

Project Management

3 CHAPTER

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GLOBAL COMPANY PROFILE
Bechtel Group

Project Management Provides a Competitive Advantage for Bechtel

Now in its 115th year, the San Francisco-based Bechtel Group (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, and rebuilding of Kuwait's oil and gas infrastructure after the invasion by Iraq in 1990. With 53,000 employees and revenues over \$25 billion, Bechtel is the largest project manager in the U.S.

Conditions weren't what Bechtel expected when it won a series of billion-dollar contracts from the U.S. government to help reconstruct Iraq in 2003–2006. Saddam Hussein's defeat by Allied forces hadn't caused much war damage. Instead, what Bechtel found was a country that had been crumbling for years. None of the sewage plants in Baghdad worked. Power flicked on and off. Towns and cities in the anti-Hussein south had been left to decay as punishment. And to complicate matters even more, 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, was reopened when Bechtel dredged the water and repaired the grain elevators. Electrical generation was back to prewar levels in 10 months. Bechtel 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



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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.



Associated Press

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.



Bill Pogue/Getty Images Inc. - Stone Allstock

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.

infrastructure. 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/Associated Press

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

LEARNING OBJECTIVES

- LO1 Use a Gantt chart for scheduling 63
- LO2 Draw AOA and AON networks 66
- LO3 Complete forward and backward passes for a project 69
- LO4 Determine a critical path 73
- LO5 Calculate the variance of activity times 75
- LO6 Crash a project 80

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.

Planning the Project (Before project)

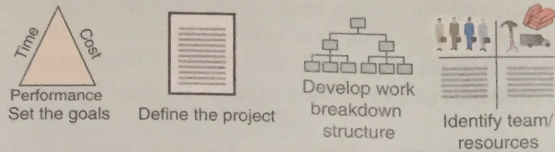
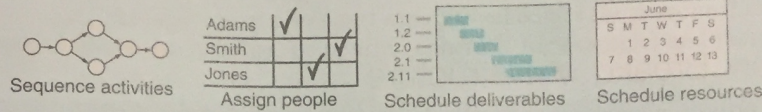


Figure 3.1

Project Planning, Scheduling, and Controlling

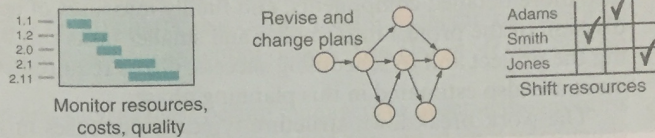
Scheduling the Project



STUDENT TIP

Managers must "make the plan and then work the plan."

Controlling the Project (During project)



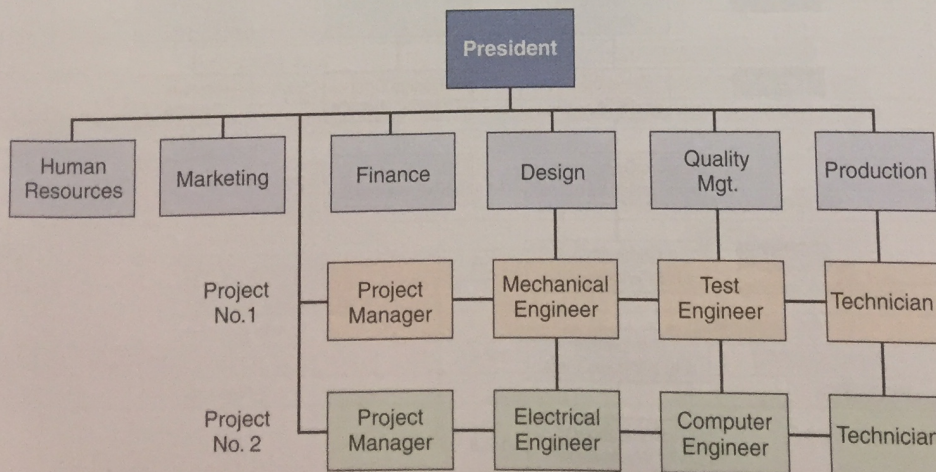
4. The project is temporary but critical to the organization.
5. The project cuts across organizational lines.

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) 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

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:

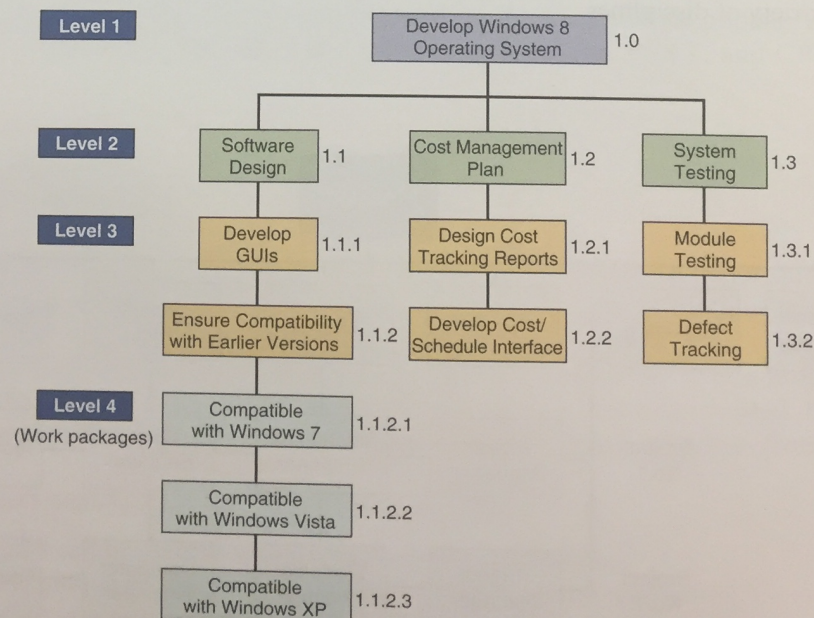
Level

- 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.

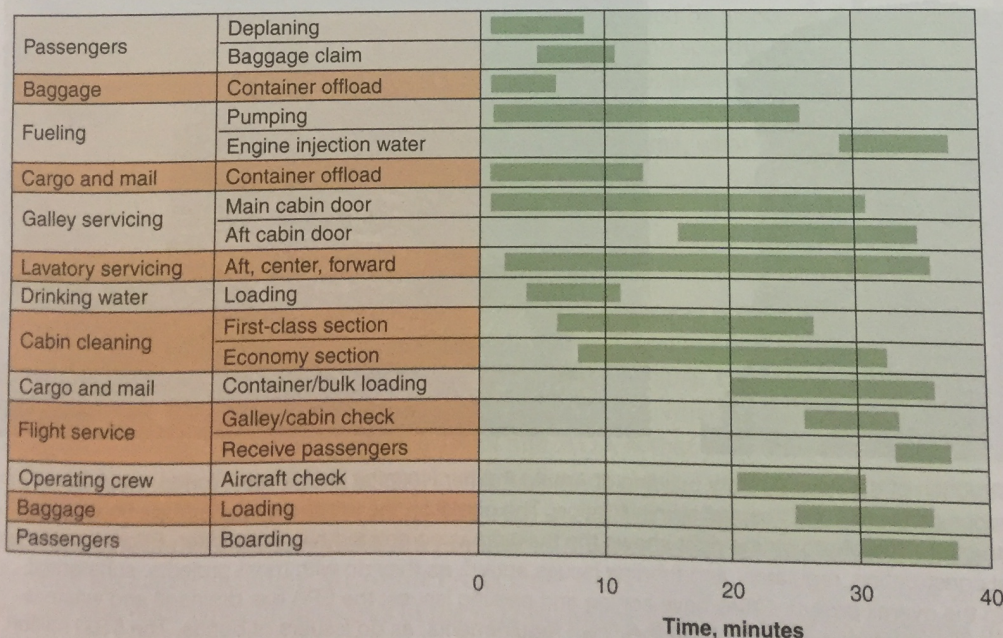
One popular project scheduling approach is the Gantt chart. **Gantt charts** are low-cost means of helping managers make sure that (1) activities are planned, (2) order of performance is documented, (3) activity time estimates are recorded, and (4) overall project time is developed. As Figure 3.4 shows, 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.

LO1 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 Trapp/Getty Images

Project Controlling

VIDEO 3.2

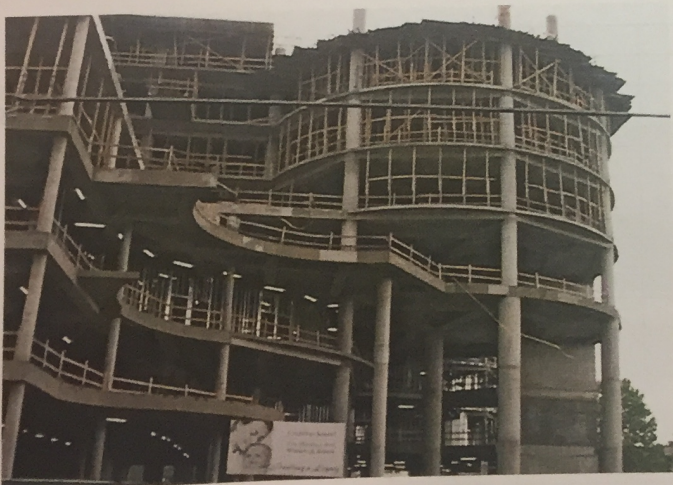
Project Management at Arnold Palmer Hospital

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 Primavera (by Primavera Systems, Inc.), MacProject (by Apple Computer Corp.), 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 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.



Pia Gandolfo/Jonathan Bailey Associates

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.

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.

Critical path

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

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 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, since 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.

Example 2

Dummy activity

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

Figure 3.5

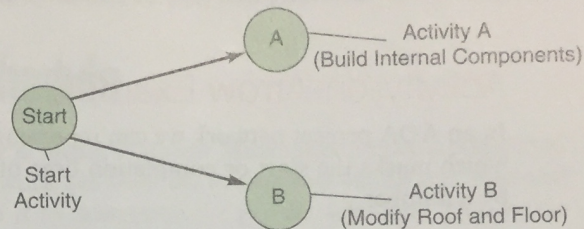
Beginning AON Network for Milwaukee Paper

AON GRAPH FOR MILWAUKEE PAPER

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

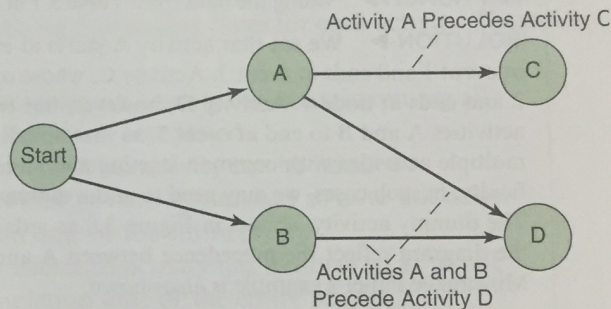
APPROACH ► In the AON approach, we denote each activity by a node. The lines, or arrows, represent the precedence relationships between the activities.

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 serves as the unique starting activity for the entire project.

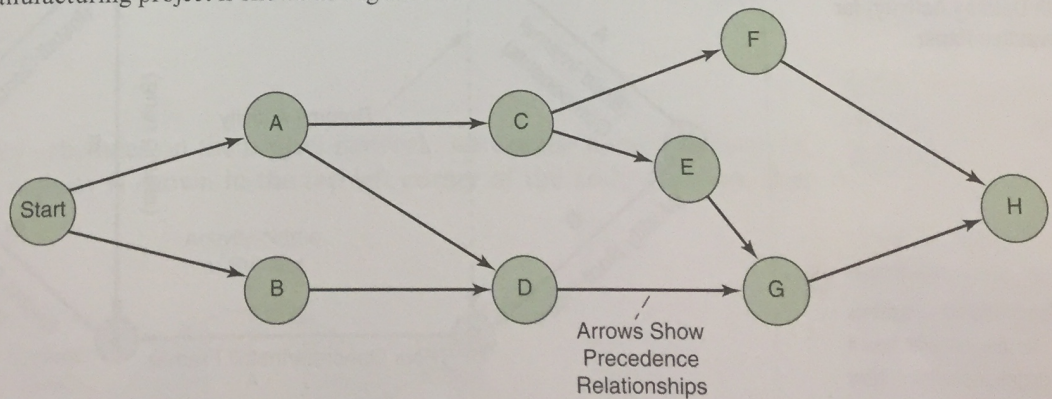


We now show the precedence relationships using lines with arrow symbols. For example, an arrow from activity *Start* to activity *A* indicates that *Start* is a predecessor for activity *A*. In a similar fashion, we draw an arrow from *Start* to *B*.

Next, we add a new node for activity *C*. Since 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, since activities *A* and *B* both precede activity *D*, we draw arrows from *A* to *D* and from *B* to *D* (see Figure 3.6).



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.



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 ► 3.3, 3.6, 3.7, 3.9a, 3.10, 3.12, 3.15a

When we first draw a project network, it is not unusual to place our nodes (activities) in the network in such a fashion that the arrows (precedence relationships) are not straight lines. That is, the lines could be intersecting each other, and even facing in opposite directions. For example, if we had switched the location of the nodes for activities E and F in Figure 3.7, the lines from F to H and E to G would have intersected. Although such a project network is perfectly valid, it is good practice to place the nodes in such a fashion that all arrows point in the same direction.

As with the unique starting node, it is convenient to have the project network finish with a unique ending 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.

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

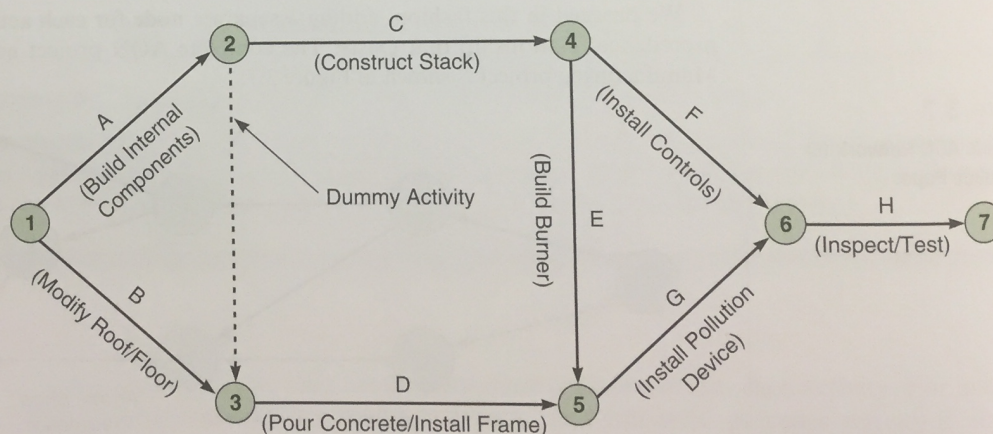
Draw the complete AOA project network for Milwaukee Paper's problem.

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 ▶ 3.4, 3.5, 3.9b

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.

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, since 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.

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

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

Critical path analysis

A process that helps determine a project schedule.

Forward pass

A process that identifies all the early times.

LO3 Complete forward and backward passes for a project

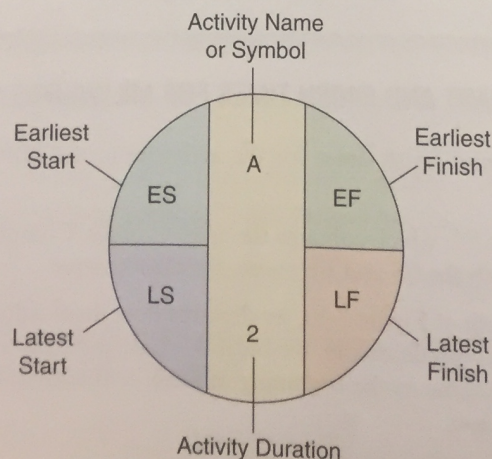


Figure 3.9

Notation Used in Nodes for Forward and Backward Pass

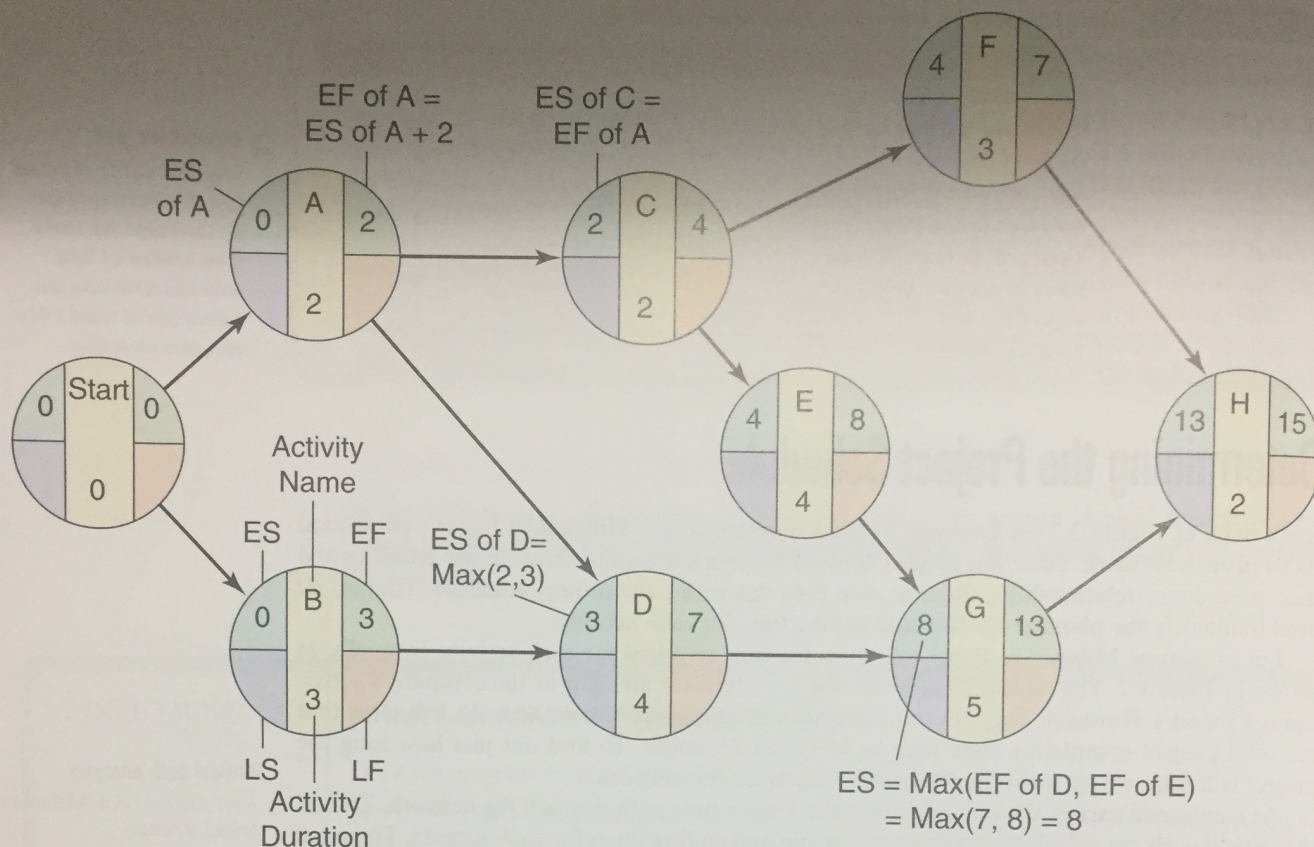


Figure 3.10

Earliest Start and Earliest Finish Times for Milwaukee Paper

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.

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:

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

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:

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

STUDENT TIP ☆

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

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.

Since 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.