

# Project Management

## CHAPTER OUTLINE

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Alaska Airlines

# Project Management Provides a Competitive Advantage for Bechtel

Over a century old, the San Francisco-based Bechtel Group ([www.bechtel.com](http://www.bechtel.com)) is the world's premier manager of massive construction and engineering projects. Known for billion-dollar projects, Bechtel is famous for its construction feats on the Hoover Dam, the Boston Central Artery/Tunnel project, the Riyadh, Saudi Arabia Metro, and over 25,000 other projects in 160 countries. With 53,000 employees and revenues over \$39 billion, Bechtel is the U.S.'s largest project manager.



Philipus/Alamy

A massive dredge hired by Bechtel removes silt from Iraq's port at Umm Qasr. This paved the way for large-scale deliveries of U.S. food and the return of commercial shipping.



Steve Hebert/Bechtel National, Inc./PRN/Newscom

In addition to major construction projects, Bechtel used its project management skills to provide emergency response to major catastrophes as it did here in the wake of Hurricane Katrina.

Conditions weren't what Bechtel expected when it won a series of billion-dollar contracts from the U.S. government to help reconstruct war-torn Iraq in the last decade. That country's defeat by Allied forces hadn't caused much war damage. Instead, what Bechtel found was a nation that had been crumbling for years. None of the sewage plants in Baghdad worked. Power flicked on and off. Towns and cities had been left to decay. And scavengers were stealing everything from museum artifacts to electric power lines. Bechtel's job was to oversee electric power, sewage, transportation, and airport repairs.

Bechtel's crews travelled under armed escort and slept in trailers surrounded by razor wire. But the company's efforts have paid off. Iraq's main seaport, Umm Qasr, has opened. Electrical generation is back to prewar levels, and Bechtel has refurbished more than 1,200 schools.

With a global procurement program, Bechtel easily tapped the company's network of suppliers and buyers worldwide to help rebuild Iraq's infrastructure.



Courtesy of Bechtel Corporation

Managing massive construction projects such as this is the strength of Bechtel. With large penalties for late completion and incentives for early completion, a good project manager is worth his or her weight in gold.

Other interesting recent Bechtel projects include:

- ◆ Constructing 30 high-security data centers worldwide for Equinix, Inc. (\$1.2 billion).
- ◆ Building and running a rail line between London and the Channel Tunnel (\$4.6 billion).
- ◆ Developing an oil pipeline from the Caspian Sea region to Russia (\$850 million).
- ◆ Expanding the Dubai Airport in the United Arab Emirates (\$600 million) and the Miami International Airport (\$2 billion).
- ◆ Building liquefied natural gas plants in Trinidad, West Indies (\$1 billion).
- ◆ Building a new subway for Athens, Greece (\$2.6 billion).
- ◆ Constructing a natural gas pipeline in Thailand (\$700 million).
- ◆ Building 30 plants for iMotors.com, a company that sells refurbished autos online (\$300 million).
- ◆ Building a highway to link the north and south of Croatia (\$303 million).

When companies or countries seek out firms to manage massive projects, they go to Bechtel, which, again and again, through outstanding project management, has demonstrated its competitive advantage. ▶

Thomas Hartwell/U.S. Agency for International Development (USAID)



Reconstructed terminal at Baghdad International Airport.



Joe Cavaretta/AP Images

Bechtel was the construction contractor for the Hoover Dam. This dam, on the Colorado River, is the highest in the Western Hemisphere.

# LEARNING OBJECTIVES

- LO 3.1** *Use* a Gantt chart for scheduling 65
- LO 3.2** *Draw* AOA and AON networks 69
- LO 3.3** *Complete* forward and backward passes for a project 72
- LO 3.4** *Determine* a critical path 76
- LO 3.5** *Calculate* the variance of activity times 78
- LO 3.6** *Crash* a project 83

## STUDENT TIP

Wherever your career takes you, one of the most useful tools you can have, as a manager, is the ability to manage a project.

## VIDEO 3.1

Project Management at Hard Rock's Rockfest

# The Importance of Project Management

When Bechtel, the subject of the opening Global Company Profile, begins a project, it quickly has to mobilize substantial resources, often consisting of manual workers, construction professionals, cooks, medical personnel, and even security forces. Its project management team develops a supply chain to access materials to build everything from ports to bridges, dams, and monorails. Bechtel is just one example of a firm that faces modern phenomena: growing project complexity and collapsing product/service life cycles. This change stems from awareness of the strategic value of time-based competition and a quality mandate for continuous improvement. Each new product/service introduction is a unique event—a project. In addition, projects are a common part of our everyday life. We may be planning a wedding or a surprise birthday party, remodeling a house, or preparing a semester-long class project.

Scheduling projects can be a difficult challenge for operations managers. The stakes in project management are high. Cost overruns and unnecessary delays occur due to poor scheduling and poor controls.

Projects that take months or years to complete are usually developed outside the normal production system. Project organizations within the firm may be set up to handle such jobs and are often disbanded when the project is complete. On other occasions, managers find projects just a part of their job. The management of projects involves three phases (see Figure 3.1):

1. *Planning*: This phase includes goal setting, defining the project, and team organization.
2. *Scheduling*: This phase relates people, money, and supplies to specific activities and relates activities to each other.
3. *Controlling*: Here the firm monitors resources, costs, quality, and budgets. It also revises or changes plans and shifts resources to meet time and cost demands.

We begin this chapter with a brief overview of these functions. Three popular techniques to allow managers to plan, schedule, and control—Gantt charts, PERT, and CPM—are also described.

## Project Planning

Projects can be defined as a series of related tasks directed toward a major output. In some firms a **project organization** is developed to make sure existing programs continue to run smoothly on a day-to-day basis while new projects are successfully completed.

For companies with multiple large projects, such as a construction firm, a project organization is an effective way of assigning the people and physical resources needed. It is a temporary organization structure designed to achieve results by using specialists from throughout the firm.

The project organization may be most helpful when:

1. Work tasks can be defined with a specific goal and deadline.
2. The job is unique or somewhat unfamiliar to the existing organization.
3. The work contains complex interrelated tasks requiring specialized skills.

### Project organization

An organization formed to ensure that programs (projects) receive the proper management and attention.

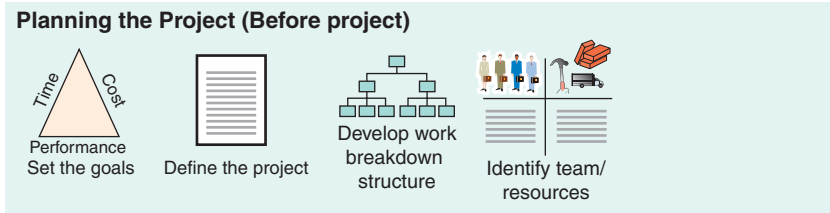
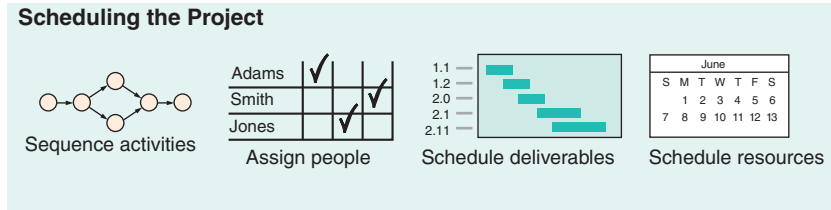


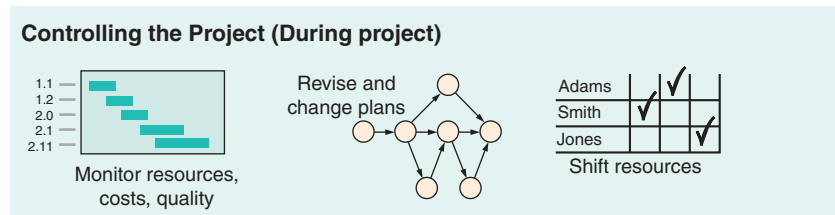
Figure 3.1

**Project Planning, Scheduling, and Controlling**



**STUDENT TIP**

Managers must “make the plan and then work the plan.”



- 4. The project is temporary but critical to the organization.
- 5. The project cuts across organizational lines.

## The Project Manager

An example of a project organization is shown in Figure 3.2. Project team members are temporarily assigned to a project and report to the project manager. The manager heading the project coordinates activities with other departments and reports directly to top management. Project managers receive high visibility in a firm and are responsible for making sure that (1) all necessary activities are finished in proper sequence and on time; (2) the project comes in within budget; (3) the project meets its quality goals; and (4) the people assigned to the project receive the motivation, direction, and information needed to do their jobs. This means that project managers should be good coaches and communicators, and be able to organize activities from a variety of disciplines.

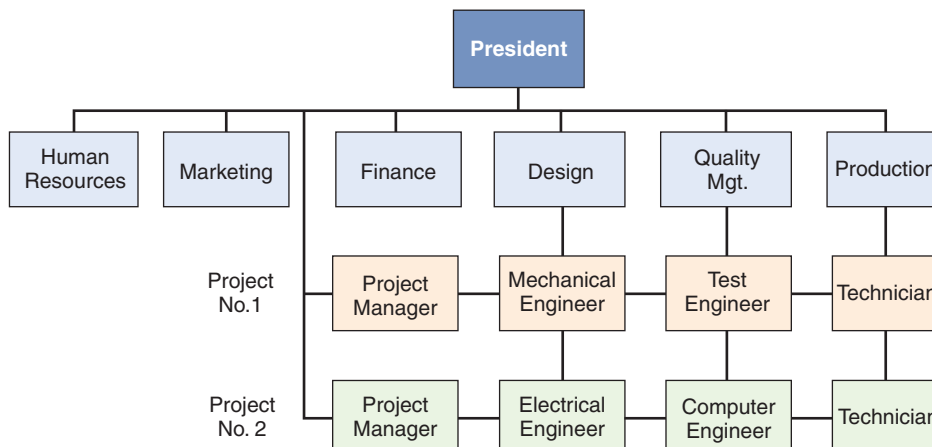


Figure 3.2

**A Sample Project Organization**

**STUDENT TIP**

Project organizations can be temporary or permanent. A permanent organization is usually called a *matrix organization*.

**Ethical Issues Faced in Project Management** Project managers not only have high visibility but they also face ethical decisions on a daily basis. How they act establishes the code of conduct for the project. Project managers often deal with (1) offers of gifts from contractors, (2) pressure to alter status reports to mask the reality of delays, (3) false reports for charges of time and expenses, and (4) pressures to compromise quality to meet bonuses or avoid penalties related to schedules.

Using the Project Management Institute’s ([www.pmi.org](http://www.pmi.org)) ethical codes is one means of trying to establish standards. These codes need to be accompanied by good leadership and a strong organizational culture, with its ingrained ethical standards and values.

## Work Breakdown Structure

### Work breakdown structure (WBS)

A hierarchical description of a project into more and more detailed components.

The project management team begins its task well in advance of project execution so that a plan can be developed. One of its first steps is to carefully establish the project’s objectives, then break the project down into manageable parts. This **work breakdown structure (WBS)** defines the project by dividing it into its major subcomponents (or tasks), which are then subdivided into more detailed components, and finally into a set of activities and their related costs. The division of the project into smaller and smaller tasks can be difficult, but is critical to managing the project and to scheduling success. Gross requirements for people, supplies, and equipment are also estimated in this planning phase.

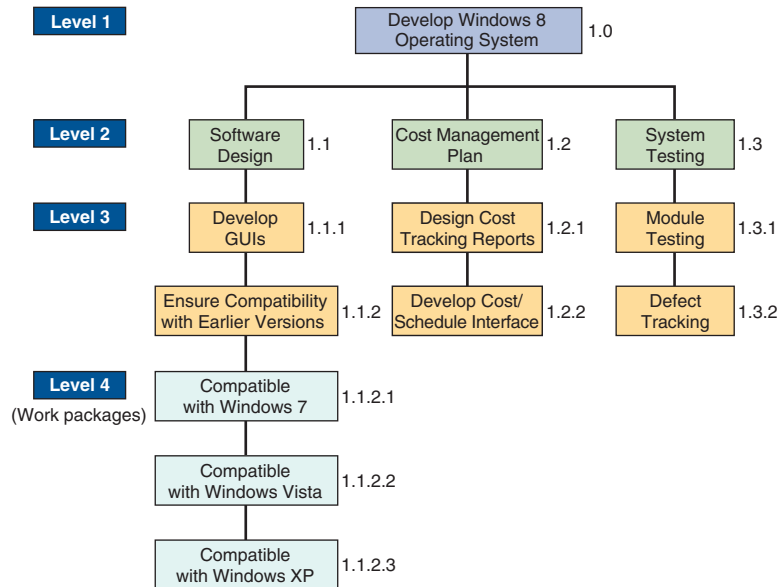
The work breakdown structure typically decreases in size from top to bottom and is indented like this:

#### Level

1. Project
2. Major tasks in the project
3. Subtasks in major tasks
4. Activities (or “work packages”) to be completed

This hierarchical framework can be illustrated with the development of Microsoft’s operating system Windows 8. As we see in Figure 3.3, the project, creating a new operating system, is labeled 1.0. The first step is to identify the major tasks in the project (level 2). Three examples would be software design (1.1), cost management plan (1.2), and system testing (1.3). Two major subtasks for 1.1 are development of graphical user interfaces (GUIs) (1.1.1) and creating compatibility with previous versions of Windows (1.1.2). The major subtasks for 1.1.2 are level-4 activities, such as creating a team to handle compatibility with Windows 7 (1.1.2.1),

Figure 3.3  
Work Breakdown Structure



creating a team for Windows Vista (1.1.2.2), and creating a team for Windows XP (1.1.2.3). There are usually many level-4 activities.

# Project Scheduling

Project scheduling involves sequencing and allotting time to all project activities. At this stage, managers decide how long each activity will take and compute the resources needed at each stage of production. Managers may also chart separate schedules for personnel needs by type of skill (management, engineering, or pouring concrete, for example) and material needs.

One popular project scheduling approach is the Gantt chart. **Gantt charts** are low-cost means of helping managers make sure that (1) activities are planned, (2) order of performance is documented, (3) activity time estimates are recorded, and (4) overall project time is developed. As Figure 3.4 shows, Gantt charts are easy to understand. Horizontal bars are drawn for each project activity along a time line. This illustration of a routine servicing of a Delta jetliner during a 40-minute layover shows that Gantt charts also can be used for scheduling repetitive operations. In this case, the chart helps point out potential delays. The *OM in Action* box on Delta provides additional insights.

On simple projects, scheduling charts such as these permit managers to observe the progress of each activity and to spot and tackle problem areas. Gantt charts, though, do not adequately illustrate the interrelationships between the activities and the resources.

PERT and CPM, the two widely used network techniques that we shall discuss shortly, *do* have the ability to consider precedence relationships and interdependency of activities. On complex projects, the scheduling of which is almost always computerized, PERT and CPM thus have an edge over the simpler Gantt charts. Even on huge projects, though, Gantt charts can be used as summaries of project status and may complement the other network approaches.

To summarize, whatever the approach taken by a project manager, project scheduling serves several purposes:

1. It shows the relationship of each activity to others and to the whole project.
2. It identifies the precedence relationships among activities.
3. It encourages the setting of realistic time and cost estimates for each activity.
4. It helps make better use of people, money, and material resources by identifying critical bottlenecks in the project.

### Gantt charts

Planning charts used to schedule resources and allocate time.

### STUDENT TIP

Gantt charts are simple and visual, making them widely used.

### LO 3.1 Use a Gantt chart for scheduling

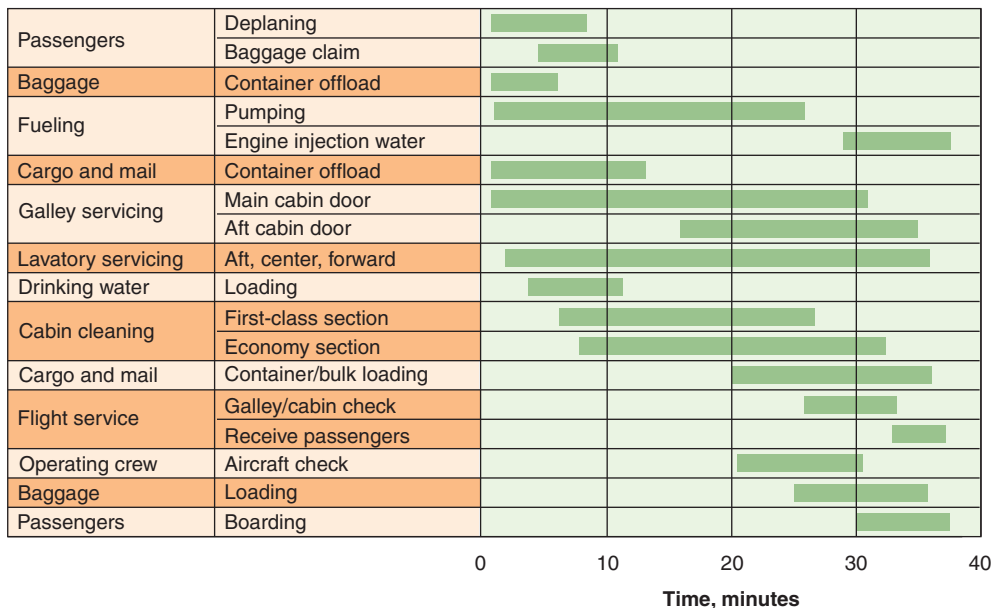


Figure 3.4

### Gantt Chart of Service Activities for a Delta Jet during a 40-Minute Layover

Delta saves \$50 million a year with this turnaround time, which is a reduction from its traditional 60-minute routine.

## OM in Action

### Delta's Ground Crew Orchestrates a Smooth Takeoff

Flight 574's engines screech its arrival as the jet lumbers down Richmond's taxiway with 140 passengers arriving from Atlanta. In 40 minutes, the plane is to be airborne again.

However, before this jet can depart, there is business to attend to: passengers, luggage, and cargo to unload and load; thousands of gallons of jet fuel and countless drinks to restock; cabin and restrooms to clean; toilet holding tanks to drain; and engines, wings, and landing gear to inspect.

The 10-person ground crew knows that a miscue anywhere—a broken cargo loader, lost baggage, misdirected passengers—can mean a late departure and trigger a chain reaction of headaches from Richmond to Atlanta to every destination of a connecting flight.

Carla Sutera, the operations manager for Delta's Richmond International Airport, views the turnaround operation like a pit boss awaiting a race car. Trained crews are in place for Flight 574 with baggage carts

and tractors, hydraulic cargo loaders, a truck to load food and drinks, another to lift the cleanup crew, another to put fuel on, and a fourth to take water off. The "pit crew" usually performs so smoothly that most passengers never suspect the proportions of the effort. Gantt charts, such as the one in Figure 3.4, aid Delta and other airlines with the staffing and scheduling that are needed for this task.

Sources: *Knight Ridder Tribune Business News* (July 16, 2005) and (November 21, 2002).



Jeff Topping/Getty Images

## Project Controlling

### VIDEO 3.2

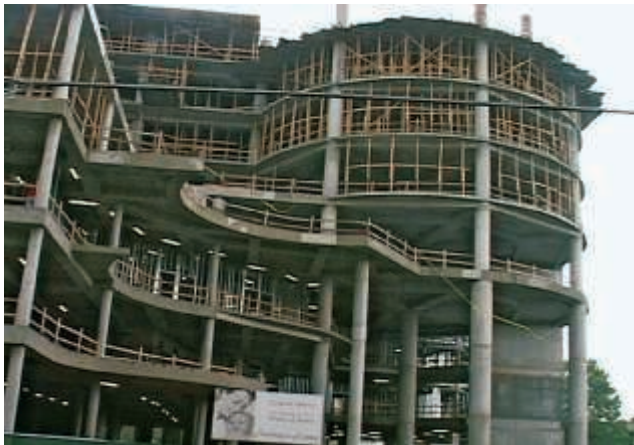
Project Management at Arnold Palmer Hospital

### STUDENT TIP

To use project management software, you first need to understand the next two sections in this chapter.

The control of projects, like the control of any management system, involves close monitoring of resources, costs, quality, and budgets. Control also means using a feedback loop to revise the project plan and having the ability to shift resources to where they are needed most. Computerized PERT/CPM reports and charts are widely available today from scores of competing software firms. Some of the more popular of these programs are Oracle Primavera (by Oracle), MindView (by Match Ware), HP Project (by Hewlett-Packard), Fast Track (by AEC Software), and Microsoft Project (by Microsoft Corp.), which we illustrate in this chapter.

These programs produce a broad variety of reports, including (1) detailed cost breakdowns, (2) labor requirements, (3) cost and hour summaries, (4) raw material and expenditure forecasts, (5) variance reports, (6) time analysis reports, and (7) work status reports.



Courtesy Arnold Palmer Medical Center



Courtesy Arnold Palmer Medical Center

Construction of the new 11-story building at Arnold Palmer Hospital in Orlando, Florida, was an enormous project for the hospital administration. The photo on the left shows the first six floors under construction. The photo on the right shows the building as completed two years later. Prior to beginning actual construction, regulatory and funding issues added, as they do with most projects, substantial time to the overall project. Cities have zoning and parking issues; the EPA has drainage and waste issues; and regulatory authorities have their own requirements, as do issuers of bonds. The \$100 million, 4-year project at Arnold Palmer Hospital is discussed in the Video Case Study at the end of this chapter.



## OM in Action

### Agile Project Management at Mastek

Agile project management has changed the way that Mastek Corp., in Mumbai, India, develops its educational software products. On a traditional well-defined project, managers are actively involved in directing work and telling their team what needs to be done—a style often referred to as a step-by-step *waterfall* style of project management.

Agile project management is different. In the early stages, the project manager creates a high-level plan, based on outline requirements and a high-level view of the solution. From that point, the end project is created iteratively and incrementally, with each increment building on the output of steps preceding it.

The principles of agile are essentially communication and transparency. Instead of waiting for something to be delivered, with limited understanding of the desired end result, there are numerous checkpoints and feedback loops to track progress.

Agile provides Mastek the ability to keep costs under control. Without agile, the cost of quality increases. “It’s much harder to correct mistakes when a software product is nearing its final phase of development,” says a company executive. “It’s much better to develop it as you go along. I think agile project management would help any software developer.”

Sources: AMPG International (2015) and [www.cprime.com](http://www.cprime.com) (2012).

Controlling projects can be difficult. The stakes are high; cost overruns and unnecessary delays can occur due to poor planning, scheduling, and controls. Some projects are “well-defined,” whereas others may be “ill-defined.” Projects typically only become well-defined after detailed extensive initial planning and careful definition of required inputs, resources, processes, and outputs. Well-established projects where constraints are known (e.g., buildings and roads) and engineered products (e.g., airplanes and cars) with well-defined specifications and drawings may fall into this category. Well-defined projects are assumed to have changes small enough to be managed without substantially revising plans. They use what is called a *waterfall* approach, where the project progresses smoothly, in a step-by-step manner, through each phase to completion.

But many projects, such as software development (e.g., 3-D games) and new technology (e.g., landing the Mars land rover) are ill-defined. These projects require what is known as an *agile* style of management with collaboration and constant feedback to adjust to the many unknowns of the evolving technology and project specifications. The *OM in Action* box “Agile Project Management at Mastek” provides such an example. Most projects fall somewhere between waterfall and agile.

## Project Management Techniques: PERT and CPM

**Program evaluation and review technique (PERT)** and the **critical path method (CPM)** were both developed in the 1950s to help managers schedule, monitor, and control large and complex projects. CPM arrived first, as a tool developed to assist in the building and maintenance of chemical plants at duPont. Independently, PERT was developed in 1958 for the U.S. Navy.

### Program evaluation and review technique (PERT)

A project management technique that employs three time estimates for each activity.

### Critical path method (CPM)

A project management technique that uses only one time factor per activity.

### The Framework of PERT and CPM

PERT and CPM both follow six basic steps:

1. Define the project and prepare the work breakdown structure.
2. Develop the relationships among the activities. Decide which activities must precede and which must follow others.
3. Draw the network connecting all the activities.
4. Assign time and/or cost estimates to each activity.
5. Compute the *longest* time path through the network. This is called the **critical path**.
6. Use the network to help plan, schedule, monitor, and control the project.

Step 5, finding the critical path, is a major part of controlling a project. The activities on the critical path represent tasks that will delay the entire project if they are not completed on time. Managers can gain the flexibility needed to complete critical tasks by identifying

### Critical path

The computed *longest* time path(s) through a network.

noncritical activities and replanning, rescheduling, and reallocating labor and financial resources.

Although PERT and CPM differ to some extent in terminology and in the construction of the network, their objectives are the same. Furthermore, the analysis used in both techniques is very similar. The major difference is that PERT employs three time estimates for each activity. These time estimates are used to compute expected values and standard deviations for the activity. CPM makes the assumption that activity times are known with certainty and hence requires only one time factor for each activity.

For purposes of illustration, the rest of this section concentrates on a discussion of PERT. Most of the comments and procedures described, however, apply just as well to CPM.

PERT and CPM are important because they can help answer questions such as the following about projects with thousands of activities:

1. When will the entire project be completed?
2. What are the critical activities or tasks in the project—that is, which activities will delay the entire project if they are late?
3. Which are the noncritical activities—the ones that can run late without delaying the whole project's completion?
4. What is the probability that the project will be completed by a specific date?
5. At any particular date, is the project on schedule, behind schedule, or ahead of schedule?
6. On any given date, is the money spent equal to, less than, or greater than the budgeted amount?
7. Are there enough resources available to finish the project on time?
8. If the project is to be finished in a shorter amount of time, what is the best way to accomplish this goal at the least cost?

## Network Diagrams and Approaches

The first step in a PERT or CPM network is to divide the entire project into significant activities in accordance with the work breakdown structure. There are two approaches for drawing a project network: **activity on node (AON)** and **activity on arrow (AOA)**. Under the AON convention, *nodes* designate activities. Under AOA, *arrows* represent activities. Activities consume time and resources. The basic difference between AON and AOA is that the nodes in an AON diagram represent activities. In an AOA network, the nodes represent the starting and finishing times of an activity and are also called *events*. So nodes in AOA consume neither time nor resources.

Although both AON and AOA are popular in practice, many of the project management software packages, including Microsoft Project, use AON networks. For this reason, although we illustrate both types of networks in the next examples, we focus on AON networks in subsequent discussions in this chapter.

### Activity-on-node (AON)

A network diagram in which nodes designate activities.

### Activity-on-arrow (AOA)

A network diagram in which arrows designate activities.

## Example 1

### PREDECESSOR RELATIONSHIPS FOR POLLUTION CONTROL AT MILWAUKEE PAPER

Milwaukee Paper Manufacturing had long delayed the expense of installing advanced computerized air pollution control equipment in its facility. But when the board of directors adopted a new proactive policy on sustainability, it did not just *authorize* the budget for the state-of-the-art equipment. It directed the plant manager, Julie Ann Williams, to complete the installation in time for a major announcement of the policy, on Earth Day, exactly 16 weeks away! Under strict deadline from her bosses, Williams needs to be sure that installation of the filtering system progresses smoothly and on time.

Given the following information, develop a table showing activity precedence relationships.

**APPROACH** ► Milwaukee Paper has identified the eight activities that need to be performed in order for the project to be completed. When the project begins, two activities can be simultaneously started: building the internal components for the device (activity A) and the modifications necessary for the floor and roof (activity B). The construction of the collection stack (activity C) can begin when

the internal components are completed. Pouring the concrete floor and installation of the frame (activity D) can be started as soon as the internal components are completed and the roof and floor have been modified.

After the collection stack has been constructed, two activities can begin: building the high-temperature burner (activity E) and installing the pollution control system (activity F). The air pollution device can be installed (activity G) after the concrete floor has been poured, the frame has been installed, and the high-temperature burner has been built. Finally, after the control system and pollution device have been installed, the system can be inspected and tested (activity H).

**SOLUTION** ► Activities and precedence relationships may seem rather confusing when they are presented in this descriptive form. It is therefore convenient to list all the activity information in a table, as shown in Table 3.1. We see in the table that activity A is listed as an *immediate predecessor* of activity C. Likewise, both activities D and E must be performed prior to starting activity G.

**TABLE 3.1** Milwaukee Paper Manufacturing's Activities and Predecessors

ACTIVITY	DESCRIPTION	IMMEDIATE PREDECESSORS
A	Build internal components	—
B	Modify roof and floor	—
C	Construct collection stack	A
D	Pour concrete and install frame	A, B
E	Build high-temperature burner	C
F	Install pollution control system	C
G	Install air pollution device	D, E
H	Inspect and test	F, G

**INSIGHT** ► To complete a network, all predecessors must be clearly defined.

**LEARNING EXERCISE** ► What is the impact on this sequence of activities if Environmental Protection Agency (EPA) approval is required after *Inspect and Test*? [Answer: The immediate predecessor for the new activity would be H, *Inspect and Test*, with *EPA approval* as the last activity.]

## Activity-on-Node Example

Note that in Example 1, we only list the *immediate* predecessors for each activity. For instance, in Table 3.1, because activity A precedes activity C, and activity C precedes activity E, the fact that activity A precedes activity E is *implicit*. This relationship need not be explicitly shown in the activity precedence relationships.

When there are many activities in a project with fairly complicated precedence relationships, it is difficult for an individual to comprehend the complexity of the project from just the tabular information. In such cases, a visual representation of the project, using a *project network*, is convenient and useful. A project network is a diagram of all the activities and the precedence relationships that exist between these activities in a project. Example 2 illustrates how to construct an AON project network for Milwaukee Paper Manufacturing.

It is convenient to have the project network start and finish with a unique node. In the Milwaukee Paper example, it turns out that a unique activity, H, is the last activity in the project. We therefore automatically have a unique ending node.

In situations in which a project has multiple ending activities, we include a “dummy” ending activity. We illustrate this type of situation in Solved Problem 3.1 at the end of this chapter.

**LO 3.2** Draw AOA and AON networks

## Example 2

### AON GRAPH FOR MILWAUKEE PAPER

Draw the AON network for Milwaukee Paper, using the data in Example 1.

**APPROACH** ▶ In the AON approach, we denote each activity by a node. The lines, or arrows, represent the precedence relationships between the activities.

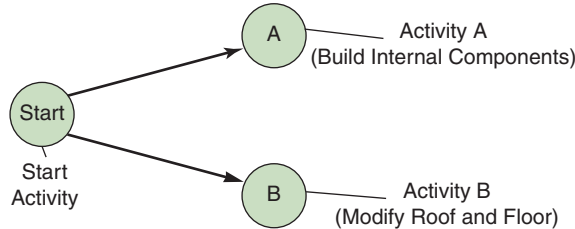
**SOLUTION** ▶ In this example, there are two activities (A and B) that do not have any predecessors. We draw separate nodes for each of these activities, as shown in Figure 3.5. Although not required, it is usually convenient to have a unique starting activity for a project. We have therefore included a *dummy activity* called *Start* in Figure 3.5. This **dummy activity** does not really exist and takes up zero time and resources. Activity *Start* is an immediate predecessor for both activities A and B, and it serves as the unique starting activity for the entire project.

#### Dummy activity

An activity having no time that is inserted into a network to maintain the logic of the network.

Figure 3.5

Beginning AON Network for Milwaukee Paper

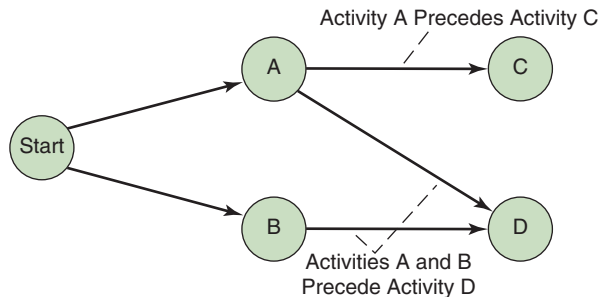


We now show the precedence relationships using lines with arrow symbols. For example, an arrow from activity *Start* to activity *A* indicates that *Start* is a predecessor for activity *A*. In a similar fashion, we draw an arrow from *Start* to *B*.

Next, we add a new node for activity *C*. Because activity *A* precedes activity *C*, we draw an arrow from node *A* to node *C* (see Figure 3.6). Likewise, we first draw a node to represent activity *D*. Then, because activities *A* and *B* both precede activity *D*, we draw arrows from *A* to *D* and from *B* to *D* (see Figure 3.6).

Figure 3.6

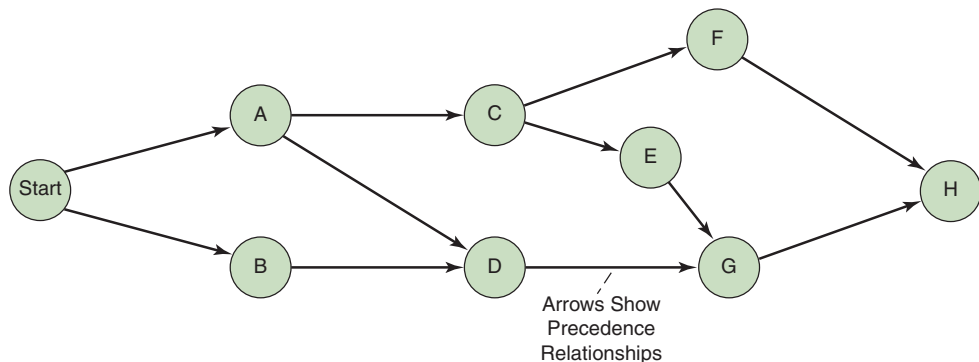
Intermediate AON Network for Milwaukee Paper



We proceed in this fashion, adding a separate node for each activity and a separate line for each precedence relationship that exists. The complete AON project network for the Milwaukee Paper Manufacturing project is shown in Figure 3.7.

Figure 3.7

Complete AON Network for Milwaukee Paper



**INSIGHT** ▶ Drawing a project network properly takes some time and experience. We would like the lines to be straight and arrows to move to the right when possible.

**LEARNING EXERCISE** ▶ If *EPA Approval* occurs after *Inspect and Test*, what is the impact on the graph? [Answer: A straight line is extended to the right beyond *H* (with a node *I* added) to reflect the additional activity.]

**RELATED PROBLEMS** ▶ 3.4a, 3.5, 3.8, 3.9, 3.10, 3.11a, 3.12 (3.13–3.14 are available in MyOMLab)

## Activity-on-Arrow Example

In an AOA project network we can represent activities by arrows. A node represents an *event*, which marks the start or completion time of an activity. We usually identify an event (node) by a number.

### Example 3

#### ACTIVITY-ON-ARROW FOR MILWAUKEE PAPER

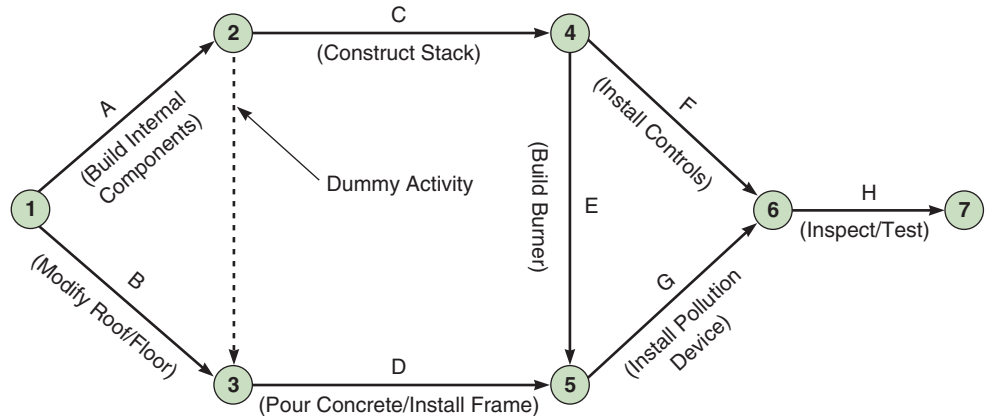
Draw the complete AOA project network for Milwaukee Paper’s problem.

**APPROACH** ▶ Using the data from Table 3.1 in Example 1, draw one activity at a time, starting with A.

**SOLUTION** ▶ We see that activity A starts at event 1 and ends at event 2. Likewise, activity B starts at event 1 and ends at event 3. Activity C, whose only immediate predecessor is activity A, starts at node 2 and ends at node 4. Activity D, however, has two predecessors (i.e., A and B). Hence, we need both activities A and B to end at event 3, so that activity D can start at that event. However, we cannot have multiple activities with common starting and ending nodes in an AOA network. To overcome this difficulty, in such cases, we may need to add a dummy line (activity) to enforce the precedence relationship. The dummy activity, shown in Figure 3.8 as a dashed line, is inserted between events 2 and 3 to make the diagram reflect the precedence between A and D. The remainder of the AOA project network for Milwaukee Paper’s example is also shown.

Figure 3.8

Complete AOA Network (with Dummy Activity) for Milwaukee Paper



**STUDENT TIP** ◀

The dummy activity consumes no time, but note how it changes precedence. Now activity D cannot begin until *both* B and the dummy are complete.

**INSIGHT** ▶ Dummy activities are common in AOA networks. They do not really exist in the project and take zero time.

**LEARNING EXERCISE** ▶ A new activity, *EPA Approval*, follows activity H. Add it to Figure 3.8. [Answer: Insert an arrowed line from node 7, which ends at a new node 8, and is labeled I (EPA Approval).]

**RELATED PROBLEMS** ▶ 3.4b, 3.6, 3.7

## Determining the Project Schedule

Look back at Figure 3.7 (in Example 2) for a moment to see Milwaukee Paper’s completed AON project network. Once this project network has been drawn to show all the activities and their precedence relationships, the next step is to determine the project schedule. That is, we need to identify the planned starting and ending time for each activity.

Let us assume Milwaukee Paper estimates the time required for each activity, in weeks, as shown in Table 3.2. The table indicates that the total time for all eight of the company’s activities is 25 weeks. However, because several activities can take place simultaneously, it is clear that the total project completion time may be less than 25 weeks. To find out just how long the project will take, we perform the **critical path analysis** for the network.

**Critical path analysis**

A process that helps determine a project schedule.

**TABLE 3.2** Time Estimates for Milwaukee Paper Manufacturing

ACTIVITY	DESCRIPTION	TIME (WEEKS)
A	Build internal components	2
B	Modify roof and floor	3
C	Construct collection stack	2
D	Pour concrete and install frame	4
E	Build high-temperature burner	4
F	Install pollution control system	3
G	Install air pollution device	5
H	Inspect and test	2
	Total time (weeks)	25

**STUDENT TIP** ⚠

Does this mean the project will take 25 weeks to complete? No. Don't forget that several of the activities are being performed at the same time. It would take 25 weeks if they were done sequentially.

As mentioned earlier, the critical path is the *longest* time path through the network. To find the critical path, we calculate two distinct starting and ending times for each activity. These are defined as follows:

*Earliest start (ES)* = earliest time at which an activity can start, assuming all predecessors have been completed

*Earliest finish (EF)* = earliest time at which an activity can be finished

*Latest start (LS)* = latest time at which an activity can start so as to not delay the completion time of the entire project

*Latest finish (LF)* = latest time by which an activity has to finish so as to not delay the completion time of the entire project

We use a two-pass process, consisting of a forward pass and a backward pass, to determine these time schedules for each activity. The early start and finish times (ES and EF) are determined during the **forward pass**. The late start and finish times (LS and LF) are determined during the backward pass.

**Forward pass**

A process that identifies all the early times.

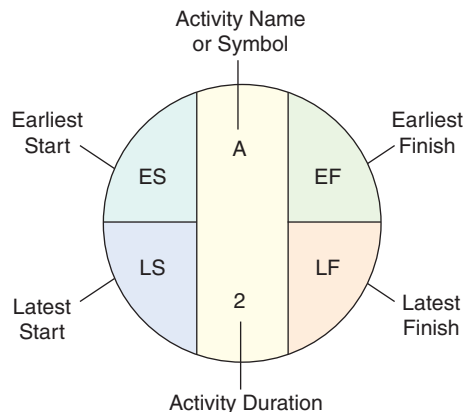
**LO 3.3** Complete forward and backward passes for a project

**Forward Pass**

To clearly show the activity schedules on the project network, we use the notation shown in Figure 3.9. The ES of an activity is shown in the top left corner of the node denoting that activity. The EF is shown in the top right corner. The latest times, LS and LF, are shown in the bottom-left and bottom-right corners, respectively.

Figure 3.9

**Notation Used in Nodes for Forward and Backward Pass**



**Earliest Start Time Rule** Before an activity can start, *all* its immediate predecessors must be finished:

- ◆ If an activity has only a single immediate predecessor, its ES equals the EF of the predecessor.
- ◆ If an activity has multiple immediate predecessors, its ES is the maximum of all EF values of its predecessors. That is:

$$ES = \text{Max} \{EF \text{ of all immediate predecessors}\} \quad (3-1)$$

**STUDENT TIP**

All predecessor activities must be completed before an activity can begin.

**Earliest Finish Time Rule** The earliest finish time (EF) of an activity is the sum of its earliest start time (ES) and its activity time. That is:

$$EF = ES + \text{Activity time} \quad (3-2)$$

## Example 4

### COMPUTING EARLIEST START AND FINISH TIMES FOR MILWAUKEE PAPER

Calculate the earliest start and finish times for the activities in the Milwaukee Paper Manufacturing project.

**APPROACH** ► Use Table 3.2, which contains the activity times. Complete the project network for the company's project, along with the ES and EF values for all activities.

**SOLUTION** ► With the help of Figure 3.10, we describe how these values are calculated.

Because activity Start has no predecessors, we begin by setting its ES to 0. That is, activity Start can begin at time 0, which is the same as the beginning of week 1. If activity Start has an ES of 0, its EF is also 0, since its activity time is 0.

Next, we consider activities A and B, both of which have only Start as an immediate predecessor. Using the earliest start time rule, the ES for both activities A and B equals zero, which is the EF of activity Start. Now, using the earliest finish time rule, the EF for A is 2 ( $= 0 + 2$ ), and the EF for B is 3 ( $= 0 + 3$ ).

Since activity A precedes activity C, the ES of C equals the EF of A ( $= 2$ ). The EF of C is therefore 4 ( $= 2 + 2$ ).

We now come to activity D. Both activities A and B are immediate predecessors for D. Whereas A has an EF of 2, activity B has an EF of 3. Using the earliest start time rule, we compute the ES of activity D as follows:

$$ES \text{ of } D = \text{Max}\{EF \text{ of } A, EF \text{ of } B\} = \text{Max}(2, 3) = 3$$

The EF of D equals 7 ( $= 3 + 4$ ). Next, both activities E and F have activity C as their only immediate predecessor. Therefore, the ES for both E and F equals 4 ( $= EF \text{ of } C$ ). The EF of E is 8 ( $= 4 + 4$ ), and the EF of F is 7 ( $= 4 + 3$ ).

Activity G has both activities D and E as predecessors. Using the earliest start time rule, its ES is therefore the maximum of the EF of D and the EF of E. Hence, the ES of activity G equals 8 ( $= \text{maximum of } 7 \text{ and } 8$ ), and its EF equals 13 ( $= 8 + 5$ ).

Finally, we come to activity H. Because it also has two predecessors, F and G, the ES of H is the maximum EF of these two activities. That is, the ES of H equals 13 ( $= \text{maximum of } 13 \text{ and } 7$ ). This implies that the EF of H is 15 ( $= 13 + 2$ ). Because H is the last activity in the project, this also implies that the earliest time in which the entire project can be completed is 15 weeks.

**INSIGHT** ► The ES of an activity that has only one predecessor is simply the EF of that predecessor. For an activity with more than one predecessor, we must carefully examine the EFs of all immediate predecessors and choose the largest one.

**LEARNING EXERCISE** ► A new activity I, *EPA Approval*, takes 1 week. Its predecessor is activity H. What are I's ES and EF? [Answer: 15, 16]

**RELATED PROBLEMS** ► 3.15, 3.16, 3.19c

EXCEL OM Data File Ch03Ex4.xls can be found in MyOMLab.

Although the forward pass allows us to determine the earliest project completion time, it does not identify the critical path. To identify this path, we need to now conduct the backward pass to determine the LS and LF values for all activities.

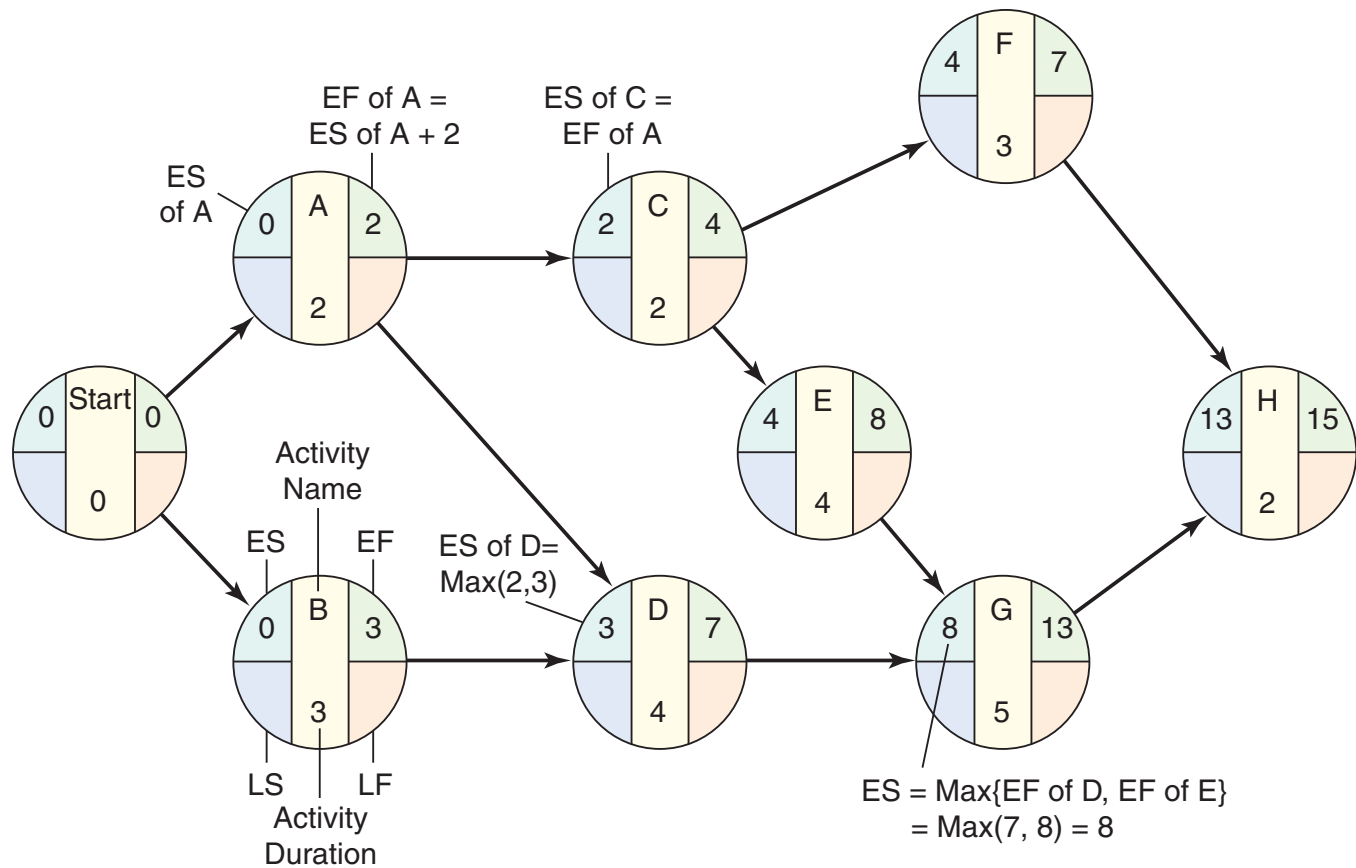


Figure 3.10 Earliest Start and Earliest Finish Times for Milwaukee Paper

## Backward Pass

### Backward pass

An activity that finds all the late start and late finish times.

Just as the forward pass began with the first activity in the project, the **backward pass** begins with the last activity in the project. For each activity, we first determine its LF value, followed by its LS value. The following two rules are used in this process.

**Latest Finish Time Rule** This rule is again based on the fact that before an activity can start, all its immediate predecessors must be finished:

- ◆ If an activity is an immediate predecessor for just a single activity, its LF equals the LS of the activity that immediately follows it.
- ◆ If an activity is an immediate predecessor to more than one activity, its LF is the minimum of all LS values of all activities that immediately follow it. That is:

$$LF = \text{Min}\{\text{LS of all immediate following activities}\} \quad (3-3)$$

**Latest Start Time Rule** The latest start time (LS) of an activity is the difference of its latest finish time (LF) and its activity time. That is:

$$LS = LF - \text{Activity time} \quad (3-4)$$

## Example 5

### COMPUTING LATEST START AND FINISH TIMES FOR MILWAUKEE PAPER

Calculate the latest start and finish times for each activity in Milwaukee Paper's pollution project.

**APPROACH** ► Use Figure 3.10 as a beginning point. Overlay 1 of Figure 3.10 shows the complete project network for Milwaukee Paper, along with added LS and LF values for all activities. In what follows, we see how these values were calculated.



**SOLUTION** ► We begin by assigning an LF value of 15 weeks for activity H. That is, we specify that the latest finish time for the entire project is the same as its earliest finish time. Using the latest start time rule, the LS of activity H is equal to 13 ( $= 15 - 2$ ).

Because activity H is the lone succeeding activity for both activities F and G, the LF for both F and G equals 13. This implies that the LS of G is 8 ( $= 13 - 5$ ), and the LS of F is 10 ( $= 13 - 3$ ).

Proceeding in this fashion, we see that the LF of E is 8 ( $=$  LS of G), and its LS is 4 ( $= 8 - 4$ ). Likewise, the LF of D is 8 ( $=$  LS of G), and its LS is 4 ( $= 8 - 4$ ).

We now consider activity C, which is an immediate predecessor to two activities: E and F. Using the latest finish time rule, we compute the LF of activity C as follows:

$$\text{LF of C} = \text{Min}\{\text{LS of E, LS of F}\} = \text{Min}(4, 10) = 4$$

The LS of C is computed as 2 ( $= 4 - 2$ ). Next, we compute the LF of B as 4 ( $=$  LS of D) and its LS as 1 ( $= 4 - 3$ ).

We now consider activity A. We compute its LF as 2 ( $=$  minimum of LS of C and LS of D). Hence, the LS of activity A is 0 ( $= 2 - 2$ ). Finally, both the LF and LS of activity Start are equal to 0.

**INSIGHT** ► The LF of an activity that is the predecessor of only one activity is just the LS of that following activity. If the activity is the predecessor to more than one activity, its LF is the smallest LS value of all activities that follow immediately.

**LEARNING EXERCISE** ► A new activity I, *EPA Approval*, takes 1 week. Its predecessor is activity H. What are I's LS and LF? [Answer: 15, 16]

**RELATED PROBLEMS** ► 3.15, 3.19c

## Calculating Slack Time and Identifying the Critical Path(s)

After we have computed the earliest and latest times for all activities, it is a simple matter to find the amount of **slack time** that each activity has. Slack is the length of time an activity can be delayed without delaying the entire project. Mathematically:

$$\text{Slack} = \text{LS} - \text{ES} \quad \text{or} \quad \text{Slack} = \text{LF} - \text{EF} \quad (3-5)$$

### Slack time

Free time for an activity. Also referred to as free float or free slack.

## Example 6

### CALCULATING SLACK TIMES FOR MILWAUKEE PAPER

Calculate the slack for the activities in the Milwaukee Paper project.

**APPROACH** ► Start with the data in Overlay 1 of Figure 3.10 in Example 5 and develop Table 3.3 one line at a time.

**SOLUTION** ► Table 3.3 summarizes the ES, EF, LS, LF, and slack time for all of the firm's activities. Activity B, for example, has 1 week of slack time because its LS is 1 and its ES is 0 (alternatively, its LF is 4 and its EF is 3). This means that activity B can be delayed by up to 1 week, and the whole project can still be finished in 15 weeks.

On the other hand, activities A, C, E, G, and H have *no* slack time. This means that none of them can be delayed without delaying the entire project. Conversely, if plant manager Julie Ann Williams wants to reduce the total project times, she will have to reduce the length of one of these activities.

Overlay 2 of Figure 3.10 shows the slack computed for each activity.

**INSIGHT** ► Slack may be computed from either early/late starts or early/late finishes. The key is to find which activities have zero slack.

TABLE 3.3 Milwaukee Paper's Schedule and Slack Times

ACTIVITY	ACTIVITY TIME	EARLIEST START ES	EARLIEST FINISH EF	LATEST START LS	LATEST FINISH LF	SLACK LS – ES	ON CRITICAL PATH
A	2	0	2	0	2	0	Yes
B	3	0	3	1	4	1	No
C	2	2	4	2	4	0	Yes
D	4	3	7	4	8	1	No
E	4	4	8	4	8	0	Yes
F	3	4	7	10	13	6	No
G	5	8	13	8	13	0	Yes
H	2	13	15	13	15	0	Yes

**LEARNING EXERCISE** ▶ A new activity I, *EPA Approval*, follows activity H and takes 1 week. Is it on the critical path? [Answer: Yes, it's  $LS - ES = 0$ ]

**RELATED PROBLEMS** ▶ 3.8d, 3.15d, 3.19c

**ACTIVE MODEL 3.1** This example is further illustrated in Active Model 3.1 in MyOMLab.

### LO 3.4 Determine a critical path

The activities with zero slack are called *critical activities* and are said to be on the critical path. The critical path is a continuous path through the project network that:

- ◆ Starts at the first activity in the project (Start in our example).
- ◆ Terminates at the last activity in the project (H in our example).
- ◆ Includes only critical activities (i.e., activities with no slack time).

## Example 7

### SHOWING CRITICAL PATH WITH BLUE ARROWS

Show Milwaukee Paper's critical path and find the project completion time.

**APPROACH** ▶ We use Table 3.3 and Overlay 3 of Figure 3.10. Overlay 3 of Figure 3.10 indicates that the total project completion time of 15 weeks corresponds to the longest path in the network. That path is Start-A-C-E-G-H in network form. It is shown with thick blue arrows.

**INSIGHT** ▶ The critical path follows the activities with slack = 0. This is considered the longest path through the network.

**LEARNING EXERCISE** ▶ Why are activities B, D, and F not on the path with the thick blue line? [Answer: They are not critical and have slack values of 1, 1, and 6 weeks, respectively.]

**RELATED PROBLEMS** ▶ 3.5–3.11, 3.16, 3.19b, 3.21a

**Total Slack Time** Look again at the project network in Overlay 3 of Figure 3.10. Consider activities B and D, which have slack of 1 week each. Does it mean that we can delay *each* activity by 1 week, and still complete the project in 15 weeks? The answer is no.

Let's assume that activity B is delayed by 1 week. It has used up its slack of 1 week and now has an EF of 4. This implies that activity D now has an ES of 4 and an EF of 8. Note that these are also its LS and LF values, respectively. That is, activity D also has no slack time now. Essentially, the slack of 1 week that activities B and D had is, for that path, *shared* between them. Delaying either activity by 1 week causes not only that activity, but also the other activity, to lose its slack. This type of a slack time is referred to as *total slack*. Typically, when two or more noncritical activities appear successively in a path, they share total slack.



Tim Coggin/Alamy

To plan, monitor, and control the huge number of details involved in sponsoring a rock festival attended by more than 100,000 fans, managers use Microsoft Project and the tools discussed in this chapter. The *Video Case Study* “Managing Hard Rock’s Rockfest,” at the end of the chapter, provides more details of the management task.

## Variability in Activity Times

In identifying all earliest and latest times so far, and the associated critical path(s), we have adopted the CPM approach of assuming that all activity times are known and fixed constants. That is, there is no variability in activity times. However, in practice, it is likely that activity completion times vary depending on various factors.

For example, building internal components (activity A) for Milwaukee Paper Manufacturing is estimated to finish in 2 weeks. Clearly, supply-chain issues such as late arrival of materials, absence of key personnel, and so on could delay this activity. Suppose activity A actually ends up taking 3 weeks. Because A is on the critical path, the entire project will now be delayed by 1 week to 16 weeks. If we had anticipated completion of this project in 15 weeks, we would obviously miss our Earth Day deadline.

Although some activities may be relatively less prone to delays, others could be extremely susceptible to delays. For example, activity B (modify roof and floor) could be heavily dependent on weather conditions. A spell of bad weather could significantly affect its completion time.

This means that we cannot ignore the impact of variability in activity times when deciding the schedule for a project. PERT addresses this issue.

### STUDENT TIP

PERT’s ability to handle three time estimates for each activity enables us to compute the probability that we can complete the project by a target date.

## Three Time Estimates in PERT

In PERT, we employ a probability distribution based on three time estimates for each activity, as follows:

- Optimistic time** ( $a$ ) = time an activity will take if everything goes as planned. In estimating this value, there should be only a small probability (say, 1/100) that the activity time will be  $< a$ .
- Pessimistic time** ( $b$ ) = time an activity will take assuming very unfavorable conditions. In estimating this value, there should also be only a small probability (also 1/100) that the activity time will be  $> b$ .
- Most likely time** ( $m$ ) = most realistic estimate of the time required to complete an activity.

### Optimistic time

The “best” activity completion time that could be obtained in a PERT network.

### Pessimistic time

The “worst” activity time that could be expected in a PERT network.

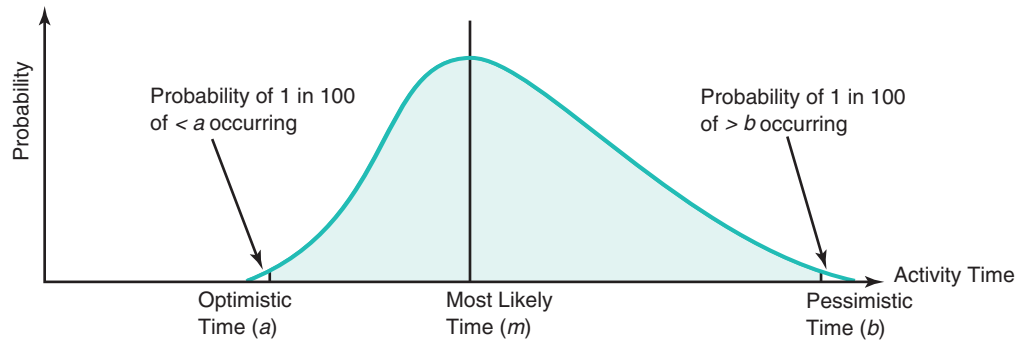
### Most likely time

The most probable time to complete an activity in a PERT network.

When using PERT, we often assume that activity time estimates follow the beta probability distribution (see Figure 3.11). This continuous distribution is often appropriate for determining the expected value and variance for activity completion times.

Figure 3.11

## Beta Probability Distribution with Three Time Estimates



To find the *expected activity time*,  $t$ , the beta distribution weights the three time estimates as follows:

$$t = (a + 4m + b)/6 \quad (3-6)$$

That is, the most likely time ( $m$ ) is given four times the weight as the optimistic time ( $a$ ) and pessimistic time ( $b$ ). The time estimate  $t$  computed using Equation (3-6) for each activity is used in the project network to compute all earliest and latest times.

To compute the *dispersion* or *variance of activity completion time*, we use the formula:<sup>1</sup>

$$\text{Variance} = [(b - a)/6]^2 \quad (3-7)$$

## Example 8

## EXPECTED TIMES AND VARIANCES FOR MILWAUKEE PAPER

Julie Ann Williams and the project management team at Milwaukee Paper want an expected time and variance for Activity F (Installing the Pollution Control System) where:

$$a = 1 \text{ week}, m = 2 \text{ weeks}, b = 9 \text{ weeks}$$

**APPROACH** ► Use Equations (3-6) and (3-7) to compute the expected time and variance for F.

**SOLUTION** ► The expected time for Activity F is:

$$t = \frac{a + 4m + b}{6} = \frac{1 + 4(2) + 9}{6} = \frac{18}{6} = 3 \text{ weeks}$$

The variance for Activity F is:

$$\text{Variance} = \left[ \frac{(b - a)}{6} \right]^2 = \left[ \frac{(9 - 1)}{6} \right]^2 = \left( \frac{8}{6} \right)^2 = \frac{64}{36} = 1.78$$

**INSIGHT** ► Williams now has information that allows her to understand and manage Activity F. The expected time is, in fact, the activity time used in our earlier computation and identification of the critical path.

**LEARNING EXERCISE** ► Review the expected times and variances for all of the other activities in the project. These are shown in Table 3.4.

TABLE 3.4 Time Estimates (in weeks) for Milwaukee Paper's Project

ACTIVITY	OPTIMISTIC $a$	MOST LIKELY $m$	PESSIMISTIC $b$	EXPECTED TIME $t = (a + 4m + b)/6$	VARIANCE $[(b - a)/6]^2$
A	1	2	3	2	$[(3 - 1)/6]^2 = 4/36 = .11$
B	2	3	4	3	$[(4 - 2)/6]^2 = 4/36 = .11$
C	1	2	3	2	$[(3 - 1)/6]^2 = 4/36 = .11$
D	2	4	6	4	$[(6 - 2)/6]^2 = 16/36 = .44$
E	1	4	7	4	$[(7 - 1)/6]^2 = 36/36 = 1.00$
F	1	2	9	3	$[(9 - 1)/6]^2 = 64/36 = 1.78$
G	3	4	11	5	$[(11 - 3)/6]^2 = 64/36 = 1.78$
H	1	2	3	2	$[(3 - 1)/6]^2 = 4/36 = .11$

**STUDENT TIP** ⚠

Can you see why the variance is higher in some activities than in others? Note the spread between the optimistic and pessimistic times.

**RELATED PROBLEMS** ► 3.17a, b, 3.18, 3.19a, 3.20a (3.26b, 3.27 are available in MyOMLab)

**EXCEL OM** Data File Ch03Ex8.xls can be found in MyOMLab.

Kim Hong-Ji/Reuters



Here we see a ship being built at the Hyundai shipyard, Asia's largest shipbuilder, in Korea. Managing this project uses the same techniques as managing the remodeling of a store, installing a new production line, or implementing a new computer system.

## Probability of Project Completion

The critical path analysis helped us determine that Milwaukee Paper's expected project completion time is 15 weeks. Julie Ann Williams knows, however, that there is significant variation in the time estimates for several activities. Variation in activities that are on the critical path can affect the overall project completion time—possibly delaying it. This is one occurrence that worries the plant manager considerably.

PERT uses the variance of critical path activities to help determine the variance of the overall project. Project variance is computed by summing variances of *critical* activities:

$$\sigma_p^2 = \text{Project variance} = \Sigma(\text{variances of activities on critical path}) \quad (3-8)$$

### Example 9

#### COMPUTING PROJECT VARIANCE AND STANDARD DEVIATION FOR MILWAUKEE PAPER

Milwaukee Paper's managers now wish to know the project's variance and standard deviation.

**APPROACH** ► Because the activities are independent, we can add the variances of the activities on the critical path and then take the square root to determine the project's standard deviation.

**SOLUTION** ► From Example 8 (Table 3.4), we have the variances of all of the activities on the critical path. Specifically, we know that the variance of activity A is 0.11, variance of activity C is 0.11, variance of activity E is 1.00, variance of activity G is 1.78, and variance of activity H is 0.11.

Compute the total project variance and project standard deviation:

$$\text{Project variance } (\sigma_p^2) = 0.11 + 0.11 + 1.00 + 1.78 + 0.11 = 3.11$$

which implies:

$$\text{Project standard deviation } (\sigma_p) = \sqrt{\text{Project variance}} = \sqrt{3.11} = 1.76 \text{ weeks}$$

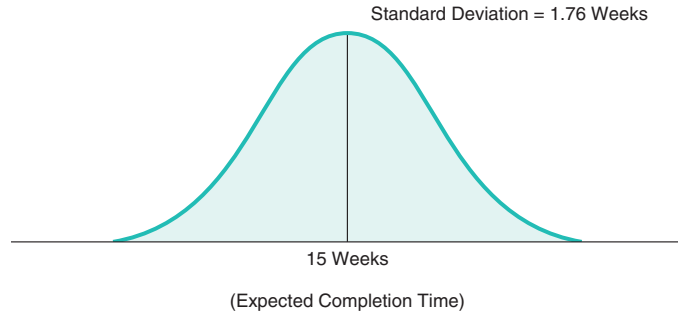
**INSIGHT** ► Management now has an estimate not only of expected completion time for the project but also of the standard deviation of that estimate.

**LEARNING EXERCISE** ► If the variance for activity A is actually 0.30 (instead of 0.11), what is the new project standard deviation? [Answer: 1.817.]

**RELATED PROBLEMS** ► 3.17e (3.24 is available in MyOMLab)

Figure 3.12

Probability Distribution  
for Project Completion Times  
at Milwaukee Paper



How can this information be used to help answer questions regarding the probability of finishing the project on time? PERT makes two more assumptions: (1) total project completion times follow a normal probability distribution, and (2) activity times are statistically independent. With these assumptions, the bell-shaped normal curve shown in Figure 3.12 can be used to represent project completion dates. This normal curve implies that there is a 50% chance that the manufacturer's project completion time will be less than 15 weeks and a 50% chance that it will exceed 15 weeks.

## Example 10

### PROBABILITY OF COMPLETING A PROJECT ON TIME

Julie Ann Williams would like to find the probability that her project will be finished on or before the 16-week Earth Day deadline.

**APPROACH** ▶ To do so, she needs to determine the appropriate area under the normal curve. This is the area to the left of the 16th week.

**SOLUTION** ▶ The standard normal equation can be applied as follows:

$$\begin{aligned} Z &= (\text{Due date} - \text{Expected date of completion})/\sigma_p \\ &= (16 \text{ weeks} - 15 \text{ weeks})/1.76 \text{ weeks} = 0.57 \end{aligned} \quad (3-9)$$

where  $Z$  is the number of standard deviations the due date or target date lies from the mean or expected date.

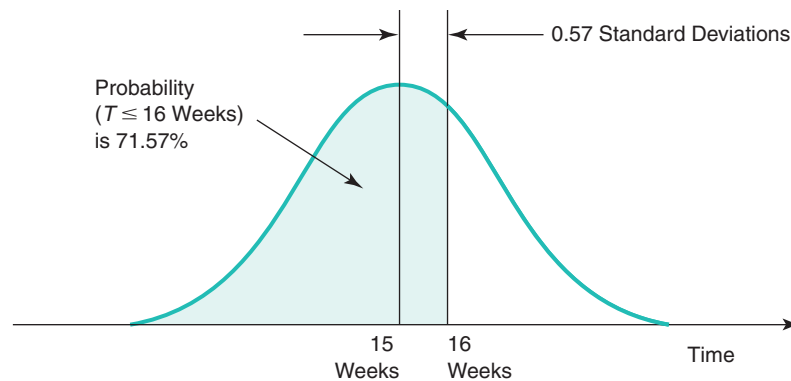
Referring to the Normal Table in Appendix I (alternatively using the Excel formula `=NORMSDIST(0.57)`), we find a  $Z$ -value of 0.57 to the right of the mean indicates a probability of 0.7157. Thus, there is a 71.57% chance that the pollution control equipment can be put in place in 16 weeks or less. This is shown in Figure 3.13.

#### STUDENT TIP

Here is a chance to review your statistical skills and use of a normal distribution table (Appendix I).

Figure 3.13

Probability That Milwaukee Paper Will Meet the 16-Week Deadline



**INSIGHT** ▶ The shaded area to the left of the 16th week (71.57%) represents the probability that the project will be completed in less than 16 weeks.

**LEARNING EXERCISE** ▶ What is the probability that the project will be completed on or before the 17th week? [Answer: About 87.2%.]

**RELATED PROBLEMS** ▶ 3.17f, 3.19d, 3.20d, 3.21b, 3.23 (3.25, 3.26e,f,g are available in MyOMLab)

**Determining Project Completion Time for a Given Confidence Level** Let's say Julie Ann Williams is worried that there is only a 71.57% chance that the pollution control equipment can be put in place in 16 weeks or less. She thinks that it may be possible to plead with the board of directors for more time. However, before she approaches the board, she wants to arm herself with sufficient information about the project. Specifically, she wants to find the deadline by which she has a 99% chance of completing the project. She hopes to use her analysis to convince the board to agree to this extended deadline, even though she is aware of the public relations damage the delay will cause.

Clearly, this due date would be greater than 16 weeks. However, what is the exact value of this new due date? To answer this question, we again use the assumption that Milwaukee Paper's project completion time follows a normal probability distribution with a mean of 15 weeks and a standard deviation of 1.76 weeks.

## Example 11

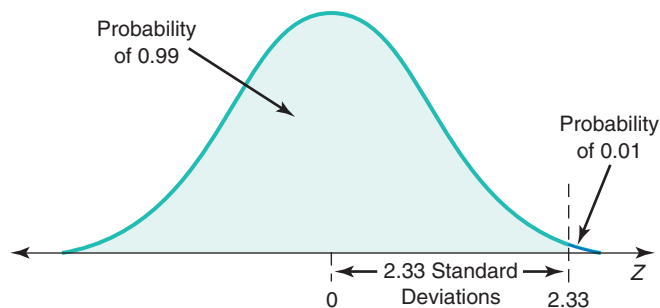
### COMPUTING PROBABILITY FOR ANY COMPLETION DATE

Julie Ann Williams wants to find the due date that gives her company's project a 99% chance of *on-time* completion.

**APPROACH** ▶ She first needs to compute the Z-value corresponding to 99%, as shown in Figure 3.14. Mathematically, this is similar to Example 10, except the unknown is now the due date rather than Z.

Figure 3.14

**Z-Value for 99% Probability of Project Completion at Milwaukee Paper**



**SOLUTION** ▶ Referring again to the Normal Table in Appendix I (alternatively using the Excel formula `=NORMSINV(0.99)`), we identify a Z-value of 2.33 as being closest to the probability of 0.99. That is, Julie Ann Williams's due date should be 2.33 standard deviations above the mean project completion time. Starting with the standard normal equation [see Equation (3-9)], we can solve for the due date and rewrite the equation as:

$$\begin{aligned} \text{Due date} &= \text{Expected completion time} + (Z \times \sigma_p) \\ &= 15 + (2.33 \times 1.76) = 19.1 \text{ weeks} \end{aligned} \quad (3-10)$$

**INSIGHT** ▶ If Williams can get the board to agree to give her a new deadline of 19.1 weeks (or more), she can be 99% sure of finishing the project by that new target date.

**LEARNING EXERCISE** ▶ What due date gives the project a 95% chance of on-time completion? [Answer: About 17.9 weeks.]

**RELATED PROBLEMS** ▶ 3.21c, 3.23e

**Variability in Completion Time of Noncritical Paths** In our discussion so far, we have focused exclusively on the variability in the completion times of activities on the critical path. This seems logical because these activities are, by definition, the more important activities in a project network. However, when there is variability in activity times, it is important that we also investigate the variability in the completion times of activities on *noncritical* paths.

Consider, for example, activity D in Milwaukee Paper's project. Recall from Overlay 3 in Figure 3.10 (in Example 7) that this is a noncritical activity, with a slack time of 1 week. We have therefore not considered the variability in D's time in computing the probabilities of project completion times. We observe, however, that D has a variance of 0.44 (see Table 3.4 in

Example 8). In fact, the pessimistic completion time for D is 6 weeks. This means that if D ends up taking its pessimistic time to finish, the project will not finish in 15 weeks, even though D is not a critical activity.

For this reason, when we find probabilities of project completion times, it may be necessary for us to not focus only on the critical path(s). Indeed, some research has suggested that expending project resources to reduce the variability of activities not on the critical path can be an effective element in project management. We may need also to compute these probabilities for noncritical paths, especially those that have relatively large variances. It is possible for a noncritical path to have a smaller probability of completion within a due date, when compared with the critical path. Determining the variance and probability of completion for a noncritical path is done in the same manner as Examples 9 and 10.

**What Project Management Has Provided So Far** Project management techniques have thus far been able to provide Julie Ann Williams with several valuable pieces of management information:

1. The project's expected completion date is 15 weeks.
2. There is a 71.57% chance that the equipment will be in place within the 16-week deadline. PERT analysis can easily find the probability of finishing by any date Williams is interested in.
3. Five activities (A, C, E, G, and H) are on the critical path. If any one of these is delayed for any reason, the entire project will be delayed.
4. Three activities (B, D, F) are not critical and have some slack time built in. This means that Williams can borrow from their resources, and, if necessary, she may be able to speed up the whole project.
5. A detailed schedule of activity starting and ending dates, slack, and critical path activities has been made available (see Table 3.3 in Example 6).

## Cost-Time Trade-Offs and Project Crashing

While managing a project, it is not uncommon for a project manager to be faced with either (or both) of the following situations: (1) the project is behind schedule, and (2) the scheduled project completion time has been moved forward. In either situation, some or all of the remaining activities need to be speeded up (usually by adding resources) to finish the project by the desired due date. The process by which we shorten the duration of a project in the cheapest manner possible is called project **crashing**.

### Crashing

Shortening activity time in a network to reduce time on the critical path so total completion time is reduced.

CPM is a technique in which each activity has a *normal* or *standard* time that we use in our computations. Associated with this normal time is the *normal* cost of the activity. However, another time in project management is the *crash time*, which is defined as the shortest duration required to complete an activity. Associated with this crash time is the *crash cost* of the activity. Usually, we can shorten an activity by adding extra resources (e.g., equipment, people) to it. Hence, it is logical for the crash cost of an activity to be higher than its normal cost.

The amount by which an activity can be shortened (i.e., the difference between its normal time and crash time) depends on the activity in question. We may not be able to shorten some activities at all. For example, if a casting needs to be heat-treated in the furnace for 48 hours, adding more resources does not help shorten the time. In contrast, we may be able to shorten some activities significantly (e.g., frame a house in 3 days instead of 10 days by using three times as many workers).

Likewise, the cost of crashing (or shortening) an activity depends on the nature of the activity. Managers are usually interested in speeding up a project at the least additional cost. Hence, when choosing which activities to crash, and by how much, we need to ensure the following:

- ◆ The amount by which an activity is crashed is, in fact, permissible
- ◆ Taken together, the shortened activity durations will enable us to finish the project by the due date
- ◆ The total cost of crashing is as small as possible



Crashing a project involves four steps:

**LO 3.6** Crash a project

**STEP 1:** Compute the crash cost per week (or other time period) for each activity in the network. If crash costs are linear over time, the following formula can be used:

$$\text{Crash cost per period} = \frac{(\text{Crash cost} - \text{Normal cost})}{(\text{Normal time} - \text{Crash time})} \quad (3-11)$$

**STEP 2:** Using the current activity times, find the critical path(s) in the project network. Identify the critical activities.

**STEP 3:** If there is only one critical path, then select the activity on this critical path that (a) can still be crashed and (b) has the smallest crash cost per period. Crash this activity by one period.

If there is more than one critical path, then select one activity from each critical path such that (a) each selected activity can still be crashed and (b) the total crash cost per period of *all* selected activities is the smallest. Crash each activity by one period. Note that the same activity may be common to more than one critical path.

**STEP 4:** Update all activity times. If the desired due date has been reached, stop. If not, return to Step 2.

We illustrate project crashing in Example 12.

### Example 12

#### PROJECT CRASHING TO MEET A DEADLINE AT MILWAUKEE PAPER

Suppose the plant manager at Milwaukee Paper Manufacturing has been given only 13 weeks (instead of 16 weeks) to install the new pollution control equipment. As you recall, the length of Julie Ann Williams’s critical path was 15 weeks, but she must now complete the project in 13 weeks.

**APPROACH** ► Williams needs to determine which activities to crash, and by how much, to meet this 13-week due date. Naturally, Williams is interested in speeding up the project by 2 weeks, at the least additional cost.

**SOLUTION** ► The company’s normal and crash times, and normal and crash costs, are shown in Table 3.5. Note, for example, that activity B’s normal time is 3 weeks (the estimate used in computing the critical path), and its crash time is 1 week. This means that activity B can be shortened by up to 2 weeks if extra resources are provided. The cost of these additional resources is \$4,000 (= difference between the crash cost of \$34,000 and the normal cost of \$30,000). If we assume that the crashing cost is linear over time (i.e., the cost is the same each week), activity B’s crash cost per week is \$2,000 (= \$4,000/2).

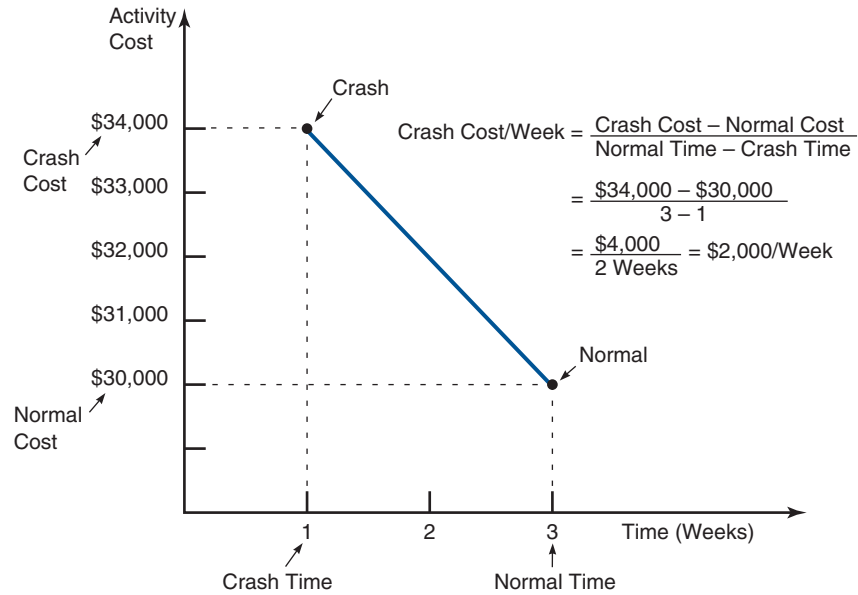
**TABLE 3.5** Normal and Crash Data for Milwaukee Paper Manufacturing

ACTIVITY	TIME (WEEKS)		COST (\$)		CRASH COST PER WEEK (\$)	CRITICAL PATH?
	NORMAL	CRASH	NORMAL	CRASH		
A	2	1	22,000	22,750	750	Yes
B	3	1	30,000	34,000	2,000	No
C	2	1	26,000	27,000	1,000	Yes
D	4	3	48,000	49,000	1,000	No
E	4	2	56,000	58,000	1,000	Yes
F	3	2	30,000	30,500	500	No
G	5	2	80,000	84,500	1,500	Yes
H	2	1	16,000	19,000	3,000	Yes

This calculation for Activity B is shown in Figure 3.15. Crash costs for all other activities can be computed in a similar fashion.

Figure 3.15

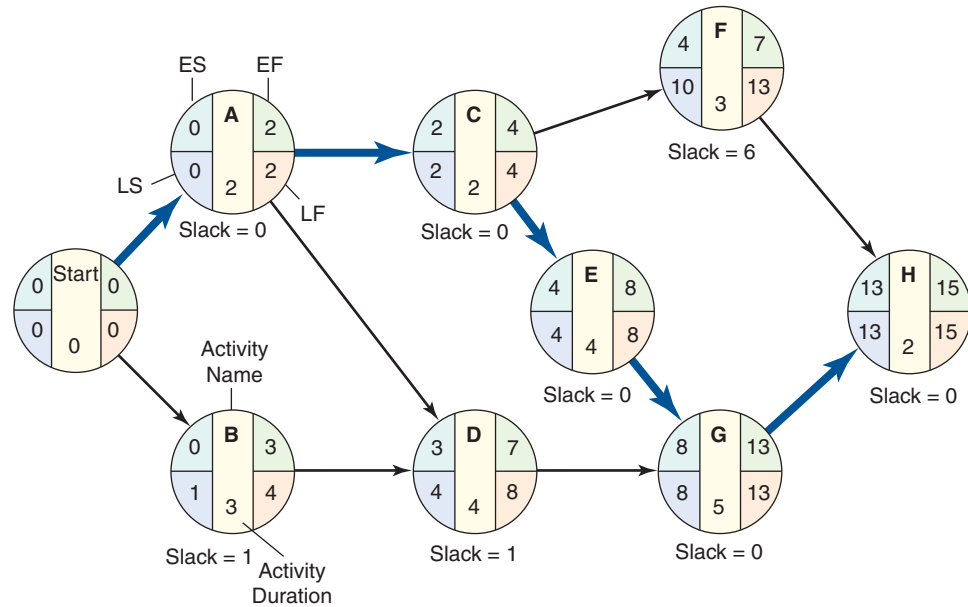
Crash and Normal Times and Costs for Activity B



Steps 2, 3, and 4 can now be applied to reduce Milwaukee Paper's project completion time at a minimum cost. We show the project network for Milwaukee Paper again in Figure 3.16.

Figure 3.16

Critical Path and Slack Times for Milwaukee Paper



The current critical path (using normal times) is Start–A–C–E–G–H, in which Start is just a dummy starting activity. Of these critical activities, activity A has the lowest crash cost per week of \$750. Julie Ann Williams should therefore crash activity A by 1 week to reduce the project completion time to 14 weeks. The cost is an additional \$750. Note that activity A cannot be crashed any further, since it has reached its crash limit of 1 week.

At this stage, the original path Start–A–C–E–G–H remains critical with a completion time of 14 weeks. However, a new path Start–B–D–G–H is also critical now, with a completion time of 14 weeks. Hence, any further crashing must be done to both critical paths.

On each of these critical paths, we need to identify one activity that can still be crashed. We also want the total cost of crashing an activity on each path to be the smallest. We might be tempted to simply pick the activities with the smallest crash cost per period in each path. If we did this, we would select activity C from the first path and activity D from the second path. The total crash cost would then be \$2,000 (= \$1,000 + \$1,000).

But we spot that activity G is common to both paths. That is, by crashing activity G, we will simultaneously reduce the completion time of both paths. Even though the \$1,500 crash cost for activity G is higher than that for activities C and D, we would still prefer crashing G because the total crashing cost will now be only \$1,500 (compared with the \$2,000 if we crash C and D).

**INSIGHT** ► To crash the project down to 13 weeks, Williams should crash activity A by 1 week and activity G by 1 week. The total additional cost will be \$2,250 (= \$750 + \$1,500). This is important because many contracts for projects include bonuses or penalties for early or late finishes.

**LEARNING EXERCISE** ► Say the crash cost for activity B is \$31,000 instead of \$34,000. How does this change the answer? [Answer: no change.]

**RELATED PROBLEMS** ► 3.28–3.32 (3.33 is available in MyOMLab)

**EXCEL OM** Data File Ch03Ex12.xls can be found in MyOMLab.

## A Critique of PERT and CPM

As a critique of our discussions of PERT, here are some of its features about which operations managers need to be aware:

### Advantages

1. Especially useful when scheduling and controlling large projects.
2. Straightforward concept and not mathematically complex.
3. Graphical networks help highlight relationships among project activities.
4. Critical path and slack time analyses help pinpoint activities that need to be closely watched.
5. Project documentation and graphs point out who is responsible for various activities.
6. Applicable to a wide variety of projects.
7. Useful in monitoring not only schedules but costs as well.

## OM in Action Behind the Tour de France

The large behind-the-scenes operations that support a football World Cup or Formula One racing team are well-known, but a Tour de France team also needs major support. “A Tour de France team is like a large traveling circus,” says the coach of the Belkin team. “The public only sees the riders, but they could not function without the unseen support staff.” The base to the team’s cycling pyramid includes everything from osteopaths to mechanics, from logistics staff to PR people. Their project management skills require substantial know-how, as well as the ability to guarantee that riders are in peak physical, nutritional, and psychological condition. This can mean deciding which snack bars to give the cyclists before, during, and after race stages, while ensuring there are scientifically based cooling regimens in place for the riders. The team’s huge truck, coach, three vans, and five cars resemble the sort of traveling convoy more associated with an international music act. Here are just some of the supplies the project management team for Belkin handles:

- ◆ 11 mattresses
- ◆ 36 aero suits, 45 bib shorts, 54 race jerseys, 250 podium caps
- ◆ 63 bikes
- ◆ 140 wheels, 220 tires
- ◆ 250 feeding bags, 3,000 water bottles
- ◆ 2,190 nutrition gels, 3,800 nutrition bars



Marc Paganini Photography/Shutterstock

- ◆ 10 jars of peanut butter, 10 boxes of chocolate sprinkles, 20 bags of wine gums, 20 jars of jam
- ◆ 80 kg of nuts, raisins, apricots, and figs, plus 50 kg of cereals

The project management behind a world-tour team is complex: These top teams often compete in two to three races simultaneously, in different countries and sometimes on different continents. Each team has 25–35 riders (9 compete in any single race), coming from different parts of the world, going to different races at different times, each with his own physique and strengths. They have customized bikes, uniforms, and food preferences. The support staff can include another 30 people.

Sources: BBC News (July 6, 2014) and *The Operations Room* (June 24, 2013).

**Limitations**

1. Project activities have to be clearly defined, independent, and stable in their relationships.
2. Precedence relationships must be specified and networked together.
3. Time estimates tend to be subjective and are subject to fudging by managers who fear the dangers of being overly optimistic or not pessimistic enough.
4. There is the inherent danger of placing too much emphasis on the longest, or critical, path. Near-critical paths need to be monitored closely as well.

## Using Microsoft Project to Manage Projects

The approaches discussed so far are effective for managing small projects. However, for large or complex projects, specialized project management software is much preferred. In this section, we provide a brief introduction to the most popular example of such specialized software, Microsoft Project. A time-limited version of Microsoft Project may be requested with this text.

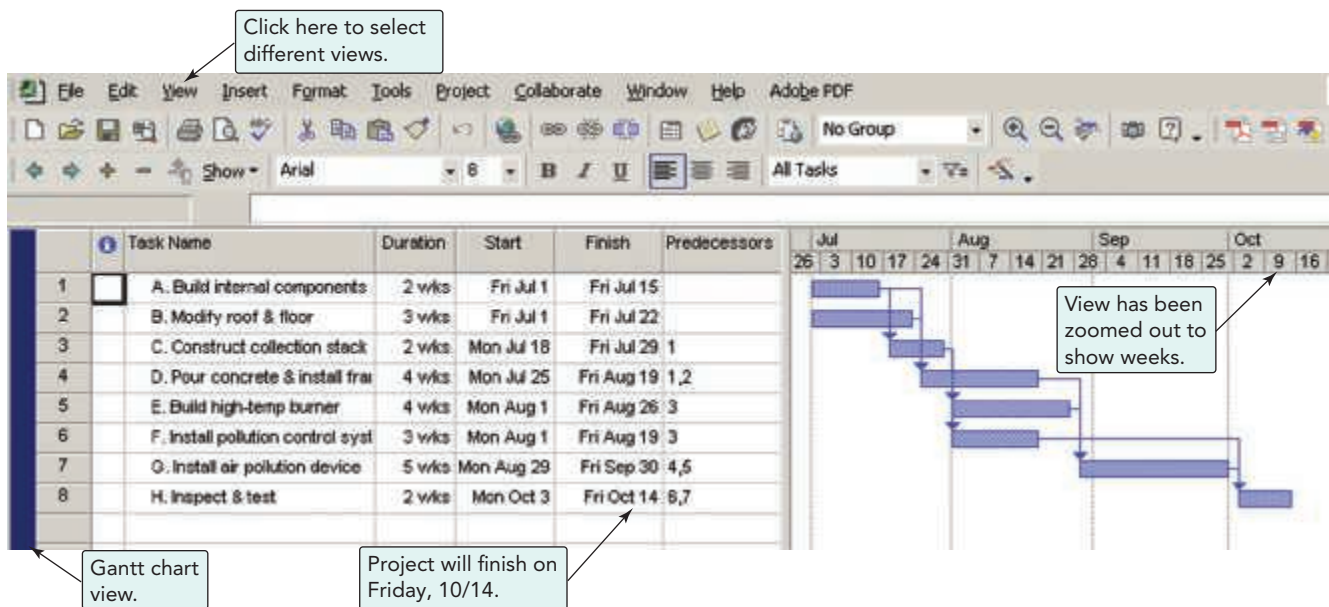
Milwaukee Paper Co. Activities		
ACTIVITY	TIME (WKS)	PREDECESSORS
A	2	—
B	3	—
C	2	A
D	4	A, B
E	4	C
F	3	C
G	5	D, E
H	2	F, G

Microsoft Project is extremely useful in drawing project networks, identifying the project schedule, and managing project costs and other resources.

**Entering Data** Let us again consider the Milwaukee Paper Manufacturing project. Recall that this project has eight activities (repeated in the margin). The first step is to define the activities and their precedence relationships. To do so, we select **File|New** to open a blank project. We type the project start date (as July 1), then enter all activity information (see Program 3.1). For each activity (or task, as Microsoft Project calls it), we fill in the name and duration. The description of the activity is also placed in the *Task Name* column in Program 3.1. As we enter activities and durations, the software automatically inserts start and finish dates.

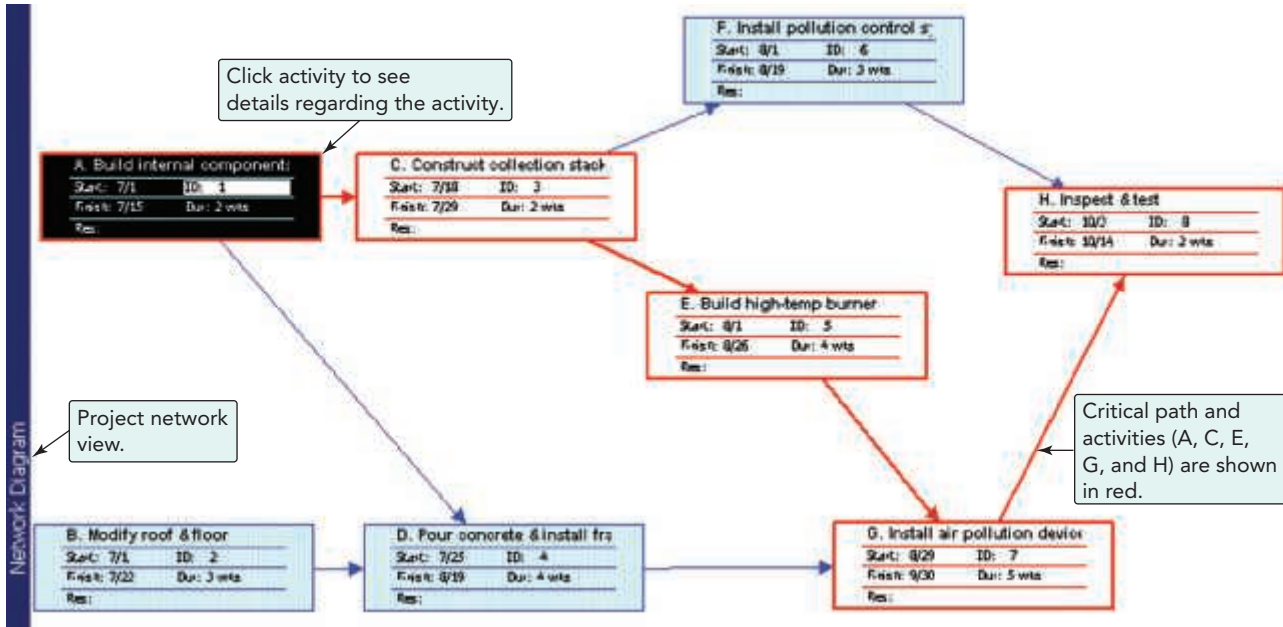
The next step is to define precedence relationships between these activities. To do so, we enter the relevant activity numbers (e.g., 1, 2) in the *Predecessors* column.

**Viewing the Project Schedule** When all links have been defined, the complete project schedule can be viewed as a Gantt chart. We can also select **View|Network Diagram** to view the schedule as a project network (shown in Program 3.2). The critical path is shown in red on the



Program 3.1

Gantt Chart in Microsoft Project for Milwaukee Paper Manufacturing



Program 3.2

**Project Network in Microsoft Project for Milwaukee Paper Manufacturing**

screen in the network diagram. We can click on any of the activities in the project network to view details of the activities. Likewise, we can easily add or remove activities from the project network. Each time we do so, Microsoft Project automatically updates all start dates, finish dates, and the critical path(s). If desired, we can manually change the layout of the network (e.g., reposition activities) by changing the options in **Format|Layout**.

Programs 3.1 and 3.2 show that if Milwaukee Paper’s project starts July 1, it can be finished on October 14. The start and finish dates for all activities are also clearly identified. Project management software, we see, can greatly simplify the scheduling procedures discussed earlier in this chapter.

**PERT Analysis** Microsoft Project does not perform the PERT probability calculations discussed in Examples 10 and 11. However, by clicking **View|Toolbars|PERT Analysis**, we can get Microsoft Project to allow us to enter optimistic, most likely, and pessimistic times for each activity. We can then choose to view Gantt charts based on any of these three times for each activity.

**Tracking the Time Status of a Project** Perhaps the biggest advantage of using software to manage projects is that it can track the progress of the project. In this regard, Microsoft Project has many features available to track individual activities in terms of time, cost, resource usage, and so on.

An easy way to track the time progress of tasks is to enter the percent of work completed for each task. One way to do so is to double-click on any activity in the *Task Name* column in Program 3.1. A window is displayed that allows us to enter the percent of work completed for each task.

The table in the margin provides data regarding the percent of each of Milwaukee Paper’s activities that are completed as of today. (Assume that today is Friday, August 12, i.e., the end of the sixth week of the project schedule.)

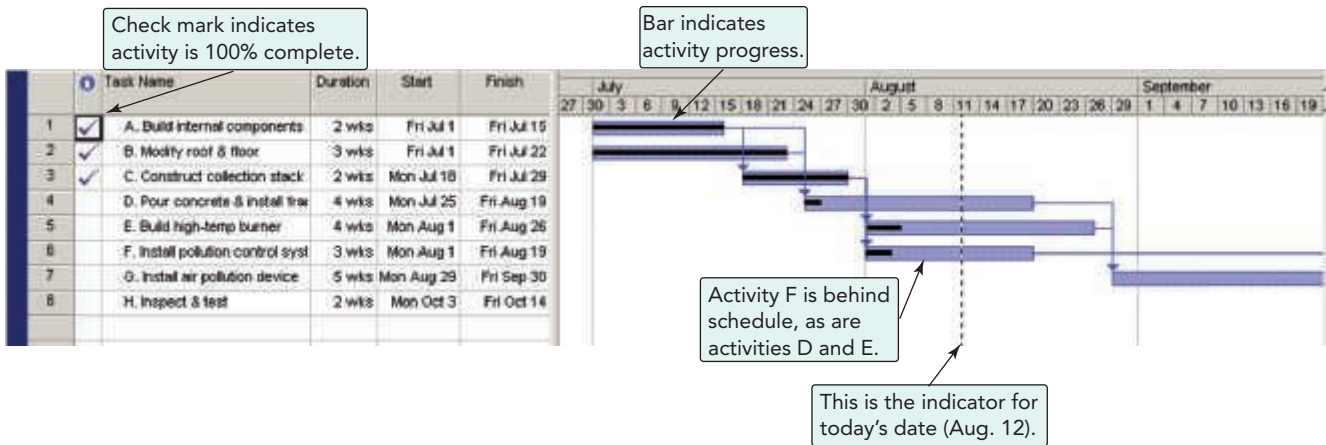
As shown in Program 3.3, the Gantt chart immediately reflects this updated information by drawing a thick line within each activity’s bar. The length of this line is proportional to the percent of that activity’s work that has been completed.

How do we know if we are on schedule? Notice that there is a vertical line shown on the Gantt chart corresponding to today’s date. Microsoft Project will automatically move this line to correspond with the current date. If the project is on schedule, we should see all bars to the *left*

**STUDENT TIP**

Now that you understand the workings of PERT and CPM, you are ready to master this useful program. Knowing such software gives you an edge over others in the job market.

Pollution Project Percentage Completed on Aug. 12	
ACTIVITY	COMPLETED
A	100
B	100
C	100
D	10
E	20
F	20
G	0
H	0



### Program 3.3

#### Tracking Project Progress in Microsoft Project

of today's line indicate that they have been completed. For example, Program 3.3 shows that activities A, B, and C are on schedule. In contrast, activities D, E, and F appear to be behind schedule. These activities need to be investigated further to determine the reason for the delay. This type of easy *visual* information is what makes such software so useful in practice for project management.

We encourage you to load the copy of Microsoft Project that may be ordered with your text and to create a project network for work you are currently doing.

## Summary

PERT, CPM, and other scheduling techniques have proven to be valuable tools in controlling large and complex projects. Managers use such techniques to segment projects into discrete activities (work breakdown structures), indentifying specific resources and time requirements for each. With PERT and CPM, managers can understand the status of each activity, including its earliest start, latest start, earliest finish, and latest finish (ES, LS, EF, and LF) times. By controlling the trade-off between ES and LS, managers can identify the activities that have slack and can address resource allocation, perhaps by smoothing resources. Effective project management also allows managers to focus on the activities that are critical to timely project

completion. By understanding the project's critical path, they know where crashing makes the most economic sense.

Good project management also allows firms to efficiently create products and services for global markets and to respond effectively to global competition. Microsoft Project, illustrated in this chapter, is one of a wide variety of software packages available to help managers handle network modeling problems.

The models described in this chapter require good management practices, detailed work breakdown structures, clear responsibilities assigned to activities, and straightforward and timely reporting systems. All are critical parts of project management.

### Key Terms

Project organization (p. 62)  
 Work breakdown structure (WBS) (p. 64)  
 Gantt charts (p. 65)  
 Program evaluation and review technique (PERT) (p. 67)  
 Critical path method (CPM) (p. 67)

Critical path (p. 67)  
 Activity-on-node (AON) (p. 68)  
 Activity-on-arrow (AOA) (p. 68)  
 Dummy activity (p. 70)  
 Critical path analysis (p. 71)  
 Forward pass (p. 72)

Backward pass (p. 74)  
 Slack time (p. 75)  
 Optimistic time (p. 77)  
 Pessimistic time (p. 77)  
 Most likely time (p. 77)  
 Crashing (p. 82)

## Ethical Dilemma

Two examples of massively mismanaged projects are TAURUS and the “Big Dig.” The first, formally called the London Stock Exchange Automation Project, cost \$575 million before it was finally abandoned. Although most IT projects have a reputation for cost overruns, delays, and underperformance, TAURUS set a new standard.

But even TAURUS paled next to the biggest, most expensive public works project in U.S. history—Boston’s 15-year-long Central Artery/Tunnel Project. Called the Big Dig, this was

perhaps the poorest and most felonious case of project mismanagement in decades. From a starting \$2 billion budget to a final price tag of \$15 billion, the Big Dig cost more than the Panama Canal, Hoover Dam, or Interstate 95, the 1,919-mile highway between Maine and Florida.

Read about one of these two projects (or another of your choice) and explain why it faced such problems. How and why do project managers allow such massive endeavors to fall into such a state? What do you think are the causes?

## Discussion Questions

1. Give an example of a situation in which project management is needed.
2. Explain the purpose of project organization.
3. What are the three phases involved in the management of a large project?
4. What are some of the questions that can be answered with PERT and CPM?
5. Define *work breakdown structure*. How is it used?
6. What is the use of Gantt charts in project management?
7. What is the difference between an activity-on-arrow (AOA) network and an activity-on-node (AON) network? Which is primarily used in this chapter?
8. What is the significance of the critical path?
9. What would a project manager have to do to crash an activity?
10. Describe how expected activity times and variances can be computed in a PERT network.
11. Define *earliest start*, *earliest finish*, *latest finish*, and *latest start* times.
12. Students are sometimes confused by the concept of critical path, and want to believe that it is the *shortest* path through a network. Convincingly explain why this is not so.
13. What are dummy activities? Why are they used in activity-on-arrow (AOA) project networks?
14. What are the three time estimates used with PERT?
15. Would a project manager ever consider crashing a noncritical activity in a project network? Explain convincingly.
16. How is the variance of the total project computed in PERT?
17. Describe the meaning of slack, and discuss how it can be determined.
18. How can we determine the probability that a project will be completed by a certain date? What assumptions are made in this computation?
19. Name some of the widely used project management software programs.
20. What is the difference between the *waterfall* approach and *agile* project management?

## Using Software to Solve Project Management Problems

In addition to the Microsoft Project software illustrated earlier, both Excel OM and POM for Windows are available to readers of this text as project management tools.

### ✕ USING EXCEL OM

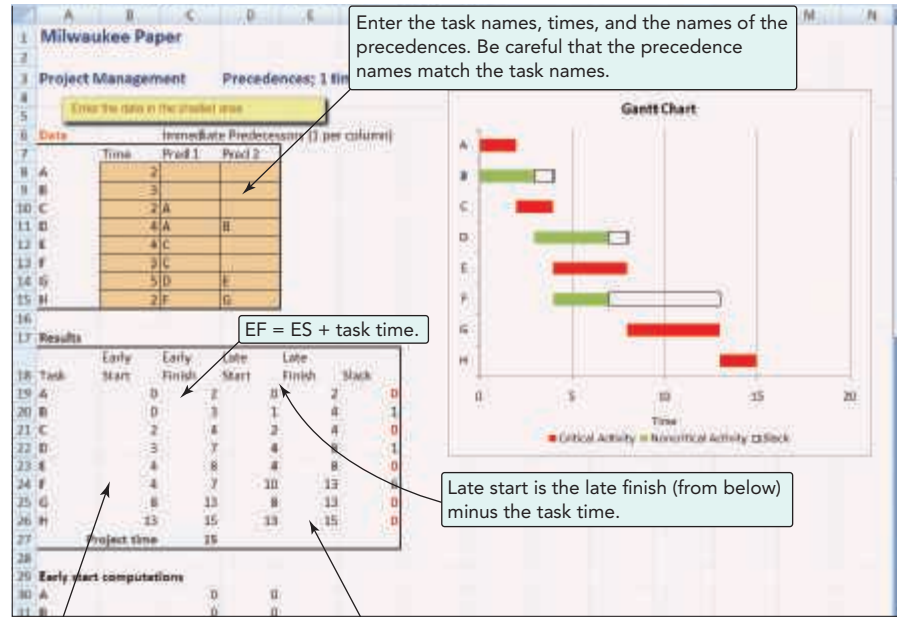
Excel OM has a Project Scheduling module. Program 3.4 uses the data from the Milwaukee Paper Manufacturing example in this chapter (see Examples 4 and 5). The PERT/CPM analysis also handles activities with three time estimates.

### P USING POM FOR WINDOWS

POM for Windows’s Project Scheduling module can also find the expected project completion time for a CPM and PERT network with either one or three time estimates. POM for Windows also performs project crashing. For further details refer to Appendix IV.

Program 3.4

Excel OM's Use of Milwaukee Paper Manufacturing's Data from Examples 4 and 5



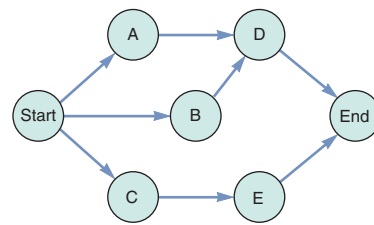
Solved Problems Virtual Office Hours help is available in MyOMLab.

SOLVED PROBLEM 3.1

Construct an AON network based on the following:

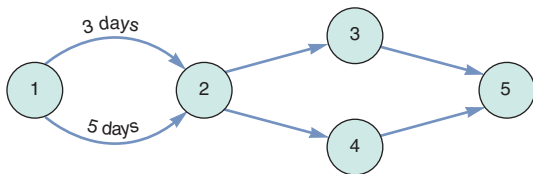
ACTIVITY	IMMEDIATE PREDECESSOR(S)
A	—
B	—
C	—
D	A, B
E	C

SOLUTION



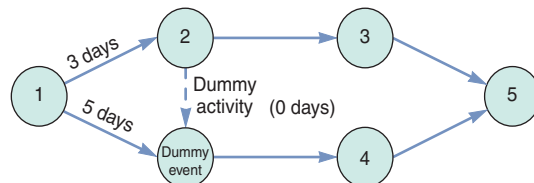
SOLVED PROBLEM 3.2

Insert a dummy activity and event to correct the following AOA network:



SOLUTION

Because we cannot have two activities starting and ending at the same node, we add the following dummy activity and dummy event to obtain the correct AOA network:

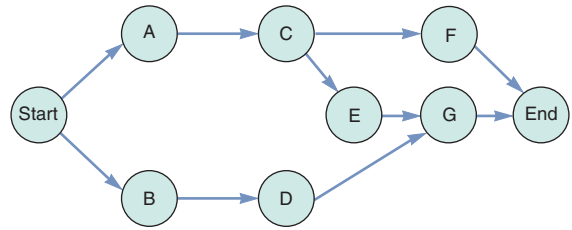




**SOLVED PROBLEM 3.3**

Calculate the critical path, project completion time  $T$ , and project variance  $\sigma_p^2$ , based on the following AON network information:

ACTIVITY	TIME	VARIANCE	ES	EF	LS	LF	SLACK
A	2	$\frac{2}{6}$	0	2	0	2	0
B	3	$\frac{2}{6}$	0	3	1	4	1
C	2	$\frac{4}{6}$	2	4	2	4	0
D	4	$\frac{4}{6}$	3	7	4	8	1
E	4	$\frac{2}{6}$	4	8	4	8	0
F	3	$\frac{1}{6}$	4	7	10	13	6
G	5	$\frac{1}{6}$	8	13	8	13	0



**SOLUTION**

We conclude that the critical path is Start–A–C–E–G–End:

Total project time =  $T = 2 + 2 + 4 + 5 = 13$   
and

$$\sigma_p^2 = \sum \text{Variances on the critical path}$$

$$= \frac{2}{6} + \frac{4}{6} + \frac{2}{6} + \frac{1}{6} = \frac{9}{6} = 1.5$$

**SOLVED PROBLEM 3.4**

To complete the wing assembly for an experimental aircraft, Jim Gilbert has laid out the seven major activities involved. These activities have been labeled A through G in the following table, which also shows their estimated completion times (in weeks) and immediate predecessors. Determine the expected time and variance for each activity.

ACTIVITY	$a$	$m$	$b$	IMMEDIATE PREDECESSORS
A	1	2	3	—
B	2	3	4	—
C	4	5	6	A
D	8	9	10	B
E	2	5	8	C, D
F	4	5	6	D
G	1	2	3	E

**SOLUTION**

Expected times and variances can be computed using Equations (3–6) and (3–7) presented on page 78 in this chapter. The results are summarized in the following table:

ACTIVITY	EXPECTED TIME (IN WEEKS)	VARIANCE
A	2	$\frac{1}{9}$
B	3	$\frac{1}{9}$
C	5	$\frac{1}{9}$
D	9	$\frac{1}{9}$
E	5	1
F	5	$\frac{1}{9}$
G	2	$\frac{1}{9}$

**SOLVED PROBLEM 3.5**

Referring to Solved Problem 3.4, now Jim Gilbert would like to determine the critical path for the entire wing assembly project as well as the expected completion time for the total project. In addition, he would like to determine the earliest and latest start and finish times for all activities.

**SOLUTION**

The AON network for Gilbert’s project is shown in Figure 3.17. Note that this project has multiple activities (A and B) with no immediate predecessors, and multiple activities (F and G) with no successors. Hence, in addition to a unique starting activity (Start), we have included a unique finishing activity (End) for the project.

Figure 3.17 shows the earliest and latest times for all activities. The results are also summarized in the following table:

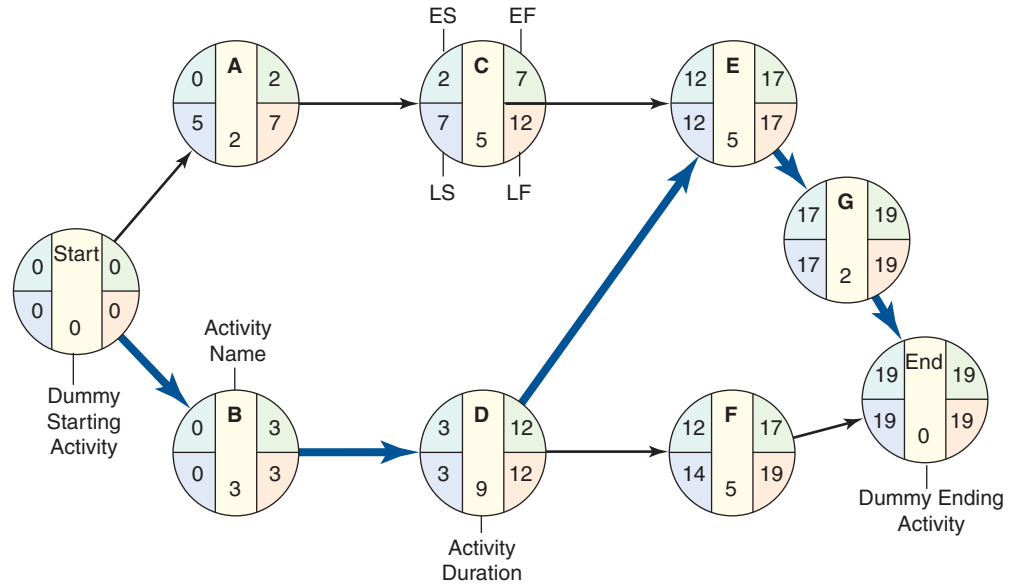
ACTIVITY	ACTIVITY TIME				SLACK
	ES	EF	LS	LF	
A	0	2	5	7	5
B	0	3	0	3	0
C	2	7	7	12	5
D	3	12	3	12	0
E	12	17	12	17	0
F	12	17	14	19	2
G	17	19	17	19	0

Expected project length = 19 weeks  
Variance of the critical path = 1.333  
Standard deviation of the critical path = 1.155 weeks

The activities along the critical path are B, D, E, and G. These activities have zero slack as shown in the table.

Figure 3.17

**Critical Path for Solved Problem 3.5**



**SOLVED PROBLEM 3.6**

The following information has been computed from a project:

Expected total project time =  $T = 62$  weeks

Project variance ( $\sigma_p^2$ ) = 81

What is the probability that the project will be completed 18 weeks before its expected completion date?

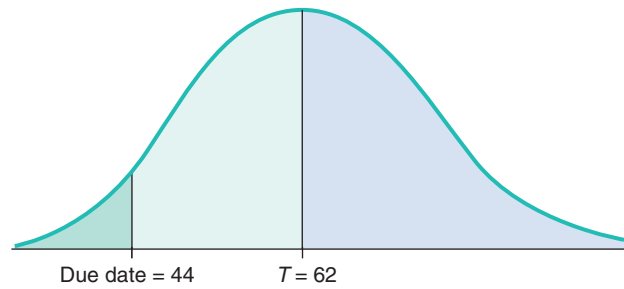
**SOLUTION**

The desired completion date is 18 weeks before the expected completion date, 62 weeks. The desired completion date is 44 (or  $62 - 18$ ) weeks:

$$\sigma_p = \sqrt{\text{Project variance}}$$

$$Z = \frac{\text{Due date} - \text{Expected completion date}}{\sigma_p} = \frac{44 - 62}{9} = \frac{-18}{9} = -2.0$$

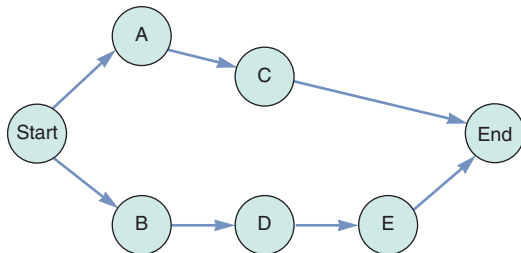
The normal curve appears as follows:



Because the normal curve is symmetrical and table values are calculated for positive values of  $Z$ , the area desired is equal to  $1 - (\text{table value})$ . For  $Z = +2.0$  the area from the table is .97725. Thus, the area corresponding to a  $Z$ -value of  $-2.0$  is .02275 (or  $1 - .97725$ ). Hence, the probability of completing the project 18 weeks before the expected completion date is approximately .023, or 2.3%.

**SOLVED PROBLEM 3.7**

Determine the least cost of reducing the project completion date by 3 months based on the following information:



ACTIVITY	NORMAL TIME (MONTHS)	CRASH TIME (MONTHS)	NORMAL COST	CRASH COST
A	6	4	\$2,000	\$2,400
B	7	5	3,000	3,500
C	7	6	1,000	1,300
D	6	4	2,000	2,600
E	9	8	8,800	9,000

**SOLUTION**

The first step in this problem is to compute ES, EF, LS, LF, and slack for each activity.

ACTIVITY	ES	EF	LS	LF	SLACK
A	0	6	9	15	9
B	0	7	0	7	0
C	6	13	15	22	9
D	7	13	7	13	0
E	13	22	13	22	0

The critical path consists of activities B, D, and E.

Next, crash cost/month must be computed for each activity:

ACTIVITY	NORMAL TIME-CRASH TIME	CRASH COST-NORMAL COST	CRASH COST/MONTH	CRITICAL PATH?
A	2	\$400	\$200/month	No
B	2	500	250/month	Yes
C	1	300	300/month	No
D	2	600	300/month	Yes
E	1	200	200/month	Yes

Finally, we will select that activity on the critical path with the smallest crash cost/month. This is activity E. Thus, we can reduce the total project completion date by 1 month for an

additional cost of \$200. We still need to reduce the project completion date by 2 more months. This reduction can be achieved at least cost along the critical path by reducing activity B by 2 months for an additional cost of \$500. Neither reduction has an effect on noncritical activities. This solution is summarized in the following table:

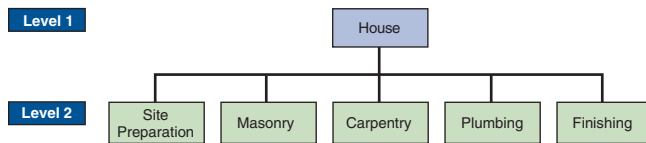
ACTIVITY	MONTHS REDUCED	COST
E	1	\$200
B	2	500
		Total: \$700

## Problems

Note: **Px** means the problem may be solved with POM for Windows and/or Excel OM.

### Problems 3.1–3.2 relate to Project Planning

- **3.1** The work breakdown structure (WBS) for building a house (levels 1 and 2) is shown below:



- Add two level-3 activities to each of the level-2 activities to provide more detail to the WBS.
- Select one of your level-3 activities and add two level-4 activities below it.

•• **3.2** James Lawson has decided to run for a seat as Congressman from the House of Representatives, District 34, in Florida. He views his 8-month campaign for office as a major project and wishes to create a work breakdown structure (WBS) to help control the detailed scheduling. So far, he has developed the following pieces of the WBS:

LEVEL	LEVEL ID NO.	ACTIVITY
1	1.0	Develop political campaign
2	1.1	Fund-raising plan
3	1.1.1	_____
3	1.1.2	_____
3	1.1.3	_____
2	1.2	Develop a position on major issues
3	1.2.1	_____
3	1.2.2	_____
3	1.2.3	_____
2	1.3	Staffing for campaign
3	1.3.1	_____
3	1.3.2	_____
3	1.3.3	_____
3	1.3.4	_____
2	1.4	Paperwork compliance for candidacy
3	1.4.1	_____
3	1.4.2	_____
2	1.5	Ethical plan/issues
3	1.5.1	_____

Help Lawson by providing details where the blank lines appear. Are there any other major (level-2) activities to create? If so, add an ID no. 1.6 and insert them.

### Problem 3.3 relates to Project Scheduling

- **3.3** The City Commission of Nashville has decided to build a botanical garden and picnic area in the heart of the city for the recreation of its citizens. The precedence table for all the activities required to construct this area successfully is given. Draw the Gantt chart for the whole construction activity.

CODE	ACTIVITY	DESCRIPTION	TIME (IN HOURS)	IMMEDIATE PREDECESSOR(S)
A	Planning	Find location; determine resource requirements	20	None
B	Purchasing	Requisition of lumber and sand	60	Planning
C	Excavation	Dig and grade	100	Planning
D	Sawing	Saw lumber into appropriate sizes	30	Purchasing
E	Placement	Position lumber in correct locations	20	Sawing, excavation
F	Assembly	Nail lumber together	10	Placement
G	Infill	Put sand in and under the equipment	20	Assembly
H	Outfill	Put dirt around the equipment	10	Assembly
I	Decoration	Put grass all over the garden, landscape, paint	30	Infill, outfill

### Problems 3.4–3.14 relate to Project Management Techniques

- **3.4** Refer to the table in Problem 3.3.
  - Draw the AON network for the construction activity.
  - Draw the AOA network for the construction activity.

• **3.5** Draw the activity-on-node (AON) project network associated with the following activities for Carl Betterton's construction project. How long should it take Carl and his team to complete this project? What are the critical path activities?

ACTIVITY	IMMEDIATE PREDECESSOR(S)	TIME (DAYS)
A	—	3
B	A	4
C	A	6
D	B	6
E	B	4
F	C	4
G	D	6
H	E, F	8

• **3.6** Given the activities whose sequence is described by the following table, draw the appropriate activity-on-arrow (AOA) network diagram.

- a) Which activities are on the critical path?
- b) What is the length of the critical path?

ACTIVITY	IMMEDIATE PREDECESSOR(S)	TIME (DAYS)
A	—	5
B	A	2
C	A	4
D	B	5
E	B	5
F	C	5
G	E, F	2
H	D	3
I	G, H	5

• **3.7** Using AOA, diagram the network described below for Lillian Fok's construction project. Calculate its critical path. How long is the minimum duration of this network?

ACTIVITY	NODES	TIME (WEEKS)	ACTIVITY	NODES	TIME (WEEKS)
J	1–2	10	N	3–4	2
K	1–3	8	O	4–5	7
L	2–4	6	P	3–5	5
M	2–3	3			

•• **3.8** Roger Ginde is developing a program in supply chain management certification for managers. Ginde has listed a number of activities that must be completed before a training program of this nature could be conducted. The activities, immediate predecessors, and times appear in the accompanying table:

ACTIVITY	IMMEDIATE PREDECESSOR(S)	TIME (DAYS)
A	—	2
B	—	5
C	—	1
D	B	10
E	A, D	3
F	C	6
G	E, F	8

- a) Develop an AON network for this problem.
- b) What is the critical path?
- c) What is the total project completion time?
- d) What is the slack time for each individual activity? **Px**

•• **3.9** Task time estimates for the modification of an assembly line at Jim Goodale's Carbondale, Illinois, factory are as follows:

ACTIVITY	TIME (IN HOURS)	IMMEDIATE PREDECESSORS
A	6.0	—
B	7.2	—
C	5.0	A
D	6.0	B, C
E	4.5	B, C
F	7.7	D
G	4.0	E, F

- a) Draw the project network using AON.
- b) Identify the critical path.
- c) What is the expected project length?
- d) Draw a Gantt chart for the project. **Px**

• **3.10** The activities described by the following table are given for the Howard Corporation in Kansas:

ACTIVITY	IMMEDIATE PREDECESSOR(S)	TIME
A	—	9
B	A	7
C	A	3
D	B	6
E	B	9
F	C	4
G	E, F	6
H	D	5
I	G, H	3

- a) Draw the appropriate AON PERT diagram for J.C. Howard's management team.
- b) Find the critical path.
- c) What is the project completion time? **Px**

•• **3.11** The following is a table of activities associated with a project at Rafay Ishfaq’s software firm in Chicago, their durations, and what activities each must precede:

ACTIVITY	DURATION (WEEKS)	PRECEDES
A (start)	1	B, C
B	1	E
C	4	F
E	2	F
F (end)	2	—

- a) Draw an AON diagram of the project, including activity durations.
- b) Define the critical path, listing all critical activities in chronological order.
- c) What is the project duration (in weeks)?
- d) What is the slack (in weeks) associated with any and all non-critical paths through the project?

• **3.12** The activities needed to build a prototype laser scanning machine at Dave Fletcher Corp. are listed in the following table. Construct an AON network for these activities.

ACTIVITY	IMMEDIATE PREDECESSOR(S)	ACTIVITY	IMMEDIATE PREDECESSOR(S)
A	—	E	B
B	—	F	B
C	A	G	C, E
D	A	H	D, F

*Additional problems 3.13–3.14 are available in MyOMLab.*


**Problems 3.15–3.16 relate to Determining the Project Schedule**

• **3.15** Dave Fletcher (see Problem 3.12) was able to determine the activity times for constructing his laser scanning machine. Fletcher would like to determine ES, EF, LS, LF, and slack for each activity. The total project completion time and the critical path should also be determined. Here are the activity times:

ACTIVITY	TIME (WEEKS)	ACTIVITY	TIME (WEEKS)
A	6	E	4
B	7	F	6
C	3	G	10
D	2	H	7

••• **3.16** The Rover 6 is a new custom-designed sports car. An analysis of the task of building the Rover 6 reveals the following list of relevant activities, their immediate predecessors, and their duration:<sup>2</sup>

JOB LETTER	DESCRIPTION	IMMEDIATE PREDECESSOR(S)	NORMAL TIME (DAYS)
A	Start	—	0
B	Design	A	8
C	Order special accessories	B	0.1
D	Build frame	B	1
E	Build doors	B	1
F	Attach axles, wheels, gas tank	D	1
G	Build body shell	B	2
H	Build transmission and drivetrain	B	3
I	Fit doors to body shell	G, E	1
J	Build engine	B	4
K	Bench-test engine	J	2
L	Assemble chassis	F, H, K	1
M	Road-test chassis	L	0.5
N	Paint body	I	2
O	Install wiring	N	1
P	Install interior	N	1.5
Q	Accept delivery of special accessories	C	5
R	Mount body and accessories on chassis	M, O, P, Q	1
S	Road test car	R	0.5
T	Attach exterior trim	S	1
U	Finish	T	0

- a) Draw a network diagram for the project.
- b) Mark the critical path and state its length.
- c) If the Rover 6 had to be completed 2 days earlier, would it help to:
  - i) Buy preassembled transmissions and drivetrains?
  - ii) Install robots to halve engine-building time?
  - iii) Speed delivery of special accessories by 3 days?
- d) How might resources be borrowed from activities on the non-critical path to speed activities on the critical path? 

**Problems 3.17–3.27 relate to Variability in Activity Times**

••• **3.17** Ross Hopkins, president of Hopkins Hospitality, has developed the tasks, durations, and predecessor relationships in the following table for building new motels. Draw the AON network and answer the questions that follow.

ACTIVITY	IMMEDIATE PREDECESSOR(S)	TIME ESTIMATES (IN WEEKS)		
		OPTIMISTIC	MOST LIKELY	PESSIMISTIC
A	—	4	8	10
B	A	2	8	24
C	A	8	12	16
D	A	4	6	10
E	B	1	2	3
F	E, C	6	8	20
G	E, C	2	3	4
H	F	2	2	2
I	F	6	6	6
J	D, G, H	4	6	12
K	I, J	2	2	3

- What is the expected (estimated) time for activity C?
- What is the variance for activity C?
- Based on the calculation of estimated times, what is the critical path?
- What is the estimated time of the critical path?
- What is the activity variance along the critical path?
- What is the probability of completion of the project before week 36? **Px**

• **3.18** A renovation of the gift shop at Orlando Amway Center has six activities (in hours). For the following estimates of *a*, *m*, and *b*, calculate the expected time and the standard deviation for each activity:

ACTIVITY	<i>a</i>	<i>m</i>	<i>b</i>
A	11	15	19
B	27	31	41
C	18	18	18
D	8	13	19
E	17	18	20
F	16	19	22

**Px**

•• **3.19** Kelle Carpet and Trim installs carpet in commercial offices. Peter Kelle has been very concerned with the amount of time it took to complete several recent jobs. Some of his workers are very unreliable. A list of activities and their optimistic completion time, the most likely completion time, and the pessimistic completion time (all in days) for a new contract are given in the following table:

ACTIVITY	TIME (DAYS)			IMMEDIATE PREDECESSOR(S)
	<i>a</i>	<i>m</i>	<i>b</i>	
A	3	6	8	—
B	2	4	4	—
C	1	2	3	—
D	6	7	8	C
E	2	4	6	B, D
F	6	10	14	A, E
G	1	2	4	A, E
H	3	6	9	F
I	10	11	12	G
J	14	16	20	C
K	2	8	10	H, I

- Determine the expected completion time and variance for each activity.
- Determine the total project completion time and the critical path for the project.
- Determine ES, EF, LS, LF, and slack for each activity.
- What is the probability that Kelle Carpet and Trim will finish the project in 40 days or less? **Px**

••• **3.20** The estimated times and immediate predecessors for the activities in a project at George Kyparis’s retinal scanning company are given in the following table. Assume that the activity times are independent.

ACTIVITY	IMMEDIATE PREDECESSOR	TIME (WEEKS)		
		<i>a</i>	<i>m</i>	<i>b</i>
A	—	9	10	11
B	—	4	10	16
C	A	9	10	11
D	B	5	8	11



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- a) Calculate the expected time and variance for each activity.
- b) What is the expected completion time of the critical path? What is the expected completion time of the other path in the network?
- c) What is the variance of the critical path? What is the variance of the other path in the network?
- d) If the time to complete path A–C is normally distributed, what is the probability that this path will be finished in 22 weeks or less?
- e) If the time to complete path B–D is normally distributed, what is the probability that this path will be finished in 22 weeks or less?
- f) Explain why the probability that the *critical path* will be finished in 22 weeks or less is not necessarily the probability that the *project* will be finished in 22 weeks or less. **Px**

••• **3.21** Rich Cole Control Devices, Inc., produces custom-built relay devices for auto makers. The most recent project undertaken by Cole requires 14 different activities. Cole’s managers would like to determine the total project completion time (in days) and those activities that lie along the critical path. The appropriate data are shown in the following table.

- a) What is the probability of being done in 53 days?
- b) What date results in a 99% probability of completion?

ACTIVITY	IMMEDIATE PREDECESSOR(S)	OPTIMISTIC TIME	MOST LIKELY TIME	PESSIMISTIC TIME
A	—	1	2	4
B	—	3	3.5	4
C	—	10	12	13
D	—	4	5	7
E	—	2	4	5
F	A	6	7	8
G	B	2	4	5.5
H	C	5	7.7	9
I	C	9.9	10	12
J	C	2	4	5
K	D	2	4	6
L	E	2	4	6
M	F, G, H	5	6	6.5
N	J, K, L	1	1.1	2
O	I, M	5	7	8
P	N	5	7	9

- b) What is the probability of completing the marketing campaign in the time (in weeks) noted in part a)?
- c) If activities I and J were not necessary, what impact would this have on the critical path and the number of weeks needed to complete the marketing campaign? **Px**

ACTIVITY	IMMEDIATE PREDECESSOR(S)	OPTIMISTIC TIME	MOST LIKELY TIME	PESSIMISTIC TIME
A	—	4	6	7
B	—	1	2	3
C	A	6	6	6
D	A	5	8	11
E	B, C	1	9	18
F	D	2	3	6
G	D	1	7	8
H	E, F	4	4	6
I	G, H	1	6	8
J	I	2	5	7
K	I	8	9	11
L	J	2	4	6
M	K	1	2	3
N	L, M	6	8	10

••• **3.22** Four Squares Productions, a firm hired to coordinate the release of the movie *Pirates of the Caribbean: On Stranger Tides* (starring Johnny Depp), identified 16 activities to be completed before the release of the film.

- a) How many weeks in advance of the film release should Four Squares have started its marketing campaign? What is the critical path? The tasks (in time units of weeks) are as follows:



••• **3.23** Using PERT, Adam Munson was able to determine that the expected project completion time for the construction of a pleasure yacht is 21 months, and the project variance is 4.

- a) What is the probability that the project will be completed in 17 months?
- b) What is the probability that the project will be completed in 20 months?
- c) What is the probability that the project will be completed in 23 months?
- d) What is the probability that the project will be completed in 25 months?
- e) What is the due date that yields a 95% chance of completion? **Px**

Additional problems 3.24–3.27 are available in MyOMLab.

**Problems 3.28–3.33 relate to Cost-Time Trade-Offs and Project Crashing**

•• **3.28** Assume that the activities in Problem 3.11 have the following costs to shorten: A, \$300/week; B, \$100/week; C, \$200/week; E, \$100/week; and F, \$400/week. Assume also that you can crash an activity down to 0 weeks in duration and that every week you can shorten the project is worth \$250 to you. What activities would you crash? What is the total crashing cost?

••• **3.29** What is the minimum cost of crashing the following project that Roger Solano manages at Slippery Rock University by 4 days?

ACTIVITY	NORMAL TIME (DAYS)	CRASH TIME (DAYS)	NORMAL COST	CRASH COST	IMMEDIATE PREDECESSOR(S)
A	6	5	\$ 900	\$1,000	—
B	8	6	300	400	—
C	4	3	500	600	—
D	5	3	900	1,200	A
E	8	5	1,000	1,600	C

•• **3.30** Three activities are candidates for crashing on a project network for a large computer installation (all are, of course, critical). Activity details are in the following table:

ACTIVITY	PREDECESSOR	NORMAL TIME	NORMAL COST	CRASH TIME	CRASH COST
A	—	7 days	\$6,000	6 days	\$6,600
B	A	4 days	1,200	2 days	3,000
C	B	11 days	4,000	9 days	6,000

- a) What action would you take to reduce the critical path by 1 day?
- b) Assuming no other paths become critical, what action would you take to reduce the critical path one additional day?
- c) What is the total cost of the 2-day reduction? **Px**

••• **3.31** Development of Version 2.0 of a particular accounting software product is being considered by Jose Noguera’s technology firm in Baton Rouge. The activities necessary for the completion of this project are listed in the following table:

ACTIVITY	NORMAL TIME (WEEKS)	CRASH TIME (WEEKS)	NORMAL COST	CRASH COST	IMMEDIATE PREDECESSOR(S)
A	4	3	\$2,000	\$2,600	—
B	2	1	2,200	2,800	—
C	3	3	500	500	—
D	8	4	2,300	2,600	A
E	6	3	900	1,200	B
F	3	2	3,000	4,200	C
G	4	2	1,400	2,000	D, E

- a) What is the project completion date?
- b) What is the total cost required for completing this project on normal time?
- c) If you wish to reduce the time required to complete this project by 1 week, which activity should be crashed, and how much will this increase the total cost?
- d) What is the maximum time that can be crashed? How much would costs increase? **Px**

••• **3.32** Kimpel Products makes pizza ovens for commercial use. James Kimpel, CEO, is contemplating producing smaller ovens for use in high school and college kitchens. The activities necessary to build an experimental model and related data are given in the following table:

ACTIVITY	NORMAL TIME (WEEKS)	CRASH TIME (WEEKS)	NORMAL COST (\$)	CRASH COST (\$)	IMMEDIATE PREDECESSOR(S)
A	3	2	1,000	1,600	—
B	2	1	2,000	2,700	—
C	1	1	300	300	—
D	7	3	1,300	1,600	A
E	6	3	850	1,000	B
F	2	1	4,000	5,000	C
G	4	2	1,500	2,000	D, E

- a) What is the project completion date?
- b) Crash this project to 10 weeks at the least cost.
- c) Crash this project to 7 weeks (which is the maximum it can be crashed) at the least cost. **Px**

Additional problem 3.33 is available in MyOMLab.

## CASE STUDIES

### Southwestern University: (A)\*

Southwestern University (SWU), a large state college in Stephenville, Texas, 30 miles southwest of the Dallas/Fort Worth metroplex, enrolls close to 20,000 students. In a typical town–gown relationship, the school is a dominant force in the small city, with more students during fall and spring than permanent residents.

A longtime football powerhouse, SWU is a member of the Big Eleven conference and is usually in the top 20 in college football rankings. To bolster its chances of reaching the elusive and long-desired number-one ranking, in 2009, SWU hired the legendary Phil Flamm as its head coach.

\*This integrated study runs throughout the text. Other issues facing Southwestern’s football expansion include (B) forecasting game attendance (Chapter 4); (C) quality of facilities (Chapter 6); (D) break-even analysis for food services (Supplement 7); (E) location of the new stadium (Chapter 8); (F) inventory planning of football programs (Chapter 12); and (G) scheduling of campus security officers/staff for game days (Chapter 13).



**TABLE 3.6** Southwestern University Project

ACTIVITY	DESCRIPTION	PREDECESSOR(S)	TIME ESTIMATES (DAYS)			
			OPTIMISTIC	MOST LIKELY	PESSIMISTIC	CRASH COST/DAY
A	Bonding, insurance, tax structuring	—	20	30	40	\$1,500
B	Foundation, concrete footings for boxes	A	20	65	80	3,500
C	Upgrading skybox stadium seating	A	50	60	100	4,000
D	Upgrading walkways, stairwells, elevators	C	30	50	100	1,900
E	Interior wiring, lathes	B	25	30	35	9,500
F	Inspection approvals	E	0.1	0.1	0.1	0
G	Plumbing	D, F	25	30	35	2,500
H	Painting	G	10	20	30	2,000
I	Hardware/AC/metal workings	H	20	25	60	2,000
J	Tile/carpet/windows	H	8	10	12	6,000
K	Inspection	J	0.1	0.1	0.1	0
L	Final detail work/cleanup	I, K	20	25	60	4,500

One of Flamm’s demands on joining SWU had been a new stadium. With attendance increasing, SWU administrators began to face the issue head-on. After 6 months of study, much political arm wrestling, and some serious financial analysis, Dr. Joel Wisner, president of Southwestern University, had reached a decision to expand the capacity at its on-campus stadium.

Adding thousands of seats, including dozens of luxury skyboxes, would not please everyone. The influential Flamm had argued the need for a first-class stadium, one with built-in dormitory rooms for his players and a palatial office appropriate for the coach of a future NCAA champion team. But the decision was made, and *everyone*, including the coach, would learn to live with it.

The job now was to get construction going immediately after the 2015 season ended. This would allow exactly 270 days until the 2016 season opening game. The contractor, Hill Construction (Bob Hill being an alumnus, of course), signed his contract. Bob Hill looked at the tasks his engineers had outlined and looked President Wisner in the eye. “I guarantee the team will be able to take the field on schedule next year,” he said with a sense of confidence. “I sure hope so,” replied Wisner. “The contract penalty

of \$10,000 per day for running late is nothing compared to what Coach Flamm will do to you if our opening game with Penn State is delayed or canceled.” Hill, sweating slightly, did not need to respond. In football-crazy Texas, Hill Construction would be *mud* if the 270-day target was missed.

Back in his office, Hill again reviewed the data (see Table 3.6) and noted that optimistic time estimates can be used as crash times. He then gathered his foremen. “Folks, if we’re not 75% sure we’ll finish this stadium in less than 270 days, I want this project crashed! Give me the cost figures for a target date of 250 days—also for 240 days. I want to be *early*, not just on time!”

**Discussion Questions**

1. Develop a network drawing for Hill Construction and determine the critical path. How long is the project expected to take?
2. What is the probability of finishing in 270 days?
3. If it is necessary to crash to 250 or 240 days, how would Hill do so, and at what costs? As noted in the case, assume that optimistic time estimates can be used as crash times.

**Project Management at Arnold Palmer Hospital**



The equivalent of a new kindergarten class is born every day at Orlando’s Arnold Palmer Hospital. With more than 13,000 births in the mid-2000s in a hospital that was designed 15 years earlier for a capacity of 6,500 births a year, the newborn intensive care unit was stretched to the limit. Moreover, with continuing strong population growth in central Florida, the hospital was often full. It was clear that new facilities were needed. After much analysis, forecasting, and discussion, the management team decided to build a new 273-bed building across the street from the existing hospital. But the facility had to be built in accordance with the hospital’s Guiding Principles and its uniqueness as a health center dedicated to the specialized needs of women and infants. Those

Guiding Principles are: *Family-centered focus, a healing environment where privacy and dignity are respected, sanctuary of caring that includes warm, serene surroundings with natural lighting, sincere and dedicated staff providing the highest quality care, and patient-centered flow and function.*

The vice president of business development, Karl Hodges, wanted a hospital that was designed from the inside out by the people who understood the Guiding Principles, who knew most about the current system, and who were going to use the new system, namely, the doctors and nurses. Hodges and his staff spent 13 months discussing expansion needs with this group, as well as with patients and the community, before developing a proposal

**TABLE 3.7** Expansion Planning and Arnold Palmer Hospital Construction Activities and Times<sup>a</sup>

ACTIVITY	SCHEDULED TIME	PRECEDENCE ACTIVITY(IES)
1. Proposal and review	1 month	—
2. Establish master schedule	2 weeks	1
3. Architect selection process	5 weeks	1
4. Survey whole campus and its needs	1 month	1
5. Conceptual architect's plans	6 weeks	3
6. Cost estimating	2 months	2, 4, 5
7. Deliver plans to board for consideration/decision	1 month	6
8. Surveys/regulatory review	6 weeks	6
9. Construction manager selection	9 weeks	6
10. State review of need for more hospital beds ("Certificate of Need")	3.5 months	7, 8
11. Design drawings	4 months	10
12. Construction documents	5 months	9, 11
13. Site preparation/demolish existing building	9 weeks	11
14. Construction start/building pad	2 months	12, 13
15. Relocate utilities	6 weeks	12
16. Deep foundations	2 months	14
17. Building structure in place	9 months	16
18. Exterior skin/roofing	4 months	17
19. Interior buildout	12 months	17
20. Building inspections	5 weeks	15, 19
21. Occupancy	1 month	20

<sup>a</sup>This list of activities is abbreviated for purposes of this case study. For simplification, assume each week = .25 months (i.e., 2 weeks = .5 month, 6 weeks = 1.5 months, etc.).

for the new facility. An administrative team created 35 user groups, which held over 1,000 planning meetings (lasting from 45 minutes to a whole day). They even created a "Supreme Court" to deal with conflicting views on the multifaceted issues facing the new hospital.

Funding and regulatory issues added substantial complexity to this major expansion, and Hodges was very concerned that the project stay on time and within budget. Tom Hyatt, director of facility development, was given the task of onsite manager of the \$100 million project, in addition to overseeing ongoing renovations, expansions, and other projects. The activities in the multi-year project for the new building at Arnold Palmer are shown in Table 3.7.

### Discussion Questions\*

1. Develop the network for planning and construction of the new hospital at Arnold Palmer.
2. What is the critical path, and how long is the project expected to take?
3. Why is the construction of this 11-story building any more complex than construction of an equivalent office building?
4. What percent of the whole project duration was spent in planning that occurred prior to the proposal and reviews? Prior to the actual building construction? Why?

\*You may wish to view the video accompanying this case before addressing these questions.

## Managing Hard Rock's Rockfest



At the Hard Rock Cafe, like many organizations, project management is a key planning tool. With Hard Rock's constant growth in hotels and cafes, remodeling of existing cafes, scheduling for Hard Rock Live concert and event venues, and planning the annual Rockfest, managers rely on project management techniques and software to maintain schedule and budget performance.

"Without Microsoft Project," says Hard Rock Vice-President Chris Tomasso, "there is no way to keep so many people on the same page." Tomasso is in charge of the Rockfest event, which is attended by well over 100,000 enthusiastic fans. The challenge is pulling it off within a tight 9-month planning horizon. As the event approaches, Tomasso devotes greater energy to its

activities. For the first 3 months, Tomasso updates his Microsoft Project charts monthly. Then at the 6-month mark, he updates his progress weekly. At the 9-month mark, he checks and corrects his schedule twice a week.

Early in the project management process, Tomasso identifies 10 major tasks (called level-2 activities in a work breakdown structure, or WBS):<sup>†</sup> talent booking, ticketing, marketing/PR, online promotion, television, show production, travel, sponsorships, operations, and merchandising. Using a WBS, each of these is further divided into a series of subtasks. Table 3.8 identifies 26 of the major activities and subactivities, their immediate predecessors, and time estimates. Tomasso enters all these into the Microsoft Project software.<sup>‡</sup> Tomasso alters the Microsoft Project document and the time line as the

project progresses. “It’s okay to change it as long as you keep on track,” he states.

The day of the rock concert itself is not the end of the project planning. “It’s nothing but surprises. A band not being able to get to the venue because of traffic jams is a surprise, but an ‘anticipated’ surprise. We had a helicopter on stand-by ready to fly the band in,” says Tomasso.

On completion of Rockfest in July, Tomasso and his team have a 3-month reprieve before starting the project planning process again.

<sup>†</sup>The level-1 activity is the Rockfest concert itself.

<sup>‡</sup>There are actually 127 activities used by Tomasso; the list is abbreviated for this case study.

**TABLE 3.8** Some of the Major Activities and Subactivities in the Rockfest Plan

ACTIVITY	DESCRIPTION	PREDECESSOR(S)	TIME (WEEKS)
A	Finalize site and building contracts	—	7
B	Select local promoter	A	3
C	Hire production manager	A	3
D	Design promotional Web site	B	5
E	Set TV deal	D	6
F	Hire director	E	4
G	Plan for TV camera placement	F	2
H	Target headline entertainers	B	4
I	Target support entertainers	H	4
J	Travel accommodations for talent	I	10
K	Set venue capacity	C	2
L	Ticketmaster contract	D, K	3
M	On-site ticketing	L	8
N	Sound and staging	C	6
O	Passes and stage credentials	G, R	7
P	Travel accommodations for staff	B	20
Q	Hire sponsor coordinator	B	4
R	Finalize sponsors	Q	4
S	Define/place signage for sponsors	R, X	3
T	Hire operations manager	A	4
U	Develop site plan	T	6
V	Hire security director	T	7
W	Set police/fire security plan	V	4
X	Power, plumbing, AC, toilet services	U	8
Y	Secure merchandise deals	B	6
Z	Online merchandise sales	Y	6

**Discussion Questions<sup>§</sup>**

1. Identify the critical path and its activities for Rockfest. How long does the project take?
2. Which activities have a slack time of 8 weeks or more?
3. Identify five major challenges a project manager faces in events such as this one.
4. Why is a work breakdown structure useful in a project such as this? Take the 26 activities and break them into what you think should be level-2, level-3, and level-4 tasks.

<sup>§</sup>You may wish to view the video accompanying this case before addressing these questions.

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- **Additional Case Study:** Visit [MyOMLab](#) for this free case study:  
**Shale Oil Company:** This oil refinery must shut down for maintenance of a major piece of equipment.

**Endnotes**

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1. This formula is based on the statistical concept that from one end of the beta distribution to the other is 6 standard deviations ( $\pm 3$  standard deviations from the mean). Because  $(b - a)$  is 6 standard deviations, the variance is  $[(b - a)/6]^2$ .
2. *Source:* Adapted from James A. D. Stoner, *Management*, 6th ed. (Upper Saddle River, NJ: Pearson).

# Chapter 3 *Rapid Review*

Main Heading	Review Material	MyOMLab
<b>THE IMPORTANCE OF PROJECT MANAGEMENT</b> (p. 62)	<p>The management of projects involves three phases:</p> <ol style="list-style-type: none"> <li>1. <i>Planning</i>—This phase includes goal setting, defining the project, and team organization.</li> <li>2. <i>Scheduling</i>—This phase relates people, money, and supplies to specific activities and relates activities to each other.</li> <li>3. <i>Controlling</i>—Here the firm monitors resources, costs, quality, and budgets. It also revises or changes plans and shifts resources to meet time and cost demands.</li> </ol>	<p>Concept Questions: 1.1–1.4</p> <p><b>VIDEO 3.1</b> Project Management at Hard Rock’s Rockfest</p>
<b>PROJECT PLANNING</b> (pp. 62–65)	<p>Projects can be defined as a series of related tasks directed toward a major output.</p> <ul style="list-style-type: none"> <li>■ <b>Project organization</b>—An organization formed to ensure that programs (projects) receive the proper management and attention.</li> <li>■ <b>Work breakdown structure (WBS)</b>—Defines a project by dividing it into more and more detailed components.</li> </ul>	<p>Concept Questions: 2.1–2.4</p> <p>Problems: 3.1–3.2</p>
<b>PROJECT SCHEDULING</b> (pp. 65–66)	<ul style="list-style-type: none"> <li>■ <b>Gantt charts</b>—Planning charts used to schedule resources and allocate time.</li> </ul> <p>Project scheduling serves several purposes:</p> <ol style="list-style-type: none"> <li>1. It shows the relationship of each activity to others and to the whole project.</li> <li>2. It identifies the precedence relationships among activities.</li> <li>3. It encourages the setting of realistic time and cost estimates for each activity.</li> <li>4. It helps make better use of people, money, and material resources by identifying critical bottlenecks in the project.</li> </ol>	<p>Concept Questions: 3.1–3.4</p> <p>Problem: 3.3</p>
<b>PROJECT CONTROLLING</b> (pp. 66–67)	<p>Computerized programs produce a broad variety of PERT/CPM reports, including (1) detailed cost breakdowns for each task, (2) total program labor curves, (3) cost distribution tables, (4) functional cost and hour summaries, (5) raw material and expenditure forecasts, (6) variance reports, (7) time analysis reports, and (8) work status reports.</p>	<p>Concept Questions: 4.1–4.2</p> <p><b>VIDEO 3.2</b> Project Management at Arnold Palmer Hospital</p>
<b>PROJECT MANAGEMENT TECHNIQUES: PERT AND CPM</b> (pp. 67–71)	<ul style="list-style-type: none"> <li>■ <b>Program evaluation and review technique (PERT)</b>—A project management technique that employs three time estimates for each activity.</li> <li>■ <b>Critical path method (CPM)</b>—A project management technique that uses only one estimate per activity.</li> <li>■ <b>Critical path</b>—The computed <i>longest</i> time path(s) through a network.</li> </ul> <p>PERT and CPM both follow six basic steps.</p> <p>The activities on the critical path will delay the entire project if they are not completed on time.</p> <ul style="list-style-type: none"> <li>■ <b>Activity-on-node (AON)</b>—A network diagram in which nodes designate activities.</li> <li>■ <b>Activity-on-arrow (AOA)</b>—A network diagram in which arrows designate activities.</li> </ul> <p>In an AOA network, the nodes represent the starting and finishing times of an activity and are also called <i>events</i>.</p> <ul style="list-style-type: none"> <li>■ <b>Dummy activity</b>—An activity having no time that is inserted into a network to maintain the logic of the network.</li> </ul> <p>A dummy ending activity can be added to the end of an AON diagram for a project that has multiple ending activities.</p>	<p>Concept Questions: 5.1–5.4</p> <p>Problems: 3.4–3.14</p> <p>Virtual Office Hours for Solved Problems: 3.1, 3.2</p>
<b>DETERMINING THE PROJECT SCHEDULE</b> (pp. 71–77)	<ul style="list-style-type: none"> <li>■ <b>Critical path analysis</b>—A process that helps determine a project schedule.</li> </ul> <p>To find the critical path, we calculate two distinct starting and ending times for each activity:</p> <ul style="list-style-type: none"> <li>■ <b>Earliest start (ES)</b> = Earliest time at which an activity can start, assuming that all predecessors have been completed</li> <li>■ <b>Earliest finish (EF)</b> = Earliest time at which an activity can be finished</li> <li>■ <b>Latest start (LS)</b> = Latest time at which an activity can start, without delaying the completion time of the entire project</li> <li>■ <b>Latest finish (LF)</b> = Latest time by which an activity has to finish so as to not delay the completion time of the entire project</li> <li>■ <b>Forward pass</b>—A process that identifies all the early start and early finish times.           <math display="block">ES = \text{Max} \{EF \text{ of all immediate predecessors}\} \quad (3-1)</math> <math display="block">EF = ES + \text{Activity time} \quad (3-2)</math> </li> <li>■ <b>Backward pass</b>—A process that identifies all the late start and late finish times.           <math display="block">LF = \text{Min} \{LS \text{ of all immediate following activities}\} \quad (3-3)</math> <math display="block">LS = LF - \text{Activity time} \quad (3-4)</math> </li> </ul>	<p>Concept Questions: 6.1–6.4</p> <p>Problems: 3.15, 3.16</p>

Main Heading	Review Material	
	<p>■ <b>Slack time</b>—Free time for an activity.</p> $\text{Slack} = \text{LS} - \text{ES} \quad \text{or} \quad \text{Slack} = \text{LF} - \text{EF} \quad (3-5)$ <p>The activities with zero slack are called <i>critical activities</i> and are said to be on the critical path.</p> <p>The critical path is a continuous path through the project network that starts at the first activity in the project, terminates at the last activity in the project, and includes only critical activities.</p>	Virtual Office Hours for Solved Problem: 3.3 <b>ACTIVE MODEL 3.1</b>
<b>VARIABILITY IN ACTIVITY TIMES</b> (pp. 77–82)	<p>■ <b>Optimistic time</b> (<math>a</math>)—The “best” activity completion time that could be obtained in a PERT network.</p> <p>■ <b>Pessimistic time</b> (<math>b</math>)—The “worst” activity time that could be expected in a PERT network.</p> <p>■ <b>Most likely time</b> (<math>m</math>)—The most probable time to complete an activity in a PERT network.</p> <p>When using PERT, we often assume that activity time estimates follow the beta distribution.</p> $\text{Expected activity time } t = (a + 4m + b)/6 \quad (3-6)$ $\text{Variance of activity completion time} = [(b - a)/6]^2 \quad (3-7)$ $\sigma_p^2 = \text{Project variance} = \Sigma (\text{variances of activities on critical path}) \quad (3-8)$ $Z = (\text{Due date} - \text{Expected date of completion})/\sigma_p \quad (3-9)$ $\text{Due date} = \text{Expected completion time} + (Z \times \sigma_p) \quad (3-10)$	Concept Questions: 7.1–7.4 Problems: 3.17–3.27 Virtual Office Hours for Solved Problems: 3.4, 3.5, 3.6
<b>COST-TIME TRADE-OFFS AND PROJECT CRASHING</b> (pp. 82–85)	<p>■ <b>Crashing</b>—Shortening activity time in a network to reduce time on the critical path so total completion time is reduced.</p> $\text{Crash cost per period} = \frac{(\text{Crash cost} - \text{Normal cost})}{(\text{Normal time} - \text{Crash time})} \quad (3-11)$	Concept Questions: 8.1–8.4 Problems: 3.28–3.33 Virtual Office Hours for Solved Problem: 3.7
<b>A CRITIQUE OF PERT AND CPM</b> (pp. 85–86)	<p>As with every technique for problem solving, PERT and CPM have a number of advantages as well as several limitations.</p>	Concept Questions: 9.1–9.4
<b>USING MICROSOFT PROJECT TO MANAGE PROJECTS</b> (pp. 86–88)	<p>Microsoft Project, the most popular example of specialized project management software, is extremely useful in drawing project networks, identifying the project schedule, and managing project costs and other resources.</p>	Concept Questions: 10.1–10.4

## Self Test

■ **Before taking the self-test**, refer to the learning objectives listed at the beginning of the chapter and the key terms listed at the end of the chapter.

- LO 3.1** Which of the following statements regarding Gantt charts is true?
- Gantt charts give a timeline and precedence relationships for each activity of a project.
  - Gantt charts use the four standard spines: Methods, Materials, Manpower, and Machinery.
  - Gantt charts are visual devices that show the duration of activities in a project.
  - Gantt charts are expensive.
  - All of the above are true.
- LO 3.2** Which of the following is true about AOA and AON networks?
- In AOA, arrows represent activities.
  - In AON, nodes represent activities.
  - Activities consume time and resources.
  - Nodes are also called *events* in AOA.
  - All of the above.
- LO 3.3** Slack time equals:
- $\text{ES} + t$ .
  - $\text{LS} - \text{ES}$ .
  - zero.
  - $\text{EF} - \text{ES}$ .
- LO 3.4** The critical path of a network is the:
- shortest-time path through the network.
  - path with the fewest activities.
  - path with the most activities.
  - longest-time path through the network.
- LO 3.5** PERT analysis computes the variance of the total project completion time as:
- the sum of the variances of all activities in the project.
  - the sum of the variances of all activities on the critical path.
  - the sum of the variances of all activities not on the critical path.
  - the variance of the final activity of the project.
- LO 3.6** The crash cost per period:
- is the difference in costs divided by the difference in times (crash and normal).
  - is considered to be linear in the range between normal and crash.
  - needs to be determined so that the smallest cost values on the critical path can be considered for time reduction first.
  - all of the above.

Answers: LO 3.1. c; LO 3.2. e; LO 3.3. b; LO 3.4. d; LO 3.5. b; LO 3.6. d.