions. These storms struck within 10 days of each other, bringing the highest flooding ever recorded for the area and destroying the main access bridge to the Te Apiti site. Contractors and staff were temporarily called away to help with the government's flood recovery efforts, and with the main water route also closed down for several weeks in the aftermath of the storms, access was limited for a time to a single route.

To meet all the project requirements, Meridian Energy Limited, which built and now operates the site, worked with its consultants and contractors from the beginning to develop a well-defined and all-inclusive project plan. Its goals were to create a robust and collaborative team culture and to promote clear communication and sound decision making. Everyone working on the site met with the rest of the team every day, and management met with all of the project vendors once a week. The results achieved all the project team's expectations. The project, the Southern Hemisphere's largest wind farm at the time it was completed, achieved an outstanding safety record over the course of 250,000 work hours. Te Apiti is now a registered "gold standard" site that diversifies the area's energy supply and showcases and helps develop the application of renewable energy in New Zealand.

Sources: Based on New Zealand Wind Energy Association, "Te Apiti Wind Farm," **www.windenergy.org.nz/te-apiti-wind-farm;** Meridian Energy, "Te Apiti Wind Farm," **www.meridianenergy.co.nz/about-us/our-power-stations/wind/te-apiti.**

INTRODUCTION

Much of this book deals with how businesses should develop and manage ongoing operations and supply chain processes. Examples include the procure-to-pay cycle, forecasting, master scheduling and MRP, kanban systems, reorder point inventory systems, and systems for tracking quality levels, to name just a few.

Project
According to PMI, "a temporary endeavor undertaken to create a unique product, service, or result." Unlike other business activities, a project has a clear starting point and ending point, after which the people and resources dedicated to the project are reassigned.

But in addition to these day-to-day activities, all businesses, at one time or another, must embark on projects. A **project** is "a temporary endeavor undertaken to create a unique product, service, or result."[1] Unlike other business activities, a project has a clear starting point and ending point, after which the people and resources dedicated to the project are reassigned.

Not all projects are as dramatic or large as the wind farm built by Meridian Energy. Examples of projects include developing a new product or service, making long-term process or

[1]Project Management Institute, *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)*, 5th ed. (Newtown Square, PA: Project Management Institute, 2013).

capacity decisions, and even implementing a new software system. All of these represent nonroutine activities that are vital to the survival of a business.

Projects are distinct from "typical" business activities in several ways. We've already noted that projects are nonroutine. For example, a company may schedule employees' work hours every month or reorder inventory items every week. These are routine business activities. On the other hand, projects such as moving headquarters, breaking into a new geographic market, and developing a new passenger jet may happen only once in a decade and have a significant impact on a firm's competitive position.

Second, the nonroutine nature of projects often makes them very difficult to manage. Consider a new product development project. At the start of the project, no one is quite sure what the final product will look like, how long it will take to complete, what resources will be needed, and what the final costs will be. This is not to say that developing a new product is more complex than, say, building a car, but at least the car manufacturer has an idea what it is building!

Third, projects typically require significant levels of cross-functional and interorganizational coordination—more, in fact, than routine business activities, which can often be formalized enough to be managed by a small group of people. The cross-functional and interorganizational nature of projects presents unique organizational challenges. For example, an engineer working on a smartphone development team may have to report to two managers: his functional (engineering) manager and a project manager charged with getting the smartphone developed on time.

Fourth, a project, unlike routine activities, has a defined ending point, at which time the project is complete. Bridges are opened. New information systems are brought online. New products or services are launched. When this occurs, the people and resources involved must be assigned to new projects.

For many organizations, such as construction firms and software developers, projects actually account for the bulk of business activity. Routine business processes pale in comparison to the time and effort these firms must spend on developing new software products on budget, on time, and as bug-free as possible. The firms that succeed under these conditions typically are highly competent at managing projects.

14.1 THE GROWING IMPORTANCE OF PROJECT MANAGEMENT

Project management
According to PMI, "the application of knowledge, skills, tools and techniques to project activities to meet project requirements."

The Project Management Institute (**www.pmi.org**) defines **project management** as "the application of knowledge, skills, tools and techniques to project activities to meet project requirements."[2] However, until recently, project management was often treated more as an art than an actual management discipline; completing projects on time and on budget was often attributed primarily to good luck. And when things didn't go right (which often happened), managers wrote it off as the inevitable consequence of managing complex, nonroutine activities.

But this is no longer the case. For one thing, companies no longer accept the premise that projects are too complex to manage well. Second, professional organizations, such as the Project Management Institute, have emerged to educate practicing managers on state-of-the-art tools and techniques. As a management discipline, project management has matured.

Industry trends have also pushed project management to the forefront. Two trends of particular interest are:

- The faster pace of strategic change
- The changing role of middle management

Let's talk about each of these in turn, starting with the pace of strategic change. New product lines must be introduced more often to fight off hungry competitors. Information technology solutions that used to last 10 years are now out of date after 5, and customer and supplier networks quickly change, requiring new supply chain solutions. The result of all this

[2]Ibid.

is that companies find themselves involved in many more projects with strategic ramifications than they were involved in just a few years ago. As the number of projects increases, the case for improved project management becomes even stronger for a firm.

Project management has also received more attention as the traditional role of middle management has shrunk. Advanced information systems now handle many of the data analysis tasks that middle managers used to perform. At the same time, many companies have taken the authority and responsibility for work outcomes away from middle managers and pushed them down to direct supervisors and workers.

While the result has been a dramatic decrease in the number of middle managers, those who are left are more involved in managing projects, with their decision-making ability and flexibility put to better use. Simply put, middle managers who hope to keep their jobs, much less advance, will need to learn how to manage projects.

14.2 PROJECT PHASES

Because of the unique characteristics of projects, a whole set of tools has been developed to plan and control projects. Before we get to these tools, however, let's look at the five phases of a generic project. (You might want to compare and contrast these phases with the detailed description of the product development process in Chapter 15.) While the amount of time and resources spent on each phase will differ from one situation to the next, nearly all projects go through these phases. Figure 14.1 emphasizes two other points: the finite nature of a project and the typically high level of resources needed to both plan and carry out the project activities.

Concept Phase

Concept phase
The first of five phases of a project. Here, project planners develop a broad definition of what the project is and what its scope will be.

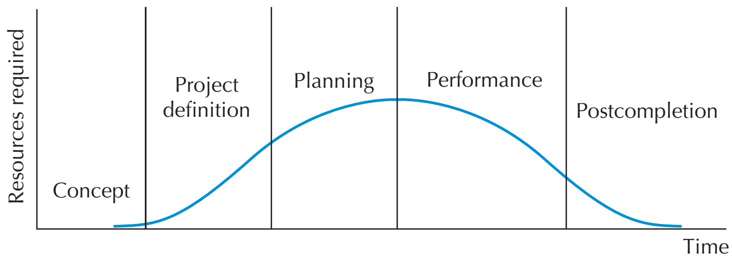
In the **concept phase,** project planners develop a broad description of what the project is and what its scope will be. For example, project planners might describe the project as "Launch a new online degree program" or "Open up a new support center in Brazil." Once the project has been broadly described, planners identify key resources, budget requirements, and time considerations. Key outputs of this phase include initial budget estimates, estimates of personnel needed, and required completion dates. Experience suggests that budget estimates made during the concept phase are usually accurate to ±30% compared to the actual final budget. Planners use this information not only to get an early fix on the scope of the project but also, in many cases, to determine whether a project is feasible. This is particularly important for new product or service development projects.

Project Definition Phase

Project definition phase
The second of five phases in a project. Here, project planners identify how to accomplish the work, how to organize for the project, the key personnel and resources required to support the project, tentative schedules, and tentative budget requirements.

If project planners believe the project is feasible, they proceed to the **project definition phase.** Project definition provides greater detail than the concept phase. The project definition identifies how to accomplish the work, how to organize for the project, the key personnel and resources required to support the project, tentative schedules, and tentative budget requirements. Budget estimates begin to become more exact, with a target of ± 5–10% compared to the actual final budget.

FIGURE 14.1 **Five Phases of a Generic Project**



Planning Phase

Planning phase
The third of five phases of a project. Here, project planners prepare detailed plans that identify activities, time and budget targets, and the resources needed to complete each task. This phase also includes putting in place the organization that will carry out the project.

Milestone
A performance or time target for each major group of activities in a project.

The **planning phase** entails preparing detailed plans that identify activities, time and budget targets, and the resources needed to complete each task. This phase also includes putting in place the organization that will carry out the project. Firms often create project teams to perform the day-to-day tasks required to complete the project. The planning phase is particularly critical because there is a strong relationship between effective planning and successful project outcomes.

Detailed planning provides an opportunity to discuss each person's role and responsibilities throughout the project. A key part of this phase is developing performance and time targets for major groups of activities, known as **milestones.** These milestones will be used to track the progress of the project. An organization must also define how the different tasks and activities that make up the project come together to result in a completed project. The detailed plan serves as a reference that enables everyone to determine how the project is progressing at various points in time. Later we will address project planning and control tools and techniques in more detail.

Table 14.1 shows an example of some of the detail that might come out of this phase. In this example, activity group 3 of a larger project has been broken down into specific activities. In addition to an overall budget and a time milestone of July 9, 2020, the table indicates personnel assignments and responsibilities, budgets, and due dates for each of the five individual activities.

Performance Phase

Performance phase
The fourth of five phases of a project. In this phase, the organization actually starts to execute the project plan.

In the **performance phase,** the organization actually starts to execute the project plan. It is here that the value of the previous phases really becomes apparent. Specifically, effective planning increases the likelihood that actual performance outcomes will meet expectations. Project managers play a particularly important role here in coordinating and directing the work effort and in ensuring that time and performance milestones are met. Depending on the type of project, this may be the longest phase.

Postcompletion Phase

Postcompletion phase
The fifth of five phases of a project. This is the phase in which the project manager or team confirms the final outcome, conducts a postimplementation meeting to critique the project and personnel, and reassigns project personnel.

The **postcompletion phase** is the "wrap-up" phase of project management, which includes several important tasks. During this phase, the project manager or team:

- Confirms that the final outcome of the project meets the expectations of management or the customers. This usually entails a comparison of actual outcomes (time, cost, etc.) to the expected outcome established during planning.
- Conducts a postimplementation meeting to discuss the strengths and weaknesses of the project effort and personnel. As we saw in our discussion of continuous improvement in Chapter 4, an effective organization learns from its experiences.
- Reassigns project personnel to other positions or projects. One of the primary characteristics of projects as a form of work is the movement of personnel from project to project.

TABLE 14.1 Example of Detailed Project Information, Including Budget and Time Milestone

ACTIVITY GROUP 3: Build and deliver product to the customer
TIME MILESTONE: 7/9/20
BUDGET: $70,000

SPECIFIC ACTIVITY	PERSONNEL	BUDGET	DUE DATE
3.1 Complete specifications	John C.* Chester B.	$15,000	6/4/20
3.2 Complete Subassembly A	Maria G.* Tom T. Debra V.	$20,000	6/19/20
3.3 Complete Subassembly B	Philip B.* Emily W.	$24,000	6/19/20
3.4 Final assembly and testing	John C.* Chester B. Anne I.	$9,000	7/2/20
3.5 Deliver and train customer	Anne I.*	$2,000	7/9/20

*Indicates person with primary responsibility.

14.3 PROJECT MANAGEMENT TOOLS

Practitioners and academics have developed a host of tools to aid organizations in their project management efforts. Project management tools are used to plan, measure, and track a project's progress. In this section, we introduce two well-accepted tools: Gantt charts and network diagrams. These tools help managers understand what activities need to be completed, who is responsible for various activities, and when the activities should be completed. These tools also allow managers to track the time it takes to complete activities as well as costs. With the proper planning and control information, managers can take corrective actions when necessary to meet project objectives.

Gantt chart
A graphical tool used to show expected start and end times for project activities and to track actual progress against these time targets.

Gantt Charts

A **Gantt chart** is a graphical tool used to show expected start and end times for project activities and to track actual progress against these time targets. A Gantt chart therefore provides both a planning function and a control function.

EXAMPLE 14.1

Gantt Chart for the Gina3000 Project

Archideaphoto/Shutterstock

Courter Corporation makes high-end speakers that are used with home entertainment systems. Courter has designed a new speaker, the Gina3000, which is louder and more reliable than Courter's earlier model. Before Courter goes any further, however, it wants to give its customers—the home entertainment system manufacturers—a chance to test and critique the Gina3000.

Management has outlined 10 activities that must be completed before the Gina3000 speakers can be released for regular production. These 10 activities are listed in Table 14.2.

There are a couple of things to note about Table 14.2. First, some activities, such as **A** (Legal department approves prototype use) and **B** (R&D builds prototype speakers) can occur simultaneously. Courter Corporation should consider this when planning the expected time for the project's completion. Second, some activities have predecessors that must be completed beforehand. Take activity **H,** for example. Obviously, one can't test sample speakers before they have been made (activity **E**). Likewise, the speakers can't be made until the new equipment has been ordered and installed (activity **D**).

TABLE 14.2 List of Activities for the Gina3000 Project

ACTIVITY		DURATION (WEEKS)	PREDECESSORS
A	Legal department approves prototype use	2	None
B	R&D* builds prototype speakers	3	None
C	Customer uses and approves prototypes	3	**A**, **B**
D	New equipment is ordered and installed	5	**C**
E	Manufacturing produces sample speakers	2	**D**
F	R&D* writes up product specifications	3	**C**
G	Customer tests and approves sample speakers	3	**E**, **F**
H	QA** tests and approves sample speakers	3	**E**
I	Manufacturing finalizes process	3	**E**
J	Management approves product for regular production	2	**G**, **H**, **I**

*Research and Development. **Quality Assurance.

Figure 14.2 shows a Gantt chart for the Gina3000 project. For simplicity, each activity is referred to by its corresponding letter in Table 14.2. The Gantt chart provides a lot of useful information at a glance. First, according to the chart, the project should be completed by the end of week 18. Second, the chart tells us when specific activities should start and finish. Note that activity **C** has a planned start date of week 4. Why week 4? Because that is the first week in which *both* activity **A** and activity **B** (**C**'s predecessors) are finished.

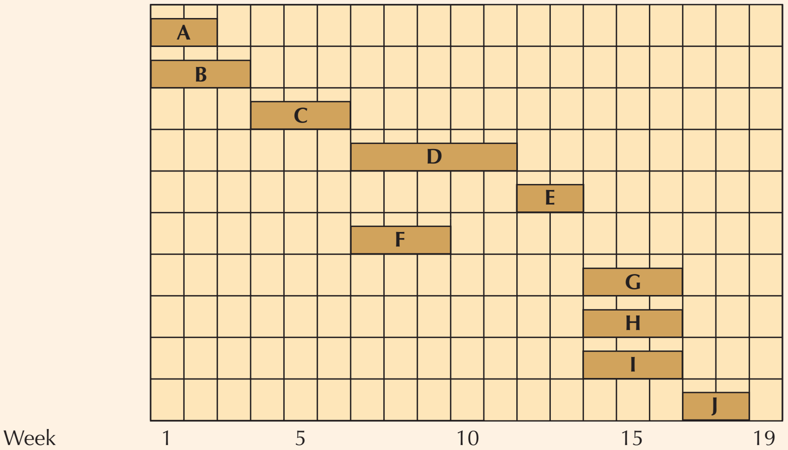


FIGURE 14.2 Initial Gantt Chart for the Gina3000 Project

As time goes on, Courter can use a Gantt chart to check its progress against the plan. In Figure 14.3, we use shading to show how much of each activity has been completed. Figure 14.3 shows that by the end of week 8, activity **F** has been completed one week ahead of schedule (i.e., the entire activity has been shaded in), while activity **D** is already two weeks late getting started (none has been shaded in). Based on this information, Courter Corporation has several options, including rescheduling the project or expediting activities to finish within the 18-week plan.

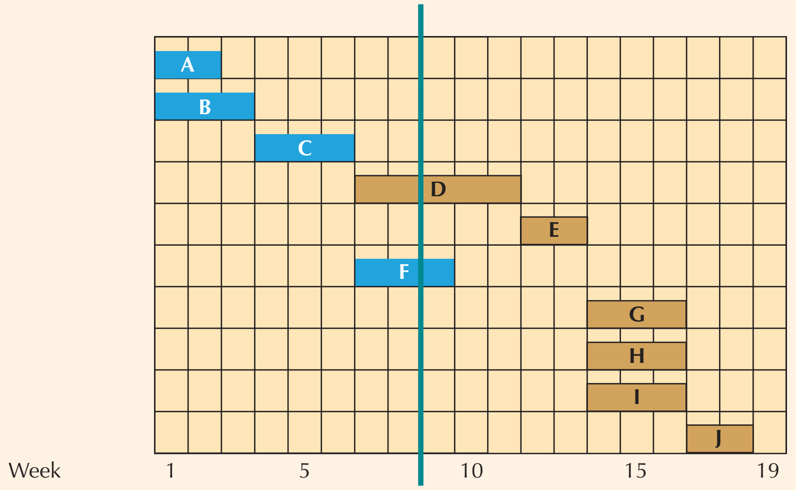


FIGURE 14.3 Gantt Chart at the End of Week 8 (blue shading indicates proportion completed)

Network Diagrams

Gantt charts have one major weakness: They fail to explicitly show precedence relationships. For example, it is unclear from Figure 14.2 or Figure 14.3 whether or not activity **F** is a predecessor of activity **G** (it is). This can be a real limitation for larger projects involving dozens or even hundreds of activities.

Network diagram
A graphical tool that shows the logical linkages between activities in a project.

Critical path method (CPM)
A network-based technique in which there is a single time estimate for each activity. An alternative approach is PERT, which has multiple time estimates for each activity.

Program evaluation and review technique (PERT)
A network-based technique in which there are multiple time estimates for each activity. An alternative approach is CPM, which has a single time estimate for each activity.

Network diagrams improve on Gantt charts by visually showing the linkages between various activities. The **critical path method (CPM)** and the **program evaluation and review technique (PERT)** are two popular network-based techniques. Like Gantt charts, these techniques require the user to identify the activities that make up a project and to determine their sequence and interrelationships.

Both CPM and PERT allow project managers to monitor progress over time while managing costs across all activities. CPM is used for projects where there is a single time estimate for each activity. PERT is used when the time estimates are less certain and it makes more sense to provide several estimates—a most likely, a pessimistic, and an optimistic estimate. These estimates are combined to arrive at a single time estimate for each project activity.

PERT users can also determine the probability of completing a project by a certain target date by using normal distribution curve statistics.[3] In reality, PERT is rarely used in practice. Most managers find that coming up with a single best estimate of an activity's time is difficult enough without introducing the added complexity of multiple estimates. We will therefore focus our attention on CPM and the use of single time estimates.

Constructing a Network Diagram

Regardless of whether one uses CPM or PERT, the underlying logic is the same. Each approach uses a network diagram to show how each individual activity relates in time and sequence to all other activities. Network diagrams show at a glance how separate activities come together to form an entire project.

Activity on node (AON) diagram
A network diagram in which each activity is represented by a node, or box, and the precedence relationships between various activities are represented with arrows.

While there are several ways to construct network diagrams, the process is much the same in both CPM and PERT. The major steps are as follows:

1. Identify each unique activity in a project by a capital letter that corresponds only to that activity.
2. Represent each activity in the project by a node that also shows the estimated time it will take to complete the activity. This style of network diagram is known as an **activity on node (AON) diagram.**

[3]For a detailed description of these methods, see L. Krajewski, M. Malhotra, and L. Ritzman, *Operations Management: Processes and Supply Chains*, 11th ed. (Upper Saddle River, NJ: Prentice Hall, 2015).

Critical activity
A project activity for which the earliest start time and latest start time are equal. A critical activity cannot be delayed without lengthening the overall project duration.

Network path
A logically linked sequence of activities in a network diagram.

Critical path
A network path that has the longest, or is tied for the longest, linked sequence of activities.

3. If an activity has an immediate predecessor(s), show the relationship by connecting the two activities with an arrow. The network diagram consists of all the activity nodes and arrows linking them together.
4. Determine the earliest start time (*ES*) and earliest finish time (*EF*) for each activity by performing a forward pass.
5. Determine the latest finish time (*LF*) and latest starting time (*LS*) for each activity by doing a backward pass.
6. Determine the critical activities and path(s) in the project. **Critical activities** are activities for which the earliest start time and the latest start time are equal. Critical activities cannot be delayed without lengthening the overall project duration. **Network paths** are logically linked sequences of activities in the network diagram. A path is a **critical path** if it is the longest path in the network (or tied for longest path). The duration of the project is equal to the duration of the critical path(s).

EXAMPLE 14.2

Network Diagram for the Gina3000 Project

Courter Corporation decides to follow the six steps outlined above to create a network diagram of the Gina3000 project.

Step 1. *Identify each unique activity in a project by a capital letter that corresponds only to that activity.* This has already been done in Table 14.2.

Step 2. *Represent each activity in the project by a node that also shows the estimated time it will take to complete the activity.* To illustrate, "Customer uses and approves prototypes" (activity **C**) is estimated to take 3 weeks. Courter represents this as follows:

Step 3. *If an activity has an immediate predecessor(s), show that relationship by connecting the two activities with an arrow.* Activity **A** immediately precedes activity **C**. This is shown as follows:

The same logic is used to link all the activities in the project. The result is the AON network diagram for the Gina3000 project shown in Figure 14.4. Note that there is one arrow for each predecessor relationship listed in Table 14.2.

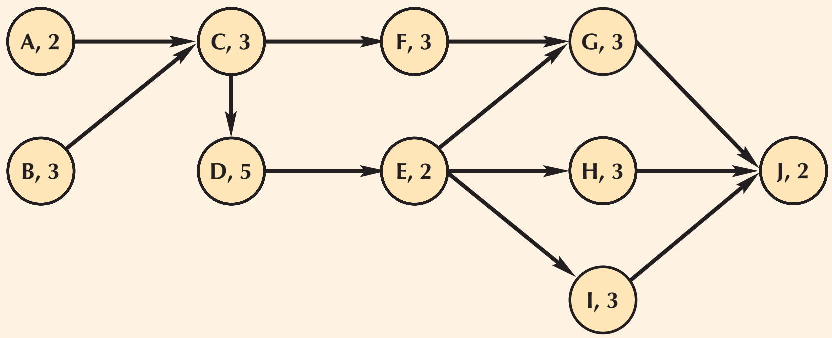


FIGURE 14.4 **AON Network Diagram for the Gina3000 Project**

Now consider the fact that even though activity **A** is not listed as an *immediate* predecessor for any activity except **C,** it must still be completed before all other activities, except for **B.** That is, all the activities except **B** are on a network path in which activity **A** is the first activity that must be completed. One path through the network is the sequence **A–C–F–G–J.** This path implies that **A** must be completed before **C, C** before **F,** and so on. Paths are the key to understanding the relationship between activities and determining the length of a project. There are a total of eight different paths in this network. Can you find all of them?

Forward pass
The determination of the earliest start and finish times for each project activity.

Earliest start time (*ES*)
The earliest an activity can be started, as determined by the earliest finish time for all immediate predecessors.

Earliest finish time (*EF*)
The earliest an activity can be finished, calculated by adding the activity's duration to its earliest start time.

Backward pass
The determination of the latest finish and start times for each project activity.

Latest finish time (*LF*)
The latest an activity can be finished and still finish the project on time, as determined by the latest start time for all immediate successors.

Latest start time (*LS*)
The latest an activity can be started and still finish the project on time, calculated by subtracting the activity's duration from its latest finish time.

Step 4. *Determine the earliest start time* (ES) *and earliest finish time* (EF) *for each activity*. This step is also known as the **forward pass** through the network. In general, the **earliest start time (*ES*)** is defined as follows:

$$\begin{aligned} ES &= \text{earliest time by which } \textit{all} \text{ immediate predecessors could be finished} \\ &= \text{latest } EF \text{ for all immediate predecessors} \end{aligned} \qquad \textbf{(14.1)}$$

Neither **A** nor **B** has any predecessors, so their $ES = 0$. But what about activity **C**? The earliest time **C** can start is based on the earliest time that *both* **A** and **B** will be finished. Because the EF for **A** $= 2$ and **B** $= 3$ the earliest start time for **C** $= 3$.

The **earliest finish time (*EF*)** is calculated as follows:

$$EF = ES + \text{activity's duration} \qquad \textbf{(14.2)}$$

For activity **A,** then, $ES = 0$ and $EF = 0 + 2 = 2$ (that is, the end of week 2). For activity **C,** $EF = 3 + 3 = 6$. Table 14.3 shows the earliest start (ES) and earliest finish (EF) times for each activity in our speaker development project. There are several interesting pieces of information in Table 14.3. First, the table indicates that the entire project can be completed by the end of week 18. That is because the highest EF value for any activity in the table is 18. This finding is consistent with the Gantt chart shown in Figure 14.2.

Second, look at the earliest start times for activities **G** and **J.** Activity **G** has two immediate predecessors, **E** and **F.** Even though activity **F** can be completed as early as week 9, activity **E** won't be completed until week 13. Therefore, week 13 is the earliest we can start activity **G.** Similarly, activity **J** must wait until activities **G, H,** and **I** are *all* finished.

Step 5. *Determine the latest finish time* (LF) *and latest start time* (LS) *for each activity*. This step is also known as the **backward pass.** Calculating the LS and LF times indicates how late specific activities can be performed and still get the project done by a certain time. This step is particularly important when trying to determine what impact a delay might have on the length of a project.

Latest finish time (*LF*) is defined as follows:

$$\begin{aligned} LF = {} & \text{latest time by which } \textit{all} \text{ immediate successors} \\ & \text{must be started in order to finish the project on time} \\ = {} & \text{earliest } LS \text{ for all immediate successors} \end{aligned} \qquad \textbf{(14.3)}$$

The **latest start time (*LS*)** is calculated as follows:

$$LS = LF - \text{activity's duration} \qquad \textbf{(14.4)}$$

The backward pass is best illustrated by example. Activity **J** has the latest EF of any activity (end of week 18). Setting the latest finish time for activity **J** equal to 18, the latest start time is as follows:

$$\begin{aligned} LS &= LF - \text{activity's duration} \\ &= 18 - 2 = 16 \end{aligned}$$

TABLE 14.3 Earliest Start (*ES*) and Earliest Finish (*EF*) Times for Gina3000 Project

ACTIVITY	DURATION	PREDECESSORS	*ES*	*EF*
A	2	None	0	2
B	3	None	0	3
C	3	**A, B**	3	6
D	5	**C**	6	11
E	2	**D**	11	13
F	3	**C**	6	9
G	3	**E, F**	13	16
H	3	**E**	13	16
I	3	**E**	13	16
J	2	**G, H, I**	16	18

The latest start time answers the question "How late can this activity be started and still complete the project on time?" Having calculated the *LF* and *LS* for activity **J,** we work backward (thus the term *backward pass*) to those activities immediately preceding **J:** activities **G, H,** and **I.** Having completed the calculations for those activities, we then work backward to activities **E** and **F.** Table 14.4 summarizes the results of the forward and backward passes.

Step 6. *Determine the critical activities and path(s) in the project.* Combined with the network diagram (Figure 14.4), the values in Table 14.4 provide Courter's management with some valuable information. First, look at activities **B, C, D, E, G, H, I,** and **J** (marked with asterisks). In each case, $ES = LS$. This means that the *latest* these activities can be started and still get the project done on time is *also the earliest* they can be started. Because *any* delay in these activities will cause the entire project to be late, these activities are critical activities.

Slack time
The difference between an activity's latest start time (*LS*) and earliest start time (*ES*). Slack time indicates the amount of allowable delay. Critical activities have a slack time of 0.

Activities **A** and **F,** in contrast, are not critical activities. The amount of allowable delay, or **slack time,** is calculated as follows:

$$\text{Slack time} = LS - ES \qquad (\mathbf{14.5})$$

For activity **A,** $3 - 2 = 1$ week of slack time; for activity **F,** $10 - 6 = 4$ weeks of slack. Now try to calculate the slack time for one of the critical activities. The answer should be zero, reinforcing the notion that critical activities cannot be delayed without delaying the entire project.

Figure 14.5 marks the critical activities in red, thereby showing the critical paths in the project. Critical paths are always the longest paths in the network, as there is no slack time in any of the activities they link together. In this case, there are three critical paths: **B–C–D–E–G–J, B–C–D–E–H–J,** and **B–C–D–E–I–J.** By adding up the times for the individual activities in each path, Courter realizes that each critical path takes 18 weeks. This result is consistent with the Gantt charts (Figures 14.2 and 14.3) and Table 14.4. A final point: While a project may have many critical paths, it must always have at least one critical path. After all, some path has to be the longest!

TABLE 14.4 Results of Forward and Backward Passes on the Gina3000 Project

ACTIVITY	DURATION (WEEKS)	PREDECESSORS	*ES*	*EF*	*LS*	*LF*
A	2	None	0	2	1	3
B*	2	None	0	3	0	3
C*	3	**A, B**	3	6	3	6
D*	5	**C**	6	11	6	11
E*	2	**D**	11	13	11	13
F	3	**C**	6	9	10	13
G*	3	**E, F**	13	16	13	16
H*	3	**E**	13	16	13	16
I*	3	**E**	13	16	13	16
J*	2	**G, H, I**	16	18	16	18

*Critical activity.

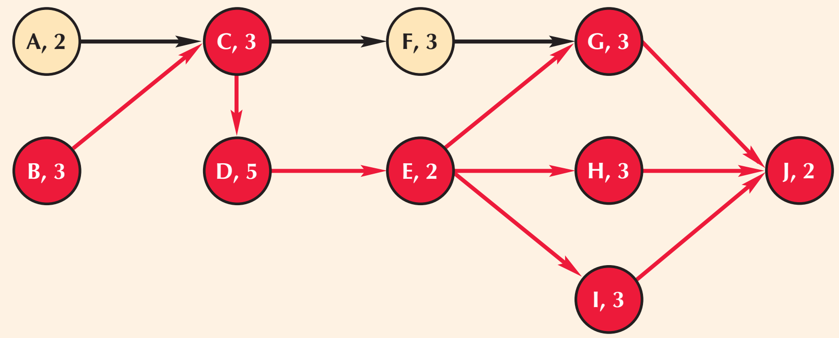


FIGURE 14.5 AON Network Diagram for the Gina3000 Project (critical activities and paths marked in red)

Crashing a Project

In many instances, the initial estimate of the time required to complete a project might be unacceptable. For high-tech products, even a few months of delay can often result in a significant loss of market share. And any city hosting the Olympics has no choice but to complete construction before the games begin; there is no room for negotiation. Alternatively, managers may be offered financial or other incentives for completing a project early.

Crashing
Shortening the overall duration of a project by reducing the time it takes to perform certain activities.

Crashing is an effort to shorten the overall duration of a project by reducing the time it takes to perform certain activities. As with the initial development of the network diagram, there is a series of steps to follow when crashing a project:

1. List all network paths and their current lengths. Mark all activities that can be crashed.
2. Focus on the critical path or paths. Working one period at a time, choose the activity or activities that will shorten all critical paths at the least cost. The one rule is this: Never crash an activity that is *not* on a critical path, regardless of the cost. Doing so will not shorten the project; it will only add costs.
3. Recalculate the lengths of all paths and repeat step 2 until the target project completion time is reached or until all options have been exhausted.

EXAMPLE 14.3

Crashing a Project at Courter Corporation

Nearly 60% of the cost of Courter Corporation's products comes from components provided by outside suppliers. As a result, management would like to:

- Develop a set of performance criteria and an evaluation system for assessing potential suppliers.
- Identify, evaluate, and select suppliers for critical components.
- Develop an IT system that will evaluate the performance of the selected suppliers on a continuous basis.

Management requires that the entire project be completed within *23 weeks*. Table 14.5 lists the various activities that must be completed. In addition to the estimated duration and predecessors for each activity, the table shows how many weeks each activity can be crashed and the crash cost for each week. For example, the expected duration of activity **B** is 6 weeks. However, for an additional $500, activity **B** can be squeezed down, or crashed, by 1 week.

TABLE 14.5 List of Activities for Supplier Selection and Evaluation Project

ACTIVITY		ORIGINAL LENGTH (WEEKS)	PREDECESSORS	NUMBER OF WEEKS ACTIVITY CAN BE CRASHED	CRASH COST PER WEEK
A	Assemble project team	2	None	—	
B	Identify potential suppliers	6	**A**	1	$500
C	Develop supplier evaluation criteria	4	**A**	—	
D	Develop audit form	3	**C**	1	$800
E	Perform supplier financial analysis	2	**B**	—	
F	Visit suppliers	8	**E, D**	2	$2,000
G	Compile visit results	5	**F**	1	$700
H	Identify needs for IT system	4	**A**	—	
I	Perform systems analysis and coding	10	**H**	2	$300
J	Test system	3	**I**	—	
K	Select final suppliers	2	**G**	—	

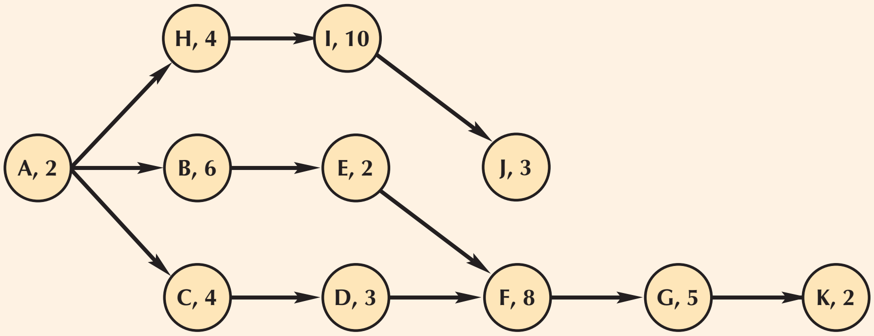


FIGURE 14.6 Network Diagram for Project

Note that not all activities can be crashed. For instance, testing of the computerized supplier evaluation system (activity **J**) and final selection (activity **K**) cannot be crashed at all.

Figure 14.6 shows the network diagram for this project. Notice that there are three paths: **A–B–E–F–G–K, A–C–D–F–G–K,** and **A–H–I–J.** Interestingly, there are *two* final activities, **K** and **J**. That is because the development of the IT system (**A–H–I–J**) is essentially independent of the supplier selection effort.

Table 14.6 contains the results of the forward and backward passes for this project. (You might want to calculate the *ES*, *EF*, *LS*, and *LF* values yourself in order to convince yourself that you understand how they were obtained.) Of the three paths, only **A–B–E–F–G–K** is critical because the activities on this path are the only ones for which $ES = LS$. Based on Table 14.6, we can conclude that the project will take 25 weeks.

Yet Courter management wants the project completed in *23* weeks, not 25. Can it be done, and if so, what is the cheapest way to accomplish the task? Crashing, like network development, can be divided into several steps.

Step 1. *List all network paths and their current lengths. Mark all activities that can be crashed.* Table 14.5 shows the duration, crash time, and crash cost for each activity in this project. The current length of each path, therefore, is as shown in Table 14.7 (where all activities that can be crashed appear in color).

TABLE 14.6 Results of Forward and Backward Passes for Project

ACTIVITY	DURATION (WEEKS)	PREDECESSORS	*ES*	*EF*	*LS*	*LF*
A*	2	None	0	2	0	2
B*	6	A	2	8	2	8
C	4	A	2	6	3	7
D	3	C	6	9	7	10
E*	2	B	8	10	8	10
F*	8	E, D	10	18	10	18
G*	5	F	18	23	18	23
H	4	A	2	6	8	12
I	10	H	6	16	12	22
J	3	I	16	19	22	25
K*	2	G	23	25	23	25

*Critical activity.

TABLE 14.7 Network Paths for Project*

PATH	LENGTH
A–B–E– F–G–K	25**
A–C–D–F–G–K	24
A–H–I–J	19

*Activities that can be crashed appear in color.
**Critical path.

Step 2. *Focus on the critical path or paths. Working one period at a time, choose the activity or activities that will shorten all critical paths at the least cost.* We will need to shorten two paths, **A–B–E–F–G–K** and **A–C–D–F–G–K,** to meet the 23-week deadline. Table 14.7 shows that there are several options for crashing each.

As we said above, it never makes sense to crash a noncritical activity. Look at activity **I.** Courter could crash that activity for only $300, but the path it is on is already shorter than necessary—just 19 weeks. And crashing it would have no effect on the length of the critical path, **A–B–E–F–G–K.** Courter would be out $300, and the project would still take 25 weeks.

Because **A–B–E–F–G–K** is the longest path, management should start there. Shortening this one path by 1 week will reduce the length of the entire project to 24 weeks. The cheapest way to shorten it is to crash activity **B** by 1 week, at a cost of $500. The new path lengths are shown in Table 14.8. Notice that neither of the other two paths is affected because activity **B** is not on them.

TABLE 14.8 **Updated Network Path Lengths**

	LENGTH	LENGTH AFTER CRASHING B
A–B–E–F–G–K	25*	24*
A–C–D–F–G–K	24	24*
A–H–I–J	19	19
Crashing cost: $500.		

*Critical path.

Step 3. *Recalculate the lengths of all paths and repeat step 2 until the target project completion time is reached or until all options have been exhausted.* After activity **B** has been crashed, two paths become critical: **A–B–E–F–G–K** and **A–C–D–F–G–K.** Any further crashing efforts must consider both those paths. The next cheapest crashing option, therefore, is to crash activity **G,** at a cost of $700 (see Table 14.5). Doing so will bring down the lengths of both **A–B–E–F–G–K** and **A–C–D–F–G–K** to the required 23 weeks. Table 14.9 shows the final results.

TABLE 14.9 **Final Results of Crashing Activities B and G**

	ORIGINAL LENGTH	LENGTH AFTER CRASHING B	LENGTH AFTER CRASHING G
A–B–E–F–G–K	25*	24*	23*
A–C–D–F–G–K	24	24*	23*
A–H–I–J	19	19	19
Crashing cost: $500 + $700 = $1,200.			

*Critical path.

If Courter wanted to collapse the project any further, it would have to reduce activity **F** by 2 weeks, at a cost of $2,000. Crashing activity **D** wouldn't be enough because it affects only path **A–C–D–F–G–K.** And crashing activity **I** wouldn't help at all because it isn't on any critical path.

14.4 PROJECT MANAGEMENT SOFTWARE

The advent of cheap computer power has resulted in an explosion in the number of project management software packages. What we did by hand in the previous section—drawing networks, determining critical paths, crashing projects—can be done automatically, using software. These software packages enable far more sophisticated planning than anything discussed here. Nearly every package, for instance, allows users to evaluate the impact of resource constraints or to consider multiple estimates of activity time, as is done in PERT. In addition, nearly every software package offers resource utilization reports and exception reports on activities that are in danger of falling behind or becoming critical. This latter feature can be particularly valuable in managing complex projects with hundreds of activities because it highlights the critical few activities that managers need to pay attention to.

To give you a flavor for how these packages work, this section includes screenshots from one popular package, Microsoft Project. Figure 14.7 shows how we might set up the Gina3000 project (discussed in Examples 14.1 and 14.2) in Project. Compare the activities ("tasks") listed here with those in Table 14.2. As you can see from the toolbar on the left side of the screen, the software package offers some fairly sophisticated resource management tools.

Figure 14.8 shows the Gantt chart that Project generated for the project. Note the similarities to Figures 14.2 and 14.3. Microsoft Project has the added advantage of showing precedence relationships using arrows.

Figure 14.9 shows the AON diagram for the project. As with other software packages of this type, Microsoft Project automatically calculates starting and ending times and identifies the critical activities and paths. In this case, the critical activities and path are highlighted in the lighter shade. Once again, you might compare this network diagram with those we showed earlier, in Figures 14.4 and 14.5. While slightly different, they contain the same basic information. One benefit of using this software package is that it automatically updates diagrams as activities are added or deleted and as time estimates change.

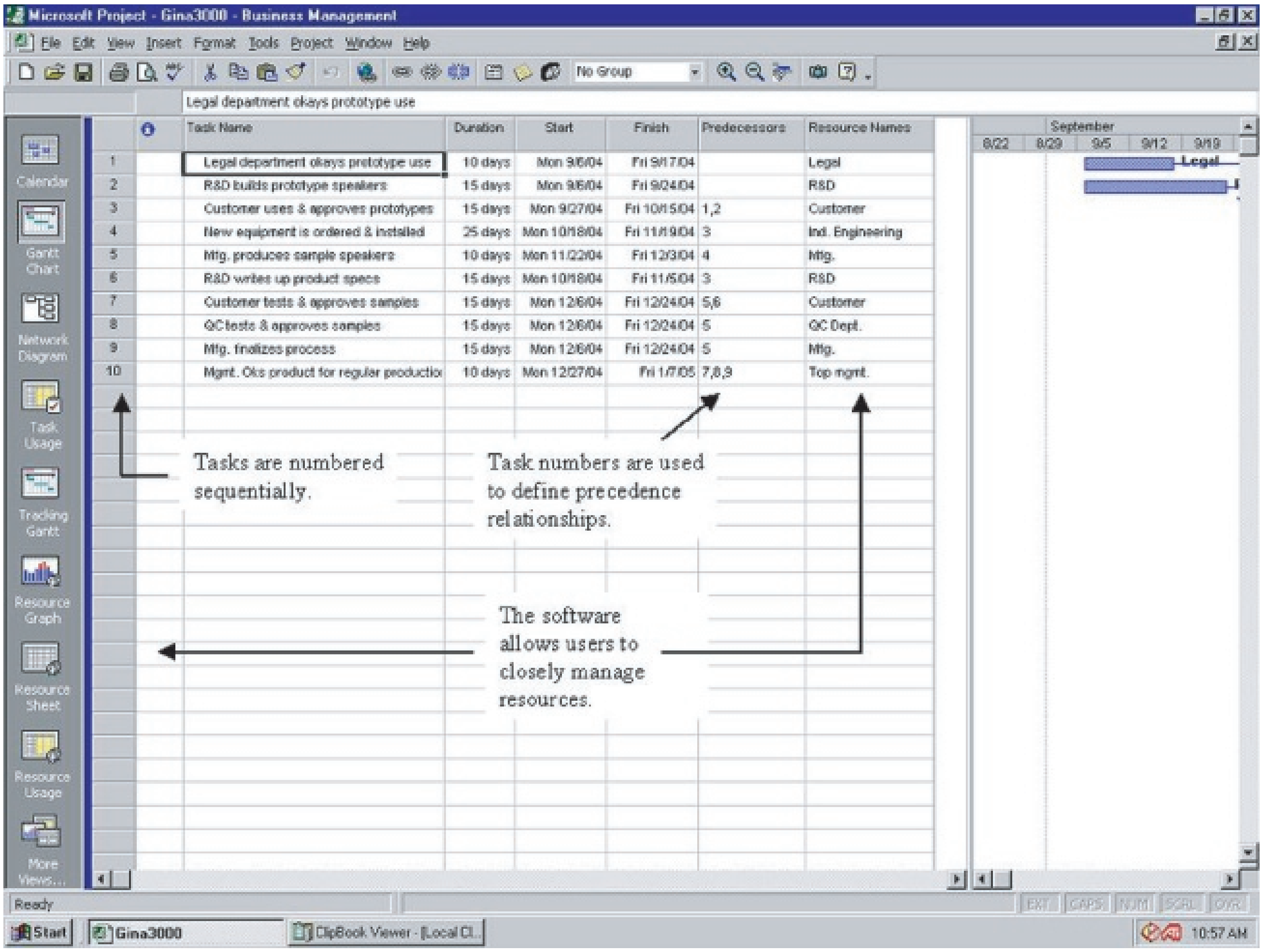
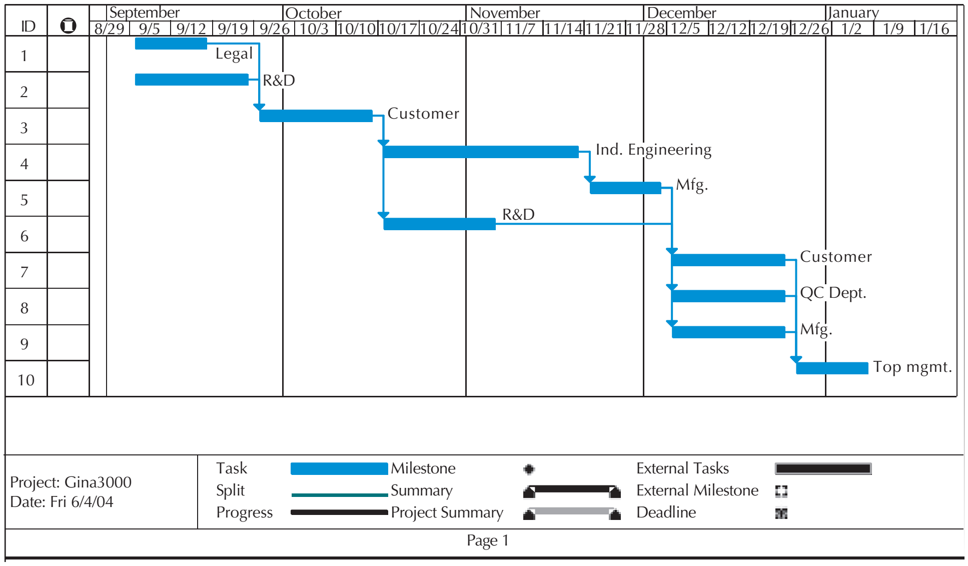


FIGURE 14.7 Entering the Gina3000 Project into Microsoft Project
Windows 10, Microsoft Corporation

FIGURE 14.8 **Computer-Generated Gantt Chart for the Gina3000 Project**



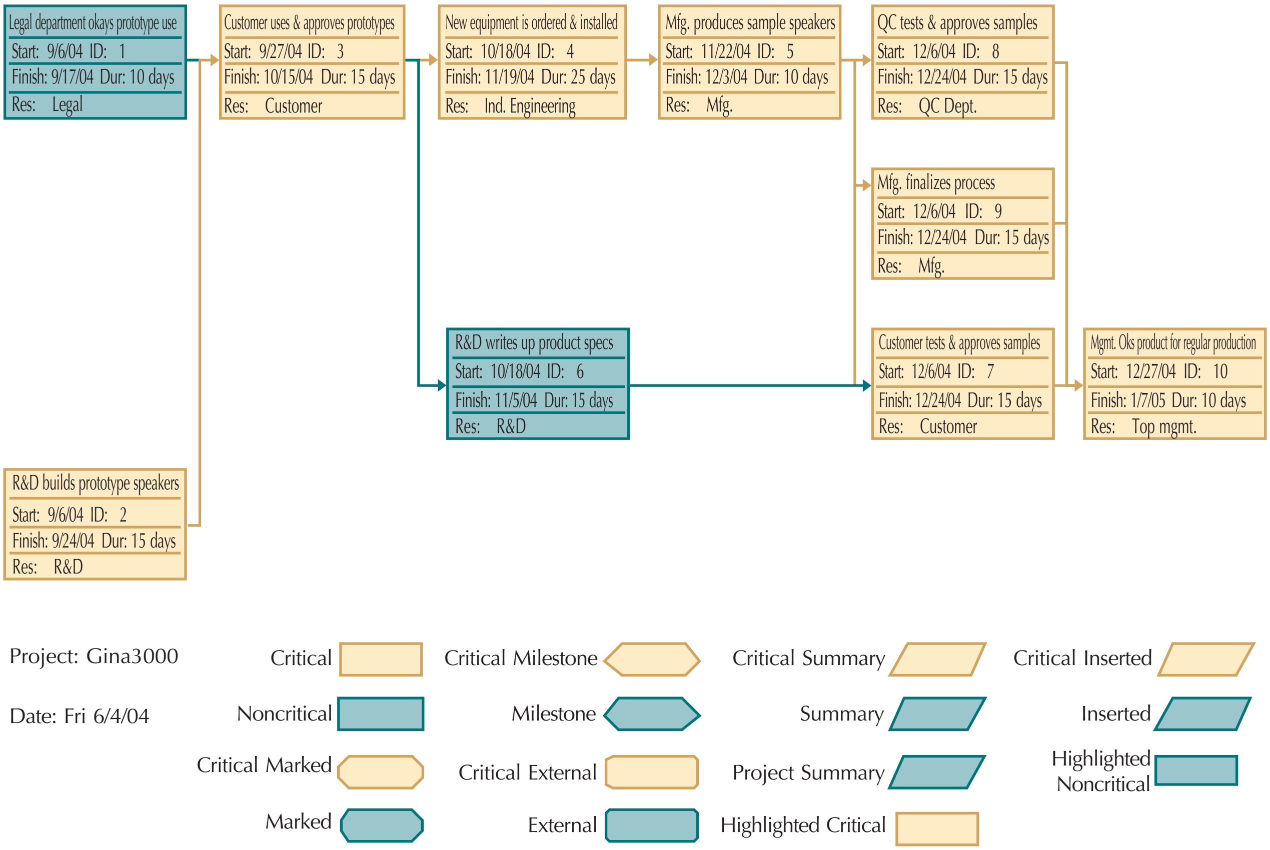


FIGURE 14.9 **Computer-Generated Network Diagram for the Gina3000 Project**

Even with almost unlimited computer power, it's still the responsibility of managers to make sure that project information is updated on a regular basis, particularly when activities or time estimates change frequently. Sophisticated users of project management software update project information on a weekly or even daily basis to stay on top of changes that could affect the timing or cost of a project.

14.5 PMI AND THE *PROJECT MANAGEMENT BODY OF KNOWLEDGE* (PMBOK®)

Throughout this book, we have identified numerous professional organizations dedicated to the advancement of operations and supply chain practices. The Project Management Institute (PMI) is one such organization. PMI serves the needs of project management professionals from a wide range of industries, including software development, construction, finance, and manufacturing. In addition to certification and other educational offerings, PMI also sponsors conferences, research, and special interest groups for individuals interested in various aspects of project management.

Perhaps the organization's best-known output is the *Guide to the Project Management Body of Knowledge* (PMBOK)[4] The PMBOK guide serves several needs. First, it provides a common language for discussing project management issues. Second, it identifies and disseminates generally accepted project management knowledge and practices. Third, and perhaps most importantly, it serves as a basic reference source for project management.

The guide divides the body of knowledge into two main parts. The first part defines the various business processes that organizations follow in carrying out projects. The PMBOK recognizes five major process groups: Initiating, Planning, Executing, Controlling and Monitoring, and Closing.

The second part of the PMBOK covers nine knowledge areas applicable to nearly all projects. These knowledge areas include such topics as managing the scope, quality, time, and cost of projects; managing human resources and communications between the various parties; and managing project risk. It's interesting to note that while the PMBOK deals with these knowledge areas within the context of project management, it draws heavily from other managerial disciplines such as organizational behavior and finance.

CHAPTER SUMMARY

Projects represent nonroutine business activities that often have long-term strategic ramifications for a firm. In this chapter, we examined how projects differ from routine business activities and discussed the major phases of projects. We noted how environmental changes have resulted in increased attention being paid to projects and project management over the past decade.

In the second half of the chapter, we introduced some basic tools that businesses can use when planning for and controlling projects. Both Gantt charts and network diagrams give managers a visual picture of how a project is going. Network diagrams have the added advantage of showing the precedence between activities, as well as the critical path(s). We wrapped up the chapter by showing how these concepts are embedded in inexpensive yet powerful software packages such as Microsoft Project.

If you want to learn more about project management, we encourage you to take a look at the Web site for the Project Management Institute (PMI) at **www.pmi.org.**

KEY FORMULAS

Earliest start time for a project activity (page 438):

$$ES = \text{latest } EF \text{ for all immediate predecessors} \quad \textbf{(14.1)}$$

Earliest finish time for a project activity (page 438):

$$EF = ES + \text{activity's duration} \quad \textbf{(14.2)}$$

Latest finish time for a project activity (page 438):

$$LS = \text{earliest } LS \text{ for all immediate predecessors} \quad \textbf{(14.3)}$$

Latest start time for a project activity (page 438):

$$LS = LF - \text{activity's duration} \quad \textbf{(14.4)}$$

Slack time for a project activity (page 439):

$$\text{Slack time} = LS - ES \quad \textbf{(14.5)}$$

[4]Project Management Institute, *A Guide to the Project Management Body of Knowledge* (PMBOK® *Guide*).

KEY TERMS

Activity on node (AON) diagram 436
Backward pass 438
Concept phase 432
Crashing 440
Critical activity 437
Critical path 437
Critical path method (CPM) 436
Earliest finish time (*EF*) 438
Earliest start time (*ES*) 438
Forward pass 438
Gantt chart 434
Latest finish time (*LF*) 438
Latest start time (*LS*) 438
Milestone 433
Network diagram 436
Network path 437
Performance phase 433
Planning phase 433
Postcompletion phase 433
Program evaluation and review technique (PERT) 436
Project 430
Project definition phase 432
Project management 431
Slack time 439

SOLVED PROBLEM

PROBLEM

Project Management at the GriddleIron

Lance Thompson is opening a new restaurant called the GriddleIron in Collegetown. The first football game of the fall is in 15 weeks, and Lance wants to be open in time to serve visiting alumni and other fans.

Table 14.10 lists all the activities that Lance needs to complete, as well as crashing options for two of the activities. How long will the project take if Lance doesn't crash any activities? Can Lance meet his 15-week deadline? If so, what will the cost be?

Solution

Figure 14.10 shows the network diagram for the GriddleIron project, while Table 14.11 shows the results of the forward and backward passes.

TABLE 14.10 Activity List for the GriddleIron Project

ACTIVITY		ORIGINAL LENGTH (WEEKS)	PREDECESSORS	NUMBER OF WEEKS ACTIVITY CAN BE CRASHED	CRASH COST PER WEEK
A	Get city council permission and permits	4	None	—	
B	Get architect to draw up renovation plans	4	**A**	—	
C	Hire manager	3	**A**	—	
D	Hire staff	3	**C**	—	
E	Train staff	1	**D**	—	
F	Select and order kitchen equipment	2	**B**	—	
G	Select and order dining room and bar furnishings	1.5	**B**	—	
H	Renovate dining area	4	**G**	1	$2,000
I	Renovate kitchen area	5	**F**	2	$1,000
J	Perform fire inspection	1	**H, I**	—	
K	Perform health inspection	1	**H, I**	—	
L	Grand opening	1	**J, K**		

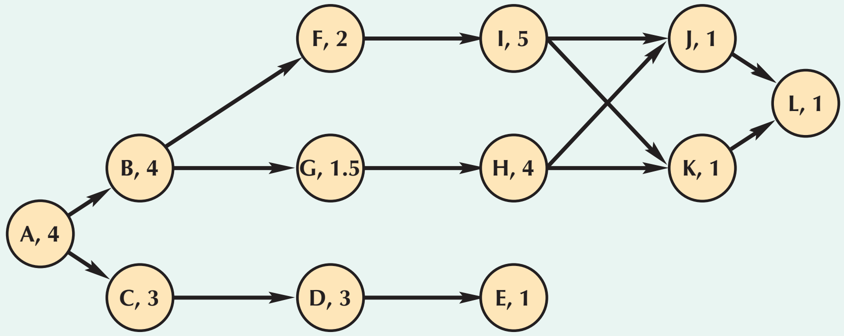


FIGURE 14.10 Network Diagram for the GriddleIron Project

TABLE 14.11 Forward and Backward Pass Results for the GriddleIron Project

ACTIVITY	EARLIEST START	EARLIEST FINISH	LATEST START	LATEST FINISH
A*	0	4	0	4
B*	4	8	4	8
C	4	7	10	13
D	7	10	13	16
E	10	11	16	17
F*	8	10	8	10
G	8	9.5	9.5	11
H	9.5	13.5	11	15
I*	10	15	10	15
J*	15	16	15	16
K*	15	16	15	16
L*	16	17	16	17

*Critical activity.

Looking at the results, we can see that there are two critical paths: **A–B–F–I–J–L** and **A–B–F–I–K–L.** The critical paths are both 17 weeks long, with the next longest paths being 15.5 weeks.

To meet the 15-week deadline, Lance must make sure that *all* paths are less than or equal to 15 weeks. Table 14.12 shows the crashing logic. First, Lance crashes activity **I** by 1 week, bringing both critical paths down to 16 weeks. Next, Lance crashes activity **I** by another week and **H** by 1 week. If Lance did not crash activity **H,** then two new paths (**A–B–G–H–J–L** and **A–B–G–H–K–L**) would become critical at 15.5 weeks, and the project would miss the deadline. The total crashing costs are $1,000 + $1,000 + $2,000 = $4,000.

TABLE 14.12 Crashing Logic for the GriddleIron Project

PATH	ORIGINAL LENGTH (WEEKS)	CRASH I 1 WEEK	CRASH I ANOTHER WEEK, AND CRASH H 1 WEEK
A–B–F–I–J–L	17*	16*	15*
A–B–F–I–K–L	17*	16*	15*
A–B–G–H–J–L	15.5	15.5	14.5
A–B–G–H–K–L	15.5	15.5	14.5
A–C–D–E	11	11	11

*Critical path.

DISCUSSION QUESTIONS

1. Visit the Web site for the Project Management Institute at **www.pmi.org.** What types of educational material are available for project managers? What types of professional certification programs are available? What do you think a professional project manager does?

2. In what businesses would you expect project management skills to be most important? In what businesses would you expect them to be least important?
3. What are the main advantages of using a network-based approach to project management rather than a Gantt chart? Under what circumstances might a Gantt chart be preferable to a network-based approach?
4. Why do you think it is important for project planners to revisit the network diagram as time goes on?

PROBLEMS

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

Problems for Section 14.3: Project Management Tools

1. Consider the following project activities:

ACTIVITY	DURATION (DAYS)	PREDECESSORS
A	3	None
B	2	None
C	6	A
D	1.5	A, B
E	2.5	C, D
F	3.5	D
G	4	E, F

 a. (*) Draw the project network diagram.
 b. (*) Identify all the paths through the network and their lengths.
 c. (**) Identify all the critical activities and path(s). How long will the entire project take?
 d. (**) Management would like to complete the project in less than 12 weeks. Management has determined that activity **C** can be crashed 4 weeks, for a total cost of $10,000. No other activities can be crashed. Will crashing activity **C** meet management's goal of less than 12 weeks? Why or why not?

2. Consider the following project activities:

ACTIVITY	DURATION (DAYS)	PREDECESSORS
A	1	None
B	2	None
C	1.5	None
D	3	A, B
E	2.5	C
F	1.5	D, E
G	4	F
H	2	F

 a. (*) Draw the project network diagram.
 b. (*) Identify all the paths through the network and their lengths. Are there any activities that are on *all* paths?
 c. (**) Identify all the critical activities and path(s). How long will the entire project take?
 d. (**) Every day the project goes on costs the company $5,000 in overhead costs. One of the managers responsible for carrying out activity **E** feels she can crash the activity by 1 week through the use of overtime. The cost would be only $2,500. Should the company do it? Why or why not?

3. Consider the following project activities:

ACTIVITY	DURATION (DAYS)	PREDECESSORS
A	4	None
B	3	A
C	7	A
D	9	A
E	8	A
F	7	B
G	6	C
H	13	C
I	4	D, E
J	12	E
K	1	E
L	5	F, G, H
M	4	I, J, K
N	5	L, M

 a. (*) Draw the project network diagram.
 b. (*) Identify all the paths through the network and their lengths.
 c. (**) Identify all the critical activities and path(s). How long will the entire project take?
 d. (**) After you complete part b and before you perform the forward and backward passes, you should already be able to tell that activities **A** and **N** are on the critical path(s). Why?
 e. (**) After constructing the project network diagram, management comes up with the following information regarding how many days certain activities can be crashed and at what cost:

ACTIVITY	NUMBER OF DAYS ACTIVITY CAN BE CRASHED	CRASH COST PER DAY
C	3	$1,000
D	3	$2,500
E	2	$5,000
G	1	$1,000
H	3	$3,000
J	2	$2,000

Suppose that every day the project goes on costs the company $3,500. How many days should management crash the project? What activities should it crash? What is the new project length?

4. Consider the following project activities:

ACTIVITY	DURATION (WEEKS)	PREDECESSORS
A	4	None
B	5	None
C	7	**B**
D	3	**A, C**
E	6	**B**
F	6	**D**
G	8	**D**
H	4	**E, G**

a. (*) Draw the project network diagram.
b. (*) Identify all the paths through the network and their lengths.
c. (**) Identify all the critical activities and path(s). How long will the entire project take?
d. (**) Which activity or activities have the most slack? What are the practical implications of this slack?
e. (**) Management has determined that the project must be completed in 25 weeks or less and that "cost is no object." How many paths will need to be crashed in order to meet this goal? Which activities do not need to be considered for crashing?
f. (**) Just before starting the project, someone points out that (1) activity **A** really needs to be done before activity **C**, and (2) activity **C** needs to be completed before activity **G** can start. What is the impact on the expected length of the project?

5. Spartan Cabinets is thinking of offering a new line of cabinets. The project activities are as follows:

ACTIVITY	DURATION (WEEKS)	PREDECESSORS
A Hire workers	8	None
B Install equipment	6	None
C Order materials	3	None
D Test equipment	4	**B**
E Train workers	6	**A, B**
F Run pilot tests	5	**C, D**

a. (**) Identify all the paths through the network and their lengths. Which activities "start" one or more paths? Which activities "end" a path? How will those activities affect *ES*/*EF* and *LS*/*LF* calculations?
b. (**) Identify all the critical activities and path(s). How long will the entire project take?
c. (**) Suppose management of Spartan Cabinets has developed additional information regarding crashing options for the various activities:

ACTIVITY	DURATION (WEEKS)	NUMBER OF WEEKS ACTIVITY CAN BE CRASHED	CRASH COST PER WEEK
A Hire workers	8	3	$2,000
B Install equipment	6	1	4,000
C Order materials	3	1	1,000
D Test equipment	4	2	2,500
E Train workers	6	2	5,000
F Run pilot tests	5	3	3,000

(Continued)

To illustrate, activity **A** can be crashed by up to 3 weeks, at a cost of $2,000 per week. Therefore, activity **A** can be 8, 7, 6, or 5 weeks long, depending on how much money Spartan Cabinets decides to spend to crash the activity. What is the cheapest way to crash the project by 2 weeks? What is the shortest time in which the project can be completed? (Assume that cost is not a concern.)

6. After graduation, you and several of your friends decide to start a new software company. As the vice president of operations, you are in charge of several production steps, including the process of recording software onto a CD. You have identified several activities that must take place before this "burn-in" process is ready to use:

ACTIVITY	DURATION (WEEKS)	PREDECESSORS
A Consult with engineering	3.5	None
B Determine equipment layout	2	None
C Install equipment	4.5	**A, B**
D Order materials	2	**A**
E Test equipment	2	**C**
F Train employees	3	**D, E**
G Perform pilot runs	2	**F**
H Get OSHA approval	4	**E**

a. (**) Draw the project network and calculate all *ES*, *EF*, *LS*, and *LF* times.
b. (**) Every week of delay in the project costs your company $3,000. Suppose you know the following: (1) Activity **G** can be crashed by 1 week, at a cost of $1,500; (2) activity **F** can be crashed by 1 week, at a cost of only $50; and (3) activity **H** can be crashed by 1 week, at a cost of $2,000. Should you try to crash the project? If not, why not? If so, how much money will the company save?

7. For this question, consider the Gina3000 project described in Examples 14.1 and 14.2 of the textbook.

a. (***) Consider Table 14.4 and Figure 14.5. Every week the project continues costs the Courter Corporation an additional $5,000 in lost profits. The quality control manager says she can crash activity **H** from 3 weeks down to 2 weeks by working overtime. Doing so would cost an additional $2,000. Should Courter do it?
b. (***) Writing up the product specifications (activity **F**) is taking longer than expected. Assuming that no other activities have been delayed or crashed, how many weeks can activity **F** be delayed without delaying the entire project?

CASE STUDY

Viva Roma!

Certe, toto, sentio nos in kansate non iam adesse.

Robert Curtis had just been hired into his first academic job as an assistant professor of classics at Topeka State University. One day in September 2020, not long after Robert had started, the department head came to talk to him.

> *Bob, I know it's a little sudden and we usually don't ask new assistant professors to handle such a task, but I'd like you to put together our summer study abroad program in Rome. Professor Wurst has done it for the past 10 years, but he won't be able to this year. Plan on about 15 to 20 students. The program usually lasts about a month, going from mid-June to mid-July, but the college is usually flexible on the exact dates. So what do you think?*

Even though he was new, Robert thought working on this project would be a great opportunity, and he started to think about what he should do next. He had never put together such a trip before, so it made sense to start by listing all the different activities that had to take place to get the trip planned in time. Robert wanted to post the complete information packet by March 31, 2021, which would give prospective students plenty of time to plan for the trip and meet the May 15 registration deadline.

The first thing Robert had to do was negotiate the exact starting and ending dates with the college, as well as make a rough estimate of the per-student costs. Specifically, Robert needed to know when the students would leave and when they would be expected to return to the United States. Robert felt he could do all this within one week.

Once Robert had these date and cost targets, he would then need to develop a daily schedule of the sites to visit, including any trips outside the Rome area (such as to Florence or Naples). Robert knew this would take a little time; museums and historical sites in Italy do not keep typical business hours, and some sites might even be closed for repair. Robert felt that this would take at least three weeks.

With a detailed schedule in hand, Robert would then have to make air transportation arrangements (one week) and local transportation arrangements (about one week) and select the pensiones to stay in during the trip (three weeks). Because Robert knew a lot of the time would be spent playing "email tag" with various people, all three of these activities could go on simultaneously.

Finally, Robert thought he would need to give himself a few weeks to finalize any loose ends. For example, he might learn that there were no rooms available during the time he wanted to schedule a side trip to Herculaneum, resulting in the need to adjust the schedule and other arrangements. With the finalized plans and costs in place, Robert would then need to develop and post the online information packet for students (one week).

Questions

1. What are the important time milestones for this project?
2. Given these time milestones, when should Robert start on the project? Draw a network diagram and determine the earliest and latest starting and finishing times for all activities. From a scheduling perspective, which activities are critical?
3. Comment on the time estimates for the various activities. Should Robert give himself more time? What are the pros and cons of doing so? Are there any pitfalls to starting too early? Where might he get good estimates of these times?

REFERENCES

Books and Articles

Krajewski, L., Malhotra, M., and Ritzman, L., *Operations Management: Processes and Supply Chains,* 11th ed. (Upper Saddle River, NJ: Prentice Hall, 2015).

Project Management Institute, *A Guide to the Project Management Body of Knowledge* (PMBOK®), 5th ed. (Newtown Square, PA: Project Management Institute, 2013).

Internet

Meridian Energy, "Te Apiti Wind Farm," **www.meridianenergy.co.nz/about-us/our-power-stations/wind/te-apiti.**

New Zealand Wind Energy Association, "Te Apiti Wind Farm," **www.windenergy.org.nz/te-apiti-wind-farm.**

Project Management Institute, **www.pmi.org.**

Project Management Institute, "New Zealand Wind Farm: Completed On-Time and within Budget Despite Record Storms," **www.pmi.org/Business-Solutions/~/media/PDF/Case%20Study/Case_New%20Zealand%20Wind%20Farm.ashx.**

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CHAPTER
fifteen

Developing Products and Services

CHAPTER OUTLINE

CHAPTER OBJECTIVES

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

- Explain why product design is important to the success of a business.
- Describe the six dimensions of product design that are of particular interest to operations and supply chain managers.
- Describe the five phases of product and service development and explain the difference between sequential development and concurrent engineering.
- Discuss the different roles played by areas such as marketing, engineering, and suppliers during the development process.
- Describe some of the most common approaches to improving product and service designs, including the Define–Measure–Analyze–Design–Verify (DMADV) process, quality function deployment (QFD), design for manufacturability (DFM), and target costing.

CASTING A NET AROUND MALARIA

Irene Abdou/Alamy Stock Photo

Henry Kimuyu, three, and his brother Vincent, eight, rest after school under an insecticide-treated mosquito net at their home in Nairobi, Kenya.

Since its symptoms were first reported in Chinese medical writings more than 4,000 years ago,[1] malaria has presented an enormous health challenge. Recent efforts to eradicate the mosquito-borne parasitic disease have met with some success: In 2016, the World Health Organization (WHO) reported that the number of cases fell from an estimated 244 million in 2005 to 212 million in 2015, while the estimated number of deaths due to malaria decreased from 985,000 in 2000 to 429,000 in 2015.[2] Malaria has had a disproportionately large impact in sub-Saharan Africa, where approximately 40% of public health expenditures can be traced back to the disease.

One relatively new product that has been used to fight the spread of malaria combines an old idea with state-of-the-art textiles and chemistry: bed nets impregnated with insecticides. One of the companies producing such bed nets is Vestergaard, a European company specializing in complex emergency response and disease control products. Recently, Vestergaard Frandsen introduced the PermaNet 3.0 Combination Net, which slowly releases insecticide embedded in the yarn onto the surface of the netting. The result is a bed net that is effective at killing mosquitoes, even after multiple washings.[3]

While the PermaNet product concept is a good one, producing and then distributing the bed nets to where they are needed presents some significant operations and supply chain challenges for Vestergaard. For one thing, the prevailing price for similar bed nets is $5 to $7 a unit. Such a low price target puts significant cost pressure on operations and supply chain activities. Second, Vestergaard must build and maintain a network of suppliers and manufacturers capable of providing the needed volumes of specialized insecticides and textiles required to produce the PermaNet bed nets. A third challenge is effectively and efficiently distributing the bed nets in countries with limited transportation infrastructures and scattered populations.

While overcoming these operations and supply chain challenges is not easy, the payoff is much more than financial. As United Nations Secretary General Ban Ki-Moon wrote in the introduction to the *World Malaria Report 2010*:[4]

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[1]Centers for Disease Control and Prevention, *The History of Malaria, an Ancient Disease*, **www.cdc.gov/malaria/about/history/.**

[2]World Health Organization, *World Malaria Report 2016*, **http://apps.who.int/iris/bitstream/10665/252038/1/9789241511711-eng.pdf?ua=1.**

[3]Vestergaard, *PermaNet*, **www.vestergaard.com/our-products/permanet.**

[4]World Health Organization, *World Malaria Report 2010*, **www.who.int/malaria/world_malaria_report_2010/en/index.html.**

Two years ago, I called for universal coverage of malaria-control interventions by the end of 2010, in order to bring an end to malaria deaths by 2015. The response was impressive. Enough insecticide-treated mosquito nets have been delivered to Sub-Saharan Africa to protect nearly 580 million people. . . . An additional 54 million nets are slated for delivery in the coming months, bringing the goal of universal coverage within reach. . . . The World Malaria Report 2010 *shows what is possible when we join forces and embrace the mission of saving lives.*

INTRODUCTION

Vestergaard's experiences highlight some of the issues companies face when developing new products and services. But how do companies go about managing the development process, and what roles do various parties within and outside the firm play? These questions are the subject of this chapter. First, we discuss the role of product and service development in today's businesses, emphasizing the impact new and enhanced products and services have on a firm's ability to compete.

We then turn our attention to the actual process by which companies develop new products and services or modify existing ones. We pay special attention to operations and supply chain perspectives on product and service design: What are the important considerations? What role do the purchasing function and suppliers play? What tools and techniques are companies using to enhance the product development effort?

Product Design and the Development Process

Product design
The characteristics or features of a product or service that determine its ability to meet the needs of the user.

Product development process
According to the PDMA, "a disciplined and defined set of tasks, steps, and phases that describe the normal means by which a company repetitively converts embryonic ideas into salable products or services."

It's important for us to distinguish between product design and the product development process. **Product design** can be thought of as the characteristics or features of a product or service that determine its ability to meet the needs of the user. In contrast, according to the Product Development and Management Association (PDMA), the **product development process** is "a disciplined and defined set of tasks, steps, and phases that describe the normal means by which a company repetitively converts embryonic ideas into salable products or services."[5] In this chapter, we focus on how product and service design affects operations and supply chain activities and what role operations and supply chains play in the development process. We use the term *product design* to refer to the development of both intangible services and physical products. As you can probably guess, product development is by necessity a cross-functional effort affecting operations and supply chain activities, as well as marketing, human resources, and finance.

Four Reasons for Developing New Products and Services

There are least four reasons why a company might develop new products or services or update its existing ones. The first is straightforward: *New products or services can give firms a competitive advantage in the marketplace*. Consider the problem facing H&R Block a few years ago: How do you attract customers when faced with increasing competition from other tax preparation firms as well as PC-based software packages that can help people do their tax returns on their own? You do it by providing new and distinctive services such as PC-based will kits, refund anticipation loans (RALs), and a Web page that provides customers free and for-fee tax preparation software, as well as valuable information in multiple languages.

Not all product development efforts *directly* benefit the customer, however. This leads to our second reason for developing new products or services: *New products or services provide benefits to the firm*. Samsung might redesign one of its products so it has fewer parts and is easier to assemble. Even though the product might look and function exactly as before, the result is improved assembly productivity and lower purchasing and production costs. Samsung might or might not share these savings with the customer.

[5]Product Development and Management Association, *The PDMA Glossary for New Product Development*, **www.pdma.org/p/cm/ld/fid=360#P.**

CNP Collection/Alamy Stock Photo

Owe Andersson/Alamy Stock Photo

Honda is a leader in the design and manufacture of gas-powered engines. These strengths have allowed the company to enter a wide range of markets, including automobiles, motorcycles, personal watercraft, and portable generators.

Third, *companies develop new products or services to exploit existing capabilities*. An excellent example is Honda. Honda progressed from making and selling motorcycles, to automobiles, lawn equipment, and personal watercraft. In retrospect, it is easy to see that Honda has built on its core competencies in the design and production of gas-powered vehicles. It will be interesting to see how Honda maintains its advantage as more products shift to alternative fuels.

Fourth, *companies can use new product development to block out competitors*. Consider the case of Gillette.[6] By the early 1990s, Gillette had grown tired of spending millions to develop a new razor blade, only to have competitors introduce cheaper (and poorer-quality) replacement blades within a few months. Gillette now makes a point of designing new razors so that they not only provide customers with a superior shave but are also difficult for competitors to copy. Developing new products like this requires a great deal of coordination with the manufacturing arm of the firm. Of course, a firm might have multiple reasons for developing a new product or service or for updating existing ones. But regardless of the underlying reasons, the development effort must be consistent with the strategy of a firm.

15.1 OPERATIONS AND SUPPLY CHAIN PERSPECTIVES ON DESIGN

If someone were to ask you, as a consumer, what the important dimensions of product design are, you might mention such aspects as functionality, aesthetics, ease of use, and cost. Operations and supply chain managers also have an interest in product design because ultimately these managers will be responsible for providing the products or services on a day-to-day basis. To understand the operations and supply chain perspective, think about a new electronic device. It is one thing for a team of highly trained engineers to build a working prototype in a lab. It's quite another thing to make millions of devices each year, using skilled and semiskilled labor, coordinate the flow of parts coming from all over the world, and ship the devices so that they arrive on time, undamaged, and at the lowest possible cost. Yet, this is exactly what the operations and supply chain managers at companies such as Lenovo and Apple are doing.

The interest of operations and supply chain management in *service* design is even greater. This is because the service design is often the operations process itself. To take an example from physical distribution, when a transportation firm agrees to provide global transportation services to a large customer, it has to make decisions regarding the number of trucks, ships, or airplanes required; the size and location of any warehousing facilities; and the information systems and personnel needed to support the new service.

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[6]L. Ingrassia, "Taming the Monster: How Big Companies Can Change: Keeping Sharp: Gillette Holds Its Edge by Endlessly Searching for a Better Shave," *Wall Street Journal*, December 10, 1992.

With this in mind, the operations and supply chain perspective on product design usually focuses on six dimensions:

1. Repeatability
2. Testability
3. Serviceability
4. Production volumes
5. Product costs
6. Match between the design and existing capabilities

Repeatability, Testability, and Serviceability

Repeatability, testability, and serviceability are dimensions of product design that affect the ability of operations to deliver the product in the first place and to provide ongoing support afterward. *Repeatability* deals with the question, Are we capable of making the product over and over again, in the volumes needed? This is addressed through robust design. The PDMA describes **robust design** as "the design of products to be less sensitive to variations, including manufacturing variation and misuse, increasing the probability that they will perform as intended."[7] Product designs that are robust are better able to meet tolerance limits (see Chapter 5), making it easier for the operations and supply chain functions to provide good products on an ongoing basis.

Robust design
According to the PDMA, "the design of products to be less sensitive to variations, including manufacturing variation and misuse, increasing the probability that they will perform as intended."

Testability
The ease with which critical components or functions can be tested during production.

Serviceability
The ease with which parts can be replaced, serviced, or evaluated.

Testability refers to the ease with which critical components or functions can be tested during production. Suppose for a moment that your company manufactures expensive electronics equipment. The manufacturing process consists of a series of steps, each of which adds parts, costs, and value to the product. If a $5 component has gone bad, you want to find this out before you assemble it with some other component or put together the final product.

Serviceability is similar to testability. In this case, serviceability refers to the ease with which parts can be replaced, serviced, or evaluated. Many modern automobiles require that the engine be unbolted from the car frame and tilted forward before the spark plugs can be changed—hardly a plus for shade-tree mechanics! On the other hand, all new cars have computer diagnostics systems that allow mechanics to quickly troubleshoot problems.

Serviceability is of particular interest to organizations that are responsible for supporting products in the field. When products are easy to service, costs can be contained, and service times become more predictable, resulting in higher productivity and greater customer satisfaction.

Production Volumes

Once a company decides to go forward with a new product or service, it becomes the job of operations and supply chain managers to make sure that the company can handle the resulting volumes. This responsibility might mean expanding the firm's own operations by building new facilities, hiring additional workers, and buying new equipment. It might also require joint planning with key suppliers.

As we saw in Chapter 3, the expected volume levels for a product or service also affect the *types* of equipment, people, or facilities needed. Highly automated processes that are too expensive and inflexible for low-volume custom products can be very cost-effective when millions of units will be made.

Product Costs

One study concluded that 80% of the cost for a typical product is "locked in" at the design stage. In other words, any effort to "tweak" costs later on will be limited by decisions that were made early in a product's life. Given the importance of costs in operations and supply chain activities,

[7] Product Development and Management Association, *The PDMA Glossary for New Product Development.*

it is not surprising that operations and supply chain managers have a vested interest in addressing cost before the product design has been finalized.

For our purposes, we can think of products and services as having obvious and hidden costs. Obvious costs include such things as the materials required, the labor hours needed, and even the equipment costs needed to provide a particular service or product. These costs are usually the easiest ones to see and manage (i.e., we can track material usage, machine time, and the amount of direct labor that goes into our products or services).

Hidden costs are not as easy to track, but can have a major impact nonetheless. Hidden costs are typically associated with the overhead and support activities driven by some aspect of design. There are numerous drivers of hidden costs, but we will talk about three to make the point:

1. The number of parts in a product
2. Engineering changes
3. Transportation costs

Think about the activities that are driven by the number of parts used in a product, such as a washing machine. Engineering specifications must be developed for each part. The manufacturer must identify a supplier for each part and then place and track orders. Furthermore, the manufacturer must monitor the inventory levels of each part in its manufacturing plants and service support centers. Even if the manufacturer stops selling the washing machine after five years, it must continue to stock each part for years to come. All these activities represent hidden costs driven by the number of parts. Clearly, the manufacturer has an incentive to reduce the number of parts in a washing machine and to share parts across as many products as possible.

Engineering change
A revision to a drawing or design released by engineering to modify or correct a part.

There are also hidden costs associated with engineering changes to a product. An **engineering change** is a revision to a drawing or design released by engineering to modify or correct a part.[8] Returning to our washing machine example, suppose the manufacturer decides to make improvements to a part once the washing machine has been on the market for a few years. Suppliers, plants, and service support centers have to be notified of the change, and inventories have to be switched over from the old part to the new one. Yet the manufacturer will still have to keep track of information on both parts for years to come. Clearly, the manufacturer has a real financial incentive to design the part right the first time.

Products can also be designed to minimize transportation costs. Oddly shaped or fragile products can quickly drive up transportation costs. In contrast, products that can be shipped in standardized containers to take advantage of lower transportation rates can hold down the costs of distribution. NordicTrack engineers designed the Walk-Fit treadmill so that the electronics could be shipped to the customer separately from the treadmill. This was important because these components were made in different parts of the world. But there was another benefit as well: By separating the electronics from the treadmill, engineers allowed the bulky treadmill to be shipped at a lower per-pound rate. If the relatively fragile electronics had been included with the bulkier treadmill, the entire product would have had to be shipped at a much higher rate.

Match with Existing Capabilities

Finally, operations and supply chain managers are always concerned with how well new products or services match up with existing products or capabilities. A new product or service that allows a manufacturer to use existing parts and manufacturing facilities is usually easier to support than one that requires new ones. Similarly, services that exploit existing capabilities are especially attractive. An excellent example is the online tracking service that FedEx provides to its customers. In fact, this service was built on an existing capability supported by FedEx's internal tracking software.

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

SUPPLY CHAIN CONNECTIONS

HOW HARD IS IT TO MAKE A COOKIE?

Nabisco Biscuit Co. makes cake and snack products that have become American classics, like Oreo, Chips Ahoy!, and Barnum's Animal Crackers. Another Nabisco classic is the story of the debut of its SnackWell's line of cookies and cakes. More than a year after launching the fat-free chocolate-and-marshmallow Devil's Food Cookie Cake in the early 1990s, Nabisco still couldn't meet consumer demand, setting off rumors of store rationing and fights among frenzied customers in search of a "healthy" snack. How hard could it be to make a cookie?

It turned out to be very hard indeed. Nabisco's senior director of operations services at the time claimed "the Devil's Food Cookie Cake is the hardest one we make." Because the cookie's center, unlike simpler confections, was covered with marshmallow all around and then drenched in chocolate icing, it would get stuck to a conventional conveyor belt. The solution was a "pin trolley system," invented in the 1920s, which set each cookie-cake center on a tiny upright pin mounted on a trolley. A chain pulled the trolley along, taking four hours to cover a mile-long track winding through the bakery while the centers were coated with marshmallow and chocolate and allowed to air-dry in between. (Because the cookie was fat-free, the company couldn't chill it to shorten the drying time.) On top of having a painfully slow manufacturing process for its product, for a time Nabisco had pin-trolley equipment available in only one bakery in South Dakota. The initial shortage was so great that when it was first introduced, the cookie was sold only in the Northeast United States.

Nabisco has long since ramped up its production of the Devil's Food Cookie Cake, and over the years the product has had to prove itself against up-and-coming competitors in the low-calorie snack-food market. Nabisco's current marketing plans call for a renewed advertising campaign for the SnackWell brand, and it's a safe bet there will be plenty of Devil's Food Cookie Cakes on the shelves this time around.

Sources: Based on the company website, **www.nabiscoworld.com,** accessed September 26, 2011; Andrew Adam Newman, "Snackwell's Nudges Up the Portion Pack," *New York Times*, April 20, 2011, **www.nytimes.com/2011/04/21/business/media/21adco.html;** K. Deveny, "Man Walked on the Moon but Man Can't Make Enough Devil's Food Cookie Cakes," *Wall Street Journal*, September 28, 1993.

It may *seem* obvious that companies should consider such factors as production volumes and existing capabilities when designing new products or services. But what happens if they don't? Well, Nabisco ran into exactly this problem in 1993, when it introduced SnackWell's Devil's Food Cookie Cakes. The *Supply Chain Connections* box reveals a classic example of what can happen when the operations and supply chain perspective is not adequately considered when designing a new product.

15.2 THE DEVELOPMENT PROCESS

In the previous section, we talked about some product design dimensions of particular interest to operations and supply chain managers. But there are other perspectives to consider, including those of the final customer, marketing, engineering, and finance, to list just a few. How do firms go about designing products and services that incorporate all these perspectives? And how do they move from the idea stage to the actual launch of a new product or service? This section describes a model of the product development process and discusses the organizational roles played by different functional areas and supply chain partners.

A Model of the Development Process

All of us have experienced products or services that for some reason stood out from the competition—a tablet computer that was easier to use or more powerful than previous models, an airline seat that was more comfortable, or an online financial service that allowed us to check our portfolios and initiate trades 24 hours a day.

Good design does not happen by accident. Rather, it requires a coordinated effort supported by many individuals, both within and outside a firm. Table 15.1 offers one view of the

TABLE 15.1
Phases of Product and Service Development

FUNCTIONAL ACTIVITIES	CONCEPT DEVELOPMENT	PLANNING	DESIGN AND DEVELOPMENT	COMMERCIAL PREPARATION	LAUNCH
Engineering	Propose new technologies; develop product ideas	Identify *general* performance characteristics for the product or service; identify underlying technologies	Develop *detailed* product specifications; build and test prototypes	Resolve remaining technical problems	Evaluate field experience with product or service
Marketing	Provide market-based input; propose and investigate product or service concepts	Define target customers' needs; estimate sales and margins; include customers in development effort	Conduct customer tests; evaluate prototypes; plan marketing rollout	Train sales force; prepare sales procedures; select distribution channels	Fill downstream supply chain; sell and promote
Operations and supply chain functions	Scan suppliers for promising technologies/capabilities	Develop initial cost estimates; identify key supply chain partners	Develop *detailed* process maps of the operations and supply chain flows; test new processes	Build pilot units using new operations; train personnel; verify that supply chain flows work as expected	Ramp up volumes; meet targets for quality, cost, and other performance goals

Source: Based on S. Wheelwright and K. Clark, *Revolutionizing Product Development* (New York: Free Press, 1992).

development process. The table divides the development process into five phases, paying particular attention to the roles played by the operations and supply chain functions, as well as by marketing and engineering.

Concept development phase
The first phase of a product development effort. Here a company identifies ideas for new or revised products and services.

In the **concept development phase,** a company identifies ideas for new or revised products and services. As Table 15.1 suggests, these ideas can come from a variety of sources, not just from customers. For example, engineering might identify a new material that can reduce the weight and cost of a product, even before marketing or the customer knows about it. The operations and supply chain functions have a role to play here as well: Purchasing personnel might look at potential suppliers to see if they have any promising new technologies or capabilities that could be turned into a new product or service.

Planning phase
The second phase of a product development effort. Here the company begins to address the feasibility of a product or service.

If a concept is approved, it will pass on to the **planning phase,** where the company begins to address the feasibility of a product or service. Customers are often brought in at this stage to evaluate ideas. Engineering might begin to identify the general performance characteristics of the product or service and the process technologies needed to produce it. Marketing will start to estimate sales volumes and expected profit margins. Operations and supply chain personnel might start identifying the key supply chain partners to be involved. Many ideas that look good in the concept development phase fail to pass the hurdles set at the planning phase. A product may be too costly to make, may not generate enough revenues, or may simply be impossible to produce in the volumes needed to support the market.

Design and development phase
The third phase of a product development effort. Here the company starts to invest heavily in the development effort and builds and evaluates prototypes.

Ideas that do clear the hurdles go on to the **design and development phase,** during which the company starts to invest heavily in the development effort. In this phase, the company builds and evaluates prototypes of the product or service. Product prototypes can range from simple Styrofoam mock-ups to fully functional units. Service prototypes can range from written descriptions to field tests using actual customers. At the same time, operations and physical distribution begin to develop detailed process maps of the physical, information, and monetary flows that will need to take place in order to provide the product or service on a regular basis (Chapter 4). They may even start to develop quality levels for key process steps (Chapter 5). The design and development phase is complete when the company approves the final design for the product and related processes.

Commercial preparation phase
The fourth phase of a product development effort. At this stage, firms start to invest heavily in the operations and supply chain resources needed to support the new product or service.

The **commercial preparation phase** is characterized by activities associated with the introduction of a new product or service. At this stage, firms start to invest heavily in the operations and supply chain resources needed to support the new product or service. This may mean new facilities, warehouses, personnel, and even information systems to handle production requirements. Obviously, this phase will go more smoothly if the new product or service can build on existing operations and supply chain systems. If new supply chain partners are required or if new technologies are needed, commercial preparation and launch can be much more difficult and expensive.

Launch phase
The final phase of a product development effort. For physical products, this usually means "filling up" the supply chain with products. For services, it can mean making the service broadly available to the target marketplace.

The last phase is the **launch phase.** For physical products, this usually means "filling up" the supply chain with products. For services, it can mean making the service broadly available to the target marketplace, as in the case of cellular service. In either case, operations and supply chain managers must closely monitor performance results to make sure that quality, cost, and delivery targets are being met and must take corrective action when necessary.

Sequential Development versus Concurrent Engineering

Sequential development process
A process in which a product or service idea must clear specific hurdles before it can go on to the next development phase.

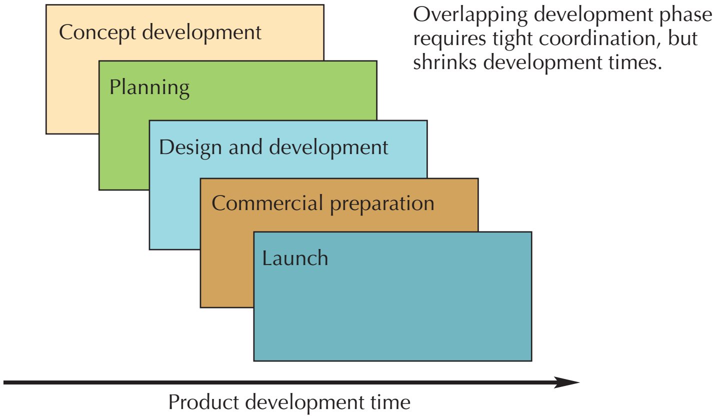
The development model in Table 15.1 outlines a sequential development process. A **sequential development process** is one in which a product or service idea must clear specific hurdles before it can go on to the next development phase. The result is that while many ideas may be considered at the relatively inexpensive concept development phase, few make it to the commercial development and launch phases, where significant resources have to be invested. Steven Wheelright and Kim Clark of the Harvard Business School describe this process as the *development funnel*.

Concurrent engineering
An alternative to sequential development in which activities in different development stages are allowed to overlap with one another, thereby shortening the total development time.

An alternative to sequential development is concurrent engineering. As the name implies, **concurrent engineering** allows activities in different development stages to overlap with one another, thereby shortening the total development time. For example, engineering may begin to build and test prototypes (design and development phase) even before the general product characteristics have been finalized (planning phase). In contrast to a sequential development process, in which there is a clear handoff from one stage to the next, concurrent engineering requires constant communication between participants at various stages in the development effort. Figure 15.1 illustrates the idea.

Concurrent engineering helps reduce development times by forcing development teams to agree on critical product and process characteristics *early* in the development process, usually in the concept through design and development phases. These broad characteristics—costs, size, materials, markets to be served, and so on—provide clear guidance and boundaries for later activities. Returning to our engineering example, the *only way* engineers can start to build prototypes before the product characteristics are finalized is if there is *general* agreement regarding the characteristics of the new product (size, basic features, etc.). When this isn't the case, firms will need to follow a more sequential approach.

FIGURE 15.1
Concurrent Engineering



15.3 ORGANIZATIONAL ROLES IN PRODUCT AND SERVICE DEVELOPMENT

Product or service development is almost always a cross-functional effort. Table 15.1 shows how various parties contribute to the development effort in different ways. How well the different functions coordinate their efforts goes a long way toward determining the success of any development effort. Marketing, for example, might need to work with engineering to know what product features are technologically feasible. Purchasing then might help identify outside sources for needed inputs or services. Let's take a moment to discuss how different functions contribute to the development effort.

Engineering

Engineering provides the expertise needed to resolve many of the technological issues associated with a firm's products or services. Some of these issues center on the actual design of a product or service. A product engineer might be asked to design a lightweight yet durable outer casing for a new smartphone. Or a team of civil and electrical engineers might be asked to design a network of transmission towers for the relay of cell phone signals.

Other issues center on operational and supply chain considerations. Industrial engineers, for instance, might develop specifications for the manufacturing equipment needed to make the smartphone casings or transmission towers. Packaging engineers might be asked to develop shipping containers that strike a balance between cost and protection against damage.

Marketing

In most firms, marketing has primary responsibility for understanding what goes on in the marketplace and applying that knowledge to the development process. Who buys our company's products or services, and how much will they pay? Who are our company's competitors, and how do their products and services stack up against ours? How large is the market for a particular product or service? Marketing professionals use a variety of research techniques to answer such questions, including surveys, focus groups, and detailed market studies. When it comes to really understanding what customers want, many companies would be lost without marketing's input.

But marketing's role goes beyond providing information in the early phases of the development process. Marketing also has to select distribution channels, train sales personnel, and develop selling and promotional strategies.

Accounting

Accounting plays the role of "scorekeeper" in many companies. Not only do accountants prepare reports for the government and outside investors, they are also responsible for developing the cost and performance information many companies need to make intelligent business decisions. How much will a new product or service cost? How many hours of labor or machine time will be needed? The answers to these types of questions often require input from the firm's accountants.

Finance

The role of finance in product and service development is twofold. First, finance establishes the criteria used to judge the financial impact of a development effort. How much time will pass before our company recoups its investment in a product or service? What is the expected rate of return? How risky is the project? Once a company decides to proceed with the development of a product or service, it is the responsibility of finance to determine exactly how the company will acquire the needed capital.

Sergii Moscaliuk/Fotolia

Forma designs of Raleigh, North Carolina, improved the grips of screwdrivers. Even small changes such as this can make a big difference in the marketplace.

Designers

Designers can come from a variety of educational backgrounds—from engineering, design, and business schools, to name a few. Their role is one of the least understood aspects of the development process. One myth is that designers only do *product* design. But they do much more than that. They create identities for companies (logos, brochures, etc.), environments (such as buildings, interiors, and exhibits), and even service experiences. To make cell towers blend in with the environment, for example, designers have camouflaged the giant poles as trees or added decorative latticework.

A second myth is that designers simply make something "look good." This suggests that design is all form and no content. Yet consider an apparently simple handheld tape measure redesigned by Forma Design of Raleigh, North Carolina. As part of the redesign effort, Forma changed the tape measure so that the thumb presses against the index finger to work the tape measure's locking mechanism. Before that, users had to apply force between the thumb and *little* finger. If you try pushing your thumb against your little finger and then your index finger, you can see for yourself that the new design results in considerably less hand fatigue. Designers also work with schedules and constraints, just like other professionals. For example, in the redesign of the tape measure, Forma was not allowed to change any of the internal mechanisms.

Purchasing

Purchasing deserves special mention because it plays several important roles in product development. As the main contact with suppliers, purchasing is in a unique position to identify the best suppliers and sign them up early in the development process. Many purchasing departments even have databases of preapproved suppliers. The process of preapproving suppliers for specific commodities or parts is known as **presourcing.**

Presourcing
The process of preapproving suppliers for specific commodities or parts.

Another role purchasing plays is that of a consultant with special knowledge of material supply markets. Purchasing personnel might recommend substitutes for high-cost or volatile materials or standard items instead of more expensive custom-made parts. Finally, purchasing plays the role of monitor, tracking forecasts of the prices and long-term supply of key materials or monitoring technological innovations that might affect purchasing decisions.

Suppliers

Suppliers can bring a fresh perspective to the table, thereby helping organizations see opportunities for improvement they might otherwise miss. Teaming up with suppliers can also help organizations divide up the development effort, thereby saving time and reducing financial risks. Boeing, for instance, uses outside suppliers to develop many of the key components and subassemblies for its jets. If Boeing tried to develop a jet on its own, the project would cost considerably more money and take much longer.

Bringing suppliers into the development effort goes beyond just sharing information with them. Important suppliers should be included early in the development of a new product, perhaps even as part of the project team. The benefits of such early inclusion include gaining a supplier's insight into the development process, allowing comparisons of proposed production requirements with a supplier's existing capabilities, and allowing a supplier to begin preproduction work early.

Gray box design
A situation in which a supplier works with a customer to jointly design the product.

Black box design
A situation in which suppliers are provided with general requirements and are asked to fill in the technical specifications.

The degree of supplier participation can also vary. At one extreme, the supplier is given blueprints and told to produce to the specifications. In a hybrid arrangement, called **gray box design,** the supplier works with the customer to jointly design the product. At the highest level of supplier participation, known as **black box design,** suppliers are provided with general requirements and are asked to fill in the technical specifications.

Black box design is best when the supplier is the acknowledged "expert." For example, an automotive manufacturer may tell a key supplier that it wants an electric window motor that costs under $15, pulls no more than 5 amps, fits within a certain space, and weighs less than 2 pounds. Given these broad specifications, the supplier is free to develop the best motor that meets the automotive manufacturer's needs.

Who Leads?

Ultimately, someone or some group has to have primary responsibility for making sure the product development process is a success. But who? The answer depends largely on the nature of the development effort and the industrial setting. In high-tech firms, scientists and engineers typically take the lead. Their scientific and technological expertise is essential to developing safe, effective products that can be made in the volumes required. In contrast, at a toy producer, the technical questions usually aren't nearly as interesting as the consumers and markets themselves: What toys will be "hot" next December? How many will be sold? Marketing is, therefore, likely to have primary responsibility for managing the development effort.

15.4 APPROACHES TO IMPROVING PRODUCT AND SERVICE DESIGNS

Coordinating a product development effort while ensuring that all dimensions of performance are adequately considered is not an easy task. As a result, organizations have developed useful approaches to help accomplish these goals. The purpose of this section is to introduce you to some of the most common approaches.

DMADV (Define–Measure–Analyze–Design–Verify)

DMADV (Define–Measure–Analyze–Design–Verify)
A Six Sigma process that outlines the steps needed to create *completely new* business processes or products.

Chapter 4 introduced the Six Sigma methodology and the DMAIC (Define–Measure–Analyze–Improve–Control) approach to improving existing business processes. The Six Sigma methodology also includes a process called **DMADV (Define–Measure–Analyze–Design–Verify),** which outlines the steps needed to create *completely new* business processes or products. As with DMAIC, the DMADV process places a premium on rigorous data analysis, and depends on teams of black belts, green belts, and champions to carry it out. The five steps of DMADV are:

Step 1. *Define* the project goals and customer deliverables. Since the focus is on a *new* process or product, the Six Sigma team must properly scope the project to ensure that the effort is carried out in a timely and efficient manner. What products or services do we want to provide and to whom? How will we know when we have completed the project successfully?

Step 2. *Measure* and determine customer needs and specifications. The second step requires the team to develop a clear picture of what the targeted customers want in terms of quality, delivery, cost or other measures of interest. Market research techniques as well as quality function deployment (QFD), which we describe shortly, are employed here.

Step 3. *Analyze* the product or process options to meet the customer needs. In this step, the Six Sigma team evaluates how the various options available stack up against the customers' requirements.

Step 4. *Design* the product or process. Here, the hard work of designing the product or process, as outlined in the "Design and Development" column of Table 15.1, takes place.

Step 5. *Verify* the new product or process. Finally, the team must verify the results. Does the product or process perform as intended? Does it meet the needs of the targeted customers?

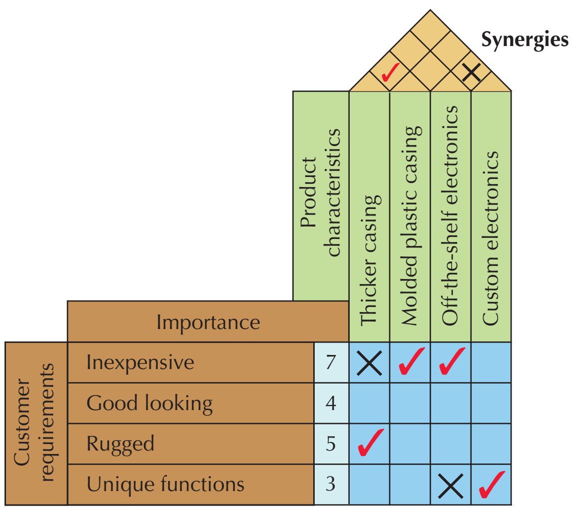
Quality Function Deployment (QFD)

Quality function deployment (QFD)
A graphical tool used to help organizations move from vague notions of what customers want to specific engineering and operational requirements. Also called the "house of quality."

One of the greatest challenges firms face when designing new products or services is moving from vague notions of what the customer wants to specific engineering or operational requirements. **Quality function deployment (QFD)** is one tool that has been developed to formalize this process. First introduced in Japan in the early 1970s, QFD became very popular in the late 1980s and continues to be used by companies.[9]

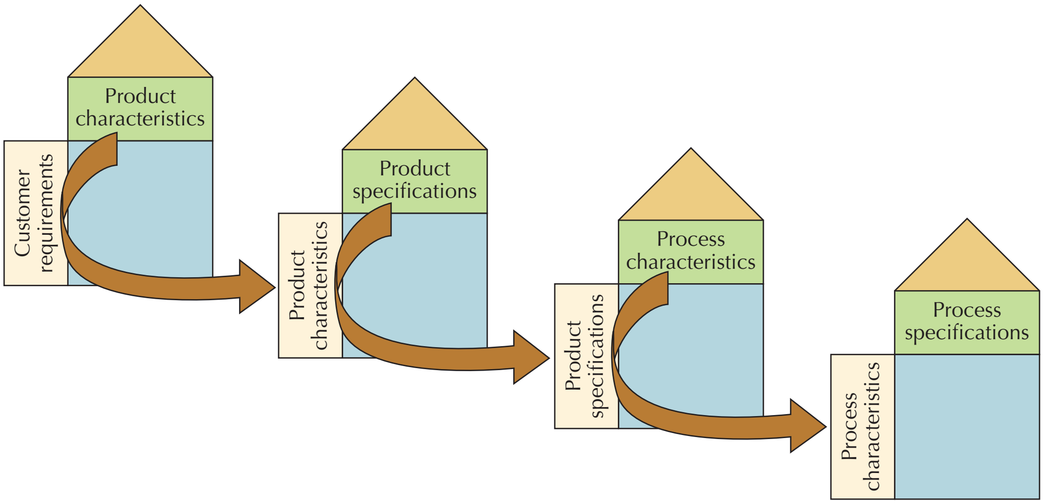
Figure 15.2 shows a simplified example of a QFD matrix for a smartphone. This matrix is sometimes called the "house of quality," due to its obvious resemblance. The left side of the matrix lists general customer requirements and their relative importance (1–10) to the target customers. Note that these requirements are stated in terms of how the product performs, not specific characteristics. Along the top is a list of specific product characteristics. The main body of the matrix shows how each of the product characteristics does or does not support the customer requirements. As you can see, there are some potential conflicts. For example, the off-the-shelf electronics characteristic is consistent with an inexpensive unit but conflicts with customers' desires for more functionality. Ultimately, a trade-off may need to be made. Finally, the "roof" of the matrix shows synergies between some of the features. Obviously, off-the-shelf electronics conflicts with customized ones. On the other hand, a molded plastic casing and a thicker casing are two product characteristics that can easily be combined.

FIGURE 15.2
QFD Matrix for a Smartphone



[9] J. Hauser and D. Clausing, "The House of Quality," *Harvard Business Review*, 66, no. 3 (May–June 1988): 63–73.

FIGURE 15.3
Using QFD Matrices to Move from Customer Requirements to Process Specifications



The matrix in Figure 15.3 moves the organization from customer requirements to broad product characteristics. But the process doesn't end here. The ultimate goal is to identify the specific manufacturing and service process steps needed to meet the customers' requirements. As a result, an organization may develop a series of QFD matrices that make the following logical linkages:

First matrix: Customer requirements → Product characteristics
Second matrix: Product characteristics → Product specifications
Third matrix: Product specifications → Process characteristics
Fourth matrix: Process characteristics → Process specifications

Figure 15.3 illustrates this idea.

In Figure 15.2, we identified "Rugged" as an important customer requirement and "Thicker Casing" as one product characteristic that would support this need. To move to *product specifications*, we need to translate "Thicker Casing" into more detailed information regarding the materials needed and the actual thickness value. Next, we have to describe the *process characteristics* needed to meet these product specifications regularly. This might include information on tolerance limits and acceptable process variability. Finally, we need to identify the specific manufacturing resources needed (e.g., "an injection molding device with computer controls") to support the process characteristics.

Computer-Aided Design (CAD) and Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM)

Computer-aided design (CAD) system
An information system that allows engineers to develop, modify, share, and even test designs in a virtual world. CAD systems help organizations avoid the time and expense of paper-based drawings and physical prototypes.

Computer-aided design/computer-aided manufacturing (CAD/CAM) system
An extension of CAD. Here, CAD-based designs are translated into machine instructions, which are then fed automatically into computer-controlled manufacturing equipment.

Advancements in information systems have also transformed the development process. In particular, **computer-aided design (CAD) systems** allow engineers to develop, modify, share, and even test designs in a virtual world. By doing so, CAD systems help organizations avoid the time and expense of paper-based drawings and physical prototypes.

Computer-aided design/computer-aided manufacturing (CAD/CAM) systems take the process a step further. Here, CAD-based designs are translated into machine instructions, which are then fed automatically into computer-controlled manufacturing equipment. Such systems allow for rapid prototyping and reduce the time and costs associated with producing one-of-a-kind pieces.

The "Design for . . . " Approaches

At a minimum, products and services must be designed to meet the needs of customers. But beyond this, organizations also want products and services to be easy to make, easy to maintain, virtually defect free (to reduce their costs as well as improve customer satisfaction), and environmentally sound. This has led to what can be called the "design for . . . " approaches to product and service design. Four critical approaches are design for manufacturability (DFM), design for maintainability (DFMt), Design for Six Sigma (DFSS), and design for the environment (DFE).

Design for manufacturability (DFM)
According to the PDMA, "the systematic consideration of manufacturing issues in the design and development process, facilitating the fabrication of the product's components and their assembly into the overall product."

Parts standardization
The planned elimination of superficial, accidental, and deliberate differences between similar parts in the interest of reducing part and supplier proliferation.

Modular architecture
According to the PDMA, a "product architecture in which each functional element maps into its own physical chunk. Different chunks perform different functions; the interactions between the chunks are minimal, and they are generally well defined."

Design for manufacturability (DFM) is "the systematic consideration of manufacturing issues in the design and development process, facilitating the fabrication of the product's components and their assembly into the overall product."[10] In general, the goal of DFM is to design a product that can be produced at consistently high quality levels, at the lowest cost, and, when possible, with existing processes.

Two ways in which organizations accomplish DFM are parts standardization and modularity. **Parts standardization** refers to the planned elimination of superficial, accidental, and deliberate differences between similar parts in the interest of reducing part and supplier proliferation. By standardizing and sharing parts across various products, companies can reduce the time and cost of developing new products and reduce the cost of the final product.

Modular architecture is another way in which organizations implement DFM. A **modular architecture** is a "product architecture in which each functional element maps into its own physical chunk. Different chunks perform different functions; the interactions between the chunks are minimal, and they are generally well defined."[11] To illustrate, consider the typical Microsoft-compatible PC. Suppose a PC retailer sells PCs that are assembled from the following module options:

- Four different system units
- Two different graphics cards
- Five different displays
- Three different printers

The visual functionality of the PC is contained within the graphics cards and displays, while the print functionality is contained within the printer. The remainder of the PC's functionality is within the system unit itself. What makes this product truly "modular" is the fact that the PC retailer can easily swap modules to make a different final configuration, as PCs use standard interfaces for plugging in displays, printers, and the like. In fact, the 14 modules above can theoretically be configured into $4 \times 2 \times 5 \times 3 = 120$ different combinations.

Design for maintainability (DFMt)
Per the PDMA, "the systematic consideration of maintainability issues over a product's projected life cycle in the design and development process."

Design for Six Sigma (DFSS)
An approach to product and process design which seeks to ensure that the organization is capable of providing products or services that meet Six Sigma quality levels—in general, no more than 3.4 defects per million opportunities.

Design for the environment (DFE)
According to the PDMA, an approach to new product design that addresses "environmental, safety, and health issues over the product's projected life cycle in the design and development process."

In contrast to DFM, **design for maintainability (DFMt)** is "the systematic consideration of maintainability issues over a product's projected life cycle in the design and development process."[12] Here the focus is on how easy it is to maintain and service a product after it has reached the customer. DFMt directly supports an organization's efforts to improve the serviceability of its products and services.

Design for Six Sigma (DFSS), as the name implies, seeks to ensure that the organization is capable of providing products or services that meet Six Sigma quality levels—in general, no more than 3.4 defects per million opportunities. DFSS is often mentioned in conjunction with DMADV, with DMADV serving as the process for achieving DFSS.

Finally, **design for the environment (DFE)** addresses "environmental, safety, and health issues over the product's projected life cycle in the design and development process."[13] DFE is becoming increasingly important for companies seeking to respond to both market pressures and regulatory requirements. To illustrate how companies are implementing DFE, consider some examples recently reported by Apple:[14]

- The 2014 iMac uses 0.9 watt of electricity in sleep mode, a 97% reduction from the first iMac.
- Between 2007 and 2011, Apple reduced the packaging for the iPhone by 42%.
- Even though it has a much larger screen than its 15-inch predecessor, the 2014 21.5-inch iMac required 50% less material.
- Computer displays are now manufactured with mercury-free LED backlighting and arsenic-free glass.

[10] Product Development and Management Association, *The PDMA Glossary for New Product Development.*
[11] Ibid.
[12] Ibid.
[13] Ibid.
[14] Apple, *The Story behind Apple's Environmental Footprint,* **www.apple.com/environment/.**

Target costing (or design to cost)
The process of designing a product to meet a specific cost objective. Target costing involves setting the planned selling price and subtracting the desired profit, as well as marketing and distribution costs, thus leaving the required target cost. Also known as *design to cost*.

Value analysis (VA)
A process that involves examining all elements of a component, an assembly, an end product, or a service to make sure it fulfills its intended function at the lowest total cost.

Target Costing and Value Analysis

Cost is such an important aspect of product and service design that organizations have developed approaches specifically focused on this dimension. In this section, we talk about two of them: target costing and value analysis. In general, target costing is done during the initial design effort, while value analysis is applied to both new and existing products and services. **Target costing,** also called **design to cost,** is the process of designing a product to meet a specific cost objective. Target costing involves setting the planned selling price and subtracting the desired profit, as well as marketing and distribution costs, thus leaving the required target cost.

Value analysis (VA) is a process that involves examining all elements of a component, an assembly, an end product, or a service to make sure it fulfills its intended function at the lowest total cost. The primary objective of value analysis is to increase the value of an item or a service at the lowest cost without sacrificing quality. In equation form, value is the relationship between the function of a product or service and its cost:

$$\text{Value} = \text{function}/\text{cost} \quad \textbf{(15.1)}$$

There are many variations of function and cost that will increase the value of a product or service. The most obvious ways to increase value include increasing the functionality or use of a product or service while holding cost constant, reducing cost while not reducing functionality, and increasing functionality more than cost (e.g., offering a five-year warranty versus a two-year warranty with no price increase raises the value of a product to the customer).

A common approach for implementing value analysis is to create a VA team composed of professionals with knowledge about a product or service. Many functional groups can contribute to the value analysis team, including engineering, marketing, purchasing, production, and key suppliers. Value analysis teams ask a number of questions to determine if opportunities exist for item, product, or service improvement. Some typical questions include the following:

1. Is the cost of the final product proportionate to its usefulness?
2. Does the product need all its features or internal parts?
3. Is there a better production method to produce the item or product?
4. Can a lower-cost standard part replace a customized part?
5. Are we using the proper tooling, considering the quantities required?
6. Will another dependable supplier provide material, components, or subassemblies for less?
7. Are there equally effective but lower-cost materials available?
8. Are packaging cost reductions possible?
9. Is the item properly classified for shipping purposes to receive the lowest transportation rates?
10. Are design or quality specifications too tight, given customer requirements?
11. If we are making an item now, can we buy it for less (and vice versa)?

The most likely VA improvements include modifying product design and material specifications, using standardized components in place of custom components, substituting lower-cost for higher-cost materials, reducing the number of parts that a product contains, and developing better production or assembly methods.

CHAPTER SUMMARY

Product and service development is critical to the success of many firms. Points to take away from this chapter include the following:

- Having a well-managed development process, whether it is a sequential process or one based on concurrent engineering, is crucial.
- It is important to consider operations and supply chain perspectives when developing new products and services, including repeatability, testability, and serviceability of the design; volumes; costs; and the match with a company's existing capabilities.

As the last section of this chapter made clear, organizations have developed various tools and techniques for ensuring that the development process not only goes smoothly but also results in "good" designs.

KEY TERMS

Black box design 462
Commercial preparation phase 459
Computer-aided design (CAD) system 464
Computer-aided design/computer-aided manufacturing (CAD/CAM) system 464
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Concurrent engineering 459
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Testability 455
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DISCUSSION QUESTIONS

1. In this chapter, we described several approaches to product design, including parts standardization and modularity. How do these two approaches relate to the dimensions of product design described earlier in the chapter?
2. We talked about concurrent engineering as an alternative to sequential development. What are the advantages of concurrent engineering? Under what circumstances might sequential development be preferable?
3. Consider some of the dimensions of product design that we listed as important to operations and supply chain managers. Are these dimensions more or less important than whether the product or service meets the customers' needs? Can you think of situations in which there might be conflict between these different perspectives?
4. Consider the phases of product and service development shown in Table 15.1. Why is it important to include customers early in the development process?
5. Which type of product development effort would be better suited to concurrent engineering: a radically new product involving cutting-edge technologies or the latest version of an existing product? Why?
6. What are some of the benefits of including suppliers in the product development process? Can you think of any risks?

CASE STUDY

Design for Supply Chain Programs

Design for Supply Chain (DfSC) is a systematic method of ensuring the best fit between the design of a product throughout its lifetime and its supply chain members' resources and capabilities. Even something as simple as flattening the tops of soda cans, as beverage makers did in the 1950s, can revolutionize product development, transform transportation and inventory processes, and generate huge cost savings and increased customer satisfaction. Hewlett-Packard (HP) has been in the forefront of adopting DfSC principles, and IBM is another staunch proponent.

IBM developed a short list of DfSC principles that have helped it create products that are both competitive and supply-chain-efficient throughout their life cycles. Briefly stated, these principles are:

1. Integrate products parts and components as much as possible to reduce product assembly time.
2. Use industry-standard parts whenever possible to lower costs and simplify sourcing efforts.
3. Reduce lead times on critical components to avoid paying premium shipping fees on rush orders.
4. Design products for supply-chain friendliness throughout their life cycle, planning for and minimizing the cost and disruption of design and technology changes as products mature.
5. Build supply chains based on the company's strategic plan, not around the idiosyncratic requirements of specific products.
6. Use common components and modular design, thereby reducing product variability.
7. Minimize inventory costs and reduce the risk of obsolescence by building to order from common components and subassemblies, rather than building to stock.
8. Design products to give customers flexibility when ordering while keeping costs in line.
9. Use high quality parts and parts which can be quickly diagnosed to minimize warranty costs and improve after sales service.

HP similarly uses DfSC to consider the impact of its design decisions over product lifetimes, from pre-launch through production to end of life cycle, in all its business units and regions. The DfSC strategy—essentially looking back in order to see ahead—helps improve HP's relationships with suppliers, manufacturers, logistics service firms, retailers, and consumers.

To use DfSC, which it adopted in the early 1990s, HP first asks four questions about its products:

1. What makes the product a good fit for a particular supply chain?
2. Which design decisions produce that result? For example, does the product have unique parts?
3. When and why are design decisions being made, and who is making them?
4. How can the company deliver great products at higher profit margins?

Since adopting DfSC and successfully propagating its use throughout the company, HP has been able to introduce more new products faster and at lower cost. It has increased its revenues and kept customers happy. At the same time, the company has found ways to improve its inventory efficiency without offsetting risks onto its suppliers (which would damage its supply-chain relationships) or reducing the quality of product inputs (which would increase the cost of honoring product warranties as well as damaging customer relationships).

HP's six DfSC techniques are:

1. **Variety control.** Having fewer SKUs allowed the company to reduce inventory 42% and increase product availability in its PC division.
2. **Logistics enhancement.** Making an InkJet printer 45% smaller saved more than $1 per unit in logistics costs.
3. **Commonality and reuse.** While unique parts make products distinctive, they increase inventory costs and, often, time to market.
4. **Postponement.** Designing products to remain generic as long as possible during the production process, until it's known how the end user wants to customize them, saves costs.
5. **Tax and duty reduction.** These costs can be higher or lower based on the country of origin.
6. **Take-back facilitation.** Design and packaging changes can reduce both manufacturing and environmental costs.

HP estimates that DfSC techniques have saved it about $200 million per year.

Questions

1. What is the relationship between design for manufacturability (DFM) and design for supply chain (DfSC)?
2. In the chapter, we discussed parts standardization and modular architecture. How do these two approaches support DfSC?
3. You hear someone say, "DfSC sounds fine in theory, but I think it will have two negative effects. First, it will slow down the product development process because now all the areas that make up supply chain management—procurement, manufacturing, and logistics—will need to be involved. Second, it gives too much power to the supply chain functions. After all, if supply chain managers think something is too difficult to ship or too expensive to make, they may say no." What do you think? Are these legitimate concerns? How should operations managers address them?

Sources: Based on Heather E. Domin, James Wisner, and Matthew Marks, "Design for Supply Chain," *Supply and Demand Chain Executive,* December 2, 2007, **www.sdcexec.com/article/10289661/design-for-supply-chain?page=3;**
Brian Cargille and Chris Fry, "Design for Supply Chain: Spreading the Word across HP," *Supply Chain Management Review,* July–August 2006, **www.strategicmgmtsolutions.com/DfSC-HP.PDF;**
"Hewlett Packard's Design for Supply Chain Program," *Supply Chain Brain,* **www.supplychainbrain.com/content/industry-verticals/high-techelectronics/single-article-page/article/hewlett-packards-design-for-supply-chain-program/,** December 1, 2005.

REFERENCES

Books and Articles

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

Deveny, K., "Man Walked on the Moon but Man Can't Make Enough Devil's Food Cookie Cakes," *Wall Street Journal*, September 28, 1993.

Griffin, A., "PDMA Research on New Product Development Practices: Updating Trends and Benchmarking Best Practices," *Journal of Product Innovation Management* 14 (1997): 429–458.

Hauser, J., and D. Clausing, "The House of Quality," *Harvard Business Review* 66, no. 3 (May–June 1988): 63–73.

Ingrassia, L., "Taming the Monster: How Big Companies Can Change: Keeping Sharp: Gillette Holds Its Edge by Endlessly Searching for a Better Shave," *Wall Street Journal*, December 10, 1992.

Wheelwright, S., and K. Clark, *Revolutionizing Product Development* (New York: Free Press, 1992).

Internet

Apple, *The Story behind Apple's Environmental Footprint*, **www.apple.com/environment/.**

Cargille, B., and C. Fry, "Design for Supply Chain: Spreading the Word across HP," *Supply Chain Management Review*, July–August 2006, **www.strategicmgmtsolutions.com/DfSC-HP.PDF.**

Centers for Disease Control and Prevention, *The History of Malaria, an Ancient Disease*, **www.cdc.gov/malaria/about/history/**.

Domin, H. E., J. Wisner, and M. Marks, "Design for Supply Chain," *Supply and Demand Chain Executive*, December 2, 2007, **www.sdcexec.com/article/10289661/design-for-supply-chain?page=3.**

"Hewlett Packard's Design for Supply Chain Program," *Supply Chain Brain*, December 1, 2005, **www.supplychainbrain.com/content/industry-verticals/high-techelectronics/single-article-page/article/hewlett-packards-design-for-supply-chain-program/.**

Newman, A. A., "Snackwell's Nudges Up the Portion Pack," *New York Times*, April 20, 2011, **www.nytimes.com/2011/04/21/business/media/21adco.html.**

Product Development and Management Association, *The PDMA Glossary for New Product Development*, **www.pdma.org/p/cm/ld/fid=27.**

Vestergaard, *PermaNet*, **www.vestergaard.com/our-products/permanet.**

World Health Organization, *World Malaria Report 2013*, **www.who.int/malaria/publications/world_malaria_report_2013/en/.**