10

Project Scheduling

Lagging, Crashing, and Activity Networks

Chapter Outline

Chapter Objectives

After completing this chapter, you should be able to:

1. Apply lag relationships to project activities.
2. Construct and comprehend Gantt charts.
3. Recognize alternative means to accelerate projects, including their benefits and drawbacks.
4. Understand the trade-offs required in the decision to crash project activities.
5. Develop activity networks using Activity-on-Arrow techniques.
6. Understand the differences in AON and AOA and recognize the advantages and disadvantages of each technique.

PROJECT MANAGEMENT BODY OF KNOWLEDGE CORE CONCEPTS COVERED IN THIS CHAPTER

1. Plan Schedule Management (PMBoK sec. 6.1)
2. Define Activities (PMBoK sec. 6.2)
3. Sequence Activities (PMBoK sec. 6.3)
4. Precedence Diagramming Method (PMBoK sec. 6.3.2.1)
5. Leads and Lags (PMBoK sec. 6.3.2.3)
6. Estimate Activity Resources (PMBoK sec. 6.4)
7. Estimate Activity Durations (PMBoK sec. 6.5)
8. Develop Schedule (PMBoK sec. 6.6)
9. Schedule Compression (PMBoK sec. 6.6.2.7)
10. Control Schedule (PMBoK sec. 6.7)

PROJECT PROFILE

Enlarging the Panama Canal

The Panama Canal has long been a marvel of civil engineering, opening originally in 1914 and now in continuous operation for 100 years. Some 40 ships a day make the 50-mile journey between the Atlantic and Pacific oceans, taking up to 10 hours and costing each ship roughly between $200,000 and $400,000. It is estimated that more than 13,000 ships annually transit oceans through the canals, providing the country of Panama with critical revenue that has been used to modernize the country and improve the standard of living for its citizens. At the same time, it has become clear, since the start of the new millennium, that the canal is in need of modernization for several reasons:

1. The construction of newer and larger cargo and container ships (so-called "post-Panamax" vessels) has put a strain on the number of ships that the canal can accommodate on any given day, lengthening the transit times, while ships can wait up to one week during heavy traffic periods for their turn through the locks.
2. Shipping firms, such as Maersk, have contracted with Asian firms to produce a new generation of massive container ships that are cost effective to operate, but too large to use the current canal locks, which are 110 feet wide. These shipping firms want to capitalize on the increased trade between China and the United States with these new, larger container ships.
3. The increasing competition from the Suez Canal and the U.S. Intermodal system. As noted above, based on current volume of trade, it has been estimated that as of 2011, approximately 37 percent of the capacity of the world's container ship fleet consists of vessels that do not fit through the current canal, and a great part of this fleet could be used on routes that compete with Panama. In fact, Maersk recently announced that it would no longer use the Panama Canal and shift its business to the Suez, due to its larger size.
4. The canal itself is old and in need of refurbishment and reconditioning. The wear and tear on the canal over the years has led to the need for extended downtime to fix problems.
5. From an environmental perspective, the canal needs upgrading. Every time the current lock system opens and closes its gates, more than 50,000 gallons of fresh water from Gatun Lake (the country's primary source of drinking water) are lost into the oceans. Further, the canal poses environmental and biohazards for indigenous Indian communities living along the canal and Gatun Lake.

In a speech announcing the need to revitalize the canal, former Panamanian president Martin Torrijos said that the canal, "is like our 'petroleum.' Just like the petroleum that has not been extracted is worthless and that in order to extract it you have to invest in infrastructure, the canal requires to expand its capacity to absorb the growing demand of cargo and generate more wealth for Panamanians."

In order to meet these needs, Panama created the Canal Expansion Project in early 2007. With a budget of $5.3 billion (including $2.3 billion in external funding), the canal expansion plan will:

- Build two new locks, one each on the Atlantic and Pacific sides. Each will have three chambers with water-saving basins.
- Excavate new channels to the new locks.
- Widen and deepen existing channels.
- Raise the maximum operating level of Lake Gatun.

(*continued*)

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FIGURE 10.1 **Scene from the Panama Canal Expansion Project**
Rafael Ibarra/Reuters/Corbis

Some of the important features of the project include work on:

Locks—The canal today has two lanes, each with its own set of locks. The expansion project will add a third lane through the construction of lock complexes at each end of the canal. The new lock chambers will be 1,400 feet long, 180 feet wide, and 60 feet deep, easily accommodating the larger-sized "post-Panamax" vessels in operation. One lock complex will be located on the Pacific side, southwest of the existing Miraflores Locks. The other will be located east of the existing Gatun Locks. Each of these new lock complexes will have three consecutive chambers designed to move vessels from sea level to the level of Gatun Lake and back down again.

Water-saving Basins—The new locks have water-saving basins to reduce the volume of water that is needed in lock operations. The operation of both the old and new locks uses gravity and valves with no pumping involved. The locks, old and new, will use water from Gatun Lake. Even in the current situation with two lock lanes, water supply can be limited at the end of Panama's dry season, when the lake's water level is low. The addition of a third set of locks means that this water supply issue must be addressed by environmentally sanctioned water systems that are expected to save thousands of gallons of water with each ship passing through the Canal.

Because of the size and scope of the project, it represents significant challenges for both Panama and the international companies hired to complete it. The project is being run by a Spanish-led consortium of European construction firms, in partnership with the Panama Canal Authority. While the actual construction work has been proceeding steadily, it has not gone smoothly. In fact, the project has realized significant cost overruns. As of 2014, the project was running about $1.6 billion over budget, raising the project's initial budget from $5.3 billion to nearly $7 billion. The construction consortium filed claim to recover the extra costs, arguing the overruns were the result of poor project controls within the country, while the Panamanian officials countered that the higher costs amounted to blackmail. Ultimately, the series of claims and disputes between the Canal Authority and the construction firms resulted in U.S. courtroom arbitration hearings to determine the party responsible for several overruns. For example, in 2014, a $180 million claim by the consortium working on the expansion project became the first of several disputed construction costs that could end up in the hands of Miami arbitrators. Additional claims totalling nearly $1.4 billion are pending, as a combination of work stoppages and poor quality construction have led to significant concrete rework and serious cost overruns. At one point in early 2014, the disputes became so severe that work was temporarily halted on the project for nearly one month, endangering nearly 10,000 jobs.

All this has complicated the development of the project and has begun to make some other parties, with a strong interest in the project, nervous. Many U.S. ports have gambled on the Panama venture by investing billions in their own expansions in order to profit from the increased Post-Panamax traffic. Miami's expanded port, for example, just opened a new, billion-dollar tunnel—part of a $2 billion makeover that includes a major dredging project and skyscraper-size loading cranes for sending more auto parts to Brazil and getting more commercial goods from China. In Boston, the canal expansion, combined with a plan to dredge Boston Harbor to accommodate larger ships, could generate

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thousands of new jobs and more than $4 billion in new business at Conley Terminal, according to the Massachusetts Port Authority. Carlos Urriola, executive vice president of the Manzanillo International Terminal, a major port at the Panama Canal's Caribbean entrance, notes: "We're all too aware that ports like Miami are definitely waiting to see when we're going to be ready with our canal."

It is expected that arbitration rulings will cut through the tangle of disputes among the various parties and the canal expansion will be ready by early 2016. Nevertheless, the construction firms are currently investigating ways to accelerate the completion of the process, so the country can gain maximum benefit from the expansion. Given the higher costs associated with accelerating the final activities, it is uncertain if this step will be taken, but it illustrates just how important the timely completion of the project is for both Panama and its construction contractors. Improving the economy, increasing traffic, and supporting a greener environment are all related and mutually reinforcing goals of the Panama Canal Expansion Project.[1]

INTRODUCTION

The previous chapter introduced the challenge of project scheduling, its important terminology, network logic, activity duration estimation, and constructing the critical path. In this chapter, we apply these concepts in order to explore other scheduling techniques, including the use of lag relationships among project activities, Gantt charts, crashing project activities, and comparing the use of Activity-on-Arrow (AOA) versus Activity-on-Node (AON) processes to construct networks. In the previous chapter, we used the analogy of a jigsaw puzzle, in which the act of constructing a schedule required a series of steps all building toward the conclusion. With the basics covered, we are now ready to consider some of the additional important elements in project scheduling, all aimed at the construction of a meaningful project plan.

10.1 LAGS IN PRECEDENCE RELATIONSHIPS

The term **lag** refers to the logical relationship between the start and finish of one activity and the start and finish of another. In practice, lags are sometimes incorporated into networks to allow for greater flexibility in network construction. Suppose we wished to expedite a schedule and determined that it was not necessary for a preceding task to be completely finished before starting its successor. We determine that once the first activity has been initiated, a two-day lag is all that is necessary before starting the next activity. Lags demonstrate this relationship between the tasks in question. They commonly occur under four logical relationships between tasks:

1. Finish to Start
2. Finish to Finish
3. Start to Start
4. Start to Finish

Finish to Start

The most common type of logical sequencing between tasks is referred to as the Finish to Start relationship. Suppose three tasks are linked in a **serial** path, similar to that shown in Figure 10.2. Activity C cannot begin until the project receives a delivery from an external supplier that is scheduled to occur four days after the completion of activity B. Figure 10.2 visually represents this Finish to Start lag of 4 days between the completion of activity B and the start of activity C.

Note in Figure 10.2 that the early start (ES) date for activity C has now been delayed for the 4 days of the lag. A Finish to Start lag delay is usually shown on the line joining the nodes; it should

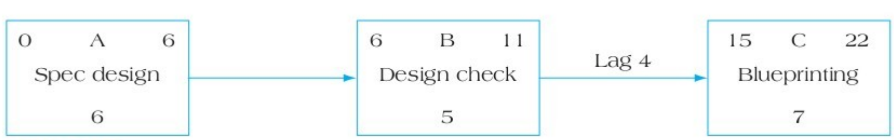

FIGURE 10.2 Network Incorporating Finish to Start Lag of 4 Days

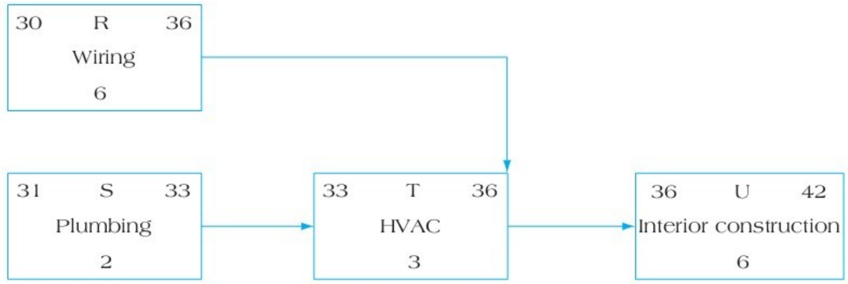

FIGURE 10.3 Finish to Finish Network Relationship

be added in forward pass calculations and subtracted in backward pass calculations. Finish to Start lags are *not* the same as additional activity slack and should not be handled in the same way.

Finish to Finish

Finish to Finish relationships require that two linked activities share a similar completion point. The link between activities R and T in Figure 10.3 shows this relationship. Although activity R begins before activity T, they share the same completion date.

In some situations, it may be appropriate for two or more activities to conclude at the same time. If, for example, a contractor building an office complex cannot begin interior wall construction until all wiring, plumbing, and heating, ventilation, and air conditioning (HVAC) have been installed, she may include a lag to ensure that the completion of the preceding activities all occur at the same time. Figure 10.4 demonstrates an example of a Finish to Finish lag, in which the preceding activities R, S, and T are completed to enable activity U to commence immediately afterward. The lag of 3 days between activities R and T enables the tasks to complete at the same point.

Start to Start

Often two or more activities can start simultaneously or a lag takes place between the start of one activity after an earlier activity has commenced. A company may wish to begin materials procurement while drawings are still being finalized. It has been argued that the Start to Start lag relationship is redundant to a normal activity network in which parallel or concurrent activities are specified as business as usual. In Figure 9.20, we saw that Activity C is a burst point in a network and its successor activities (tasks D and G) are, in effect, operating with Start to Start logic. The subtle difference between this example and a Start to Start specification is that in Figure 9.20 it is not necessary for both activities to begin simultaneously; in a Start to Start relationship the logic must be maintained by both the forward and backward pass through the network and can, therefore, alter the amount of float available to activity G.

Start to Start lags are becoming increasingly used as a means to accelerate projects (we will discuss this in greater detail later in the chapter) through a process known as **fast-tracking**. Instead of relying on the more common Finish to Start relationships between activities, organizations are attempting to compress their schedules through adopting parallel task scheduling of the sort that is typified by Start to Start. For example, it may be possible to overlap activities in a variety of

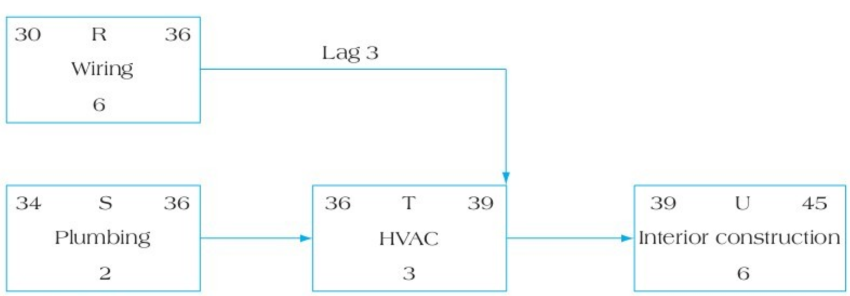

FIGURE 10.4 Finish to Finish Relationship with Lag Incorporated

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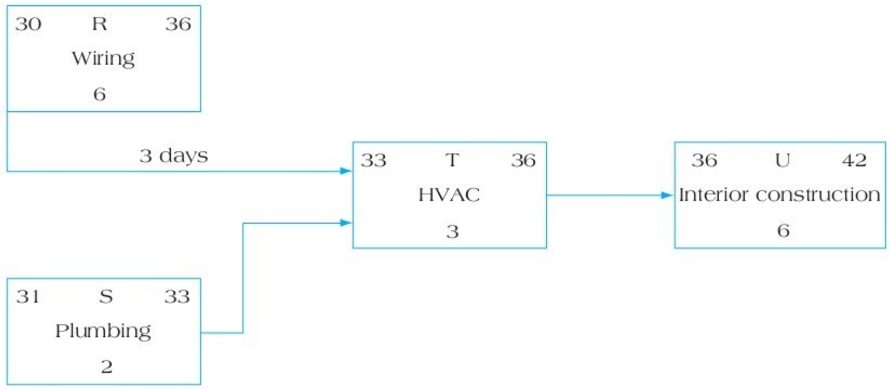

FIGURE 10.5 **Start to Start Network Relationship**

different settings. Proofreading a book manuscript need not wait until the entire document is completed; a copy editor can begin working on chapter one while the author is still writing the drafts. Further, in software development projects, it is common to begin coding various sequences while the overall design of the software's functions is still being laid out. It is not always possible to reconfigure predecessor/successor relationships into a Start to Start schedule, but where it is possible to do so, the result is to create a more fast-paced and compressed schedule.

Figure 10.5 demonstrates an example of a Start to Start network, in which the lag of 3 days has been incorporated into the network logic for the relationship between activities R, S, and T.

Start to Finish

Perhaps the least common type of lag relationship occurs when a successor's finish is dependent upon a predecessor's start (Start to Finish). An example of such a situation is construction in an area with poor groundwater drainage. Figure 10.6 shows this relationship. The completion of the concrete pouring activity, Y, is dependent upon the start of site water drainage, W. Although an uncommon occurrence, the Start to Finish option cannot be automatically rejected. As with the other types of predecessor/successor relationships, we must examine our network logic to ascertain the most appropriate manner for linking networked activities with each other.

10.2 GANTT CHARTS

Developed by Harvey Gantt in 1917, Gantt charts are another extremely useful tool for creating a project network. **Gantt charts** establish a time-phased network, which links project activities to a project schedule baseline. They can also be used as a project tracking tool to assess the difference

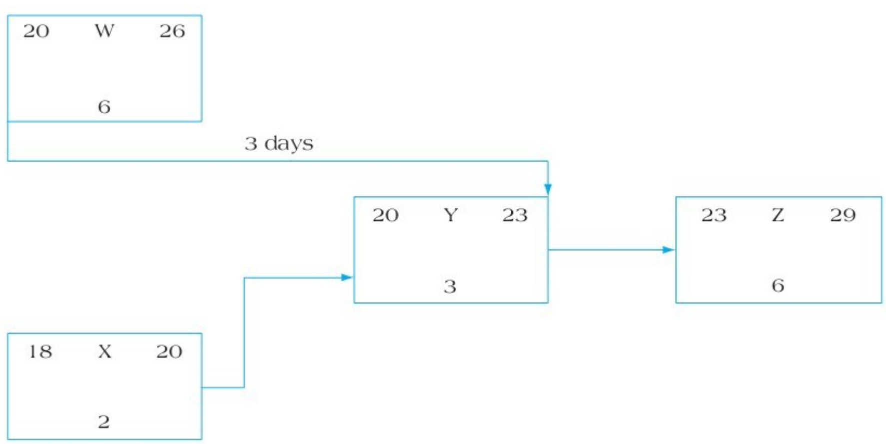

FIGURE 10.6 **Start to Finish Network Relationship**

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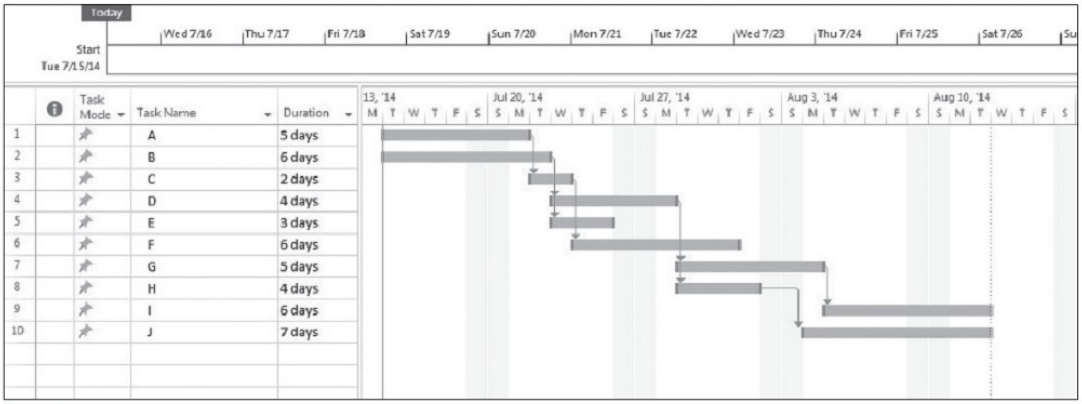

FIGURE 10.7 Sample Gantt Chart using Microsoft Project 2013

Note: Weekend days are not counted for activity duration times.
Source: MS Project 2013, Microsoft Corporation.

between planned and actual performance. A sample of a basic Gantt chart is shown in Figure 10.7. Activities are ordered from first to last along a column on the left side of the chart with their ES and EF durations drawn horizontally. The ES and EF dates correspond to the baseline calendar drawn at the top of the figure. Gantt charts represent one of the first attempts to develop a network diagram that specifically orders project activities by baseline calendar dates, allowing the project team to be able to focus on project status at any date during the project's development.

Some benefits of Gantt charts are (1) they are very easy to read and comprehend, (2) they identify the project network coupled with its schedule baseline, (3) they allow for updating and project control, (4) they are useful for identifying resource needs and assigning resources to tasks, and (5) they are easy to create.

1. ***Comprehension***—Gantt charts work as a precedence diagram for the overall project by linking together all activities. The Gantt chart is laid out along a horizontal time line so that viewers can quickly identify the current date and see what activities should have been completed, which should be in progress, and which are scheduled for the future. Further, because these activities are linking in the network, it is possible to identify predecessor and successor activities.
2. ***Schedule baseline network***—The Gantt chart is linked to real-time information, so that all project activities have more than just ES, EF, LS, LF, and float attached to them. They also have the dates when they are expected to be started and completed, just as they can be laid out in conjunction with the overall project schedule.
3. ***Updating and control***—Gantt charts allow project teams to readily access project information activity by activity. Suppose, for example, that a project activity is late by 4 days. It is possible on a Gantt chart to update the overall network by factoring in the new time and seeing a revised project status. Many firms use Gantt charts to continually update the status of ongoing activities. Gantt charts allow managers to assess current activity status, making it possible to begin planning for remedial steps in cases where an activity's completion is lagging behind expectations.
4. ***Identifying resource needs***—Laying the whole project out on a schedule baseline permits the project team to begin scheduling resources well before they are needed, and resource planning becomes easier.
5. ***Easy to create***—Gantt charts, because they are intuitive, are among the easiest scheduling devices for project teams to develop. The key is having a clear understanding of the length of activities (their duration), the overall precedence network, the date the project is expected to begin, and any other information needed to construct the schedule baseline, such as whether **overtime** will be needed.

Figure 10.8 uses the information contained in the Project Delta example from the previous chapter to construct a Gantt chart using MS Project 2013 (see Figure 9.11). The start and finish dates and length are ascribed to each activity and represented by the horizontal bar drawn from left to right through the network. The chart lists the early activities in order from top to bottom. The overall "flow: of the chart moves from the top left corner down to the bottom right. The baseline schedule

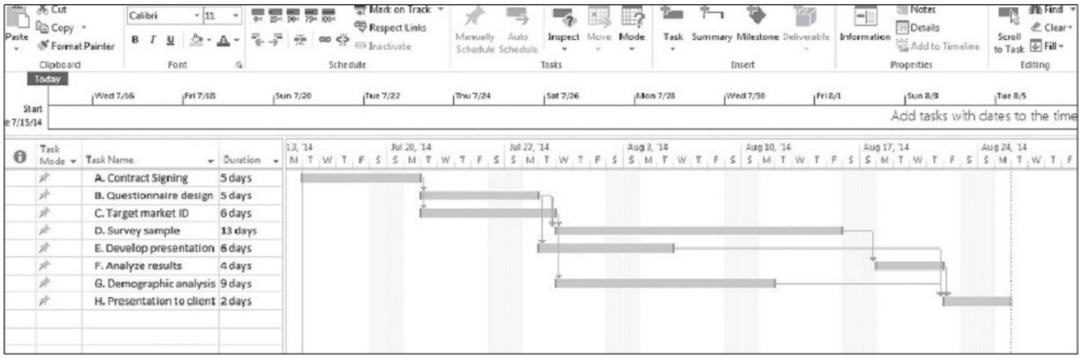

FIGURE 10.8 **Completed Gantt Chart for Project Delta**

Source: MS Project 2013, Microsoft Corporation.

is shown horizontally across the top of the page. Each activity is linked to indicate precedence logic through the network. All activities are entered based on their early start (ES) times. We can adjust the network to change the logic underlying the sequencing of the tasks. For example, the activities can be adjusted based on the late start (LS) date or some other convention.

As we continue to fill out the Gantt chart with the complete Project Delta (see Figure 10.8), it is possible to determine additional information from the network. First, activity slack is represented by the long arrows that link activities to their successors. For example, activity E, with its 60 days (12 weeks) of slack or float, is represented by the solid bar showing the activity's duration and the lengthy arrow that connects the activity to the next task in the network sequence (activity H). Finally, a number of software-generated Gantt charts will also automatically calculate the critical path, identifying the critical activities as the chart is constructed. Figure 10.9 shows the critical path as it is highlighted on the schedule baseline.

Adding Resources to Gantt Charts

Adding resources to the Gantt chart is very straightforward, consisting of supplying the name or names of the resources that are assigned to perform the various activities. Figure 10.10 gives an MS Project output showing the inclusion of a set of project team resources assigned to the various tasks. It is also possible to assign the percentage of time each resource is assigned to each activity. This feature is important because, as we will see in later chapters, it forms the basis for tracking and control of the project, particularly in terms of cost control.

Figure 10.10 shows six project team members assigned across the six tasks of another project example. Remember that the Gantt chart is based on activity durations calculated with full commitment of resources. Suppose, however, that we were only able to assign resources to the tasks at a lesser figure (say 50%) because we do not have sufficient resources available when they are needed. The result will be to increase the length of time necessary to complete the project activities. The challenge of resource management as it applies to network scheduling is important and will be covered in detail in Chapter 12.

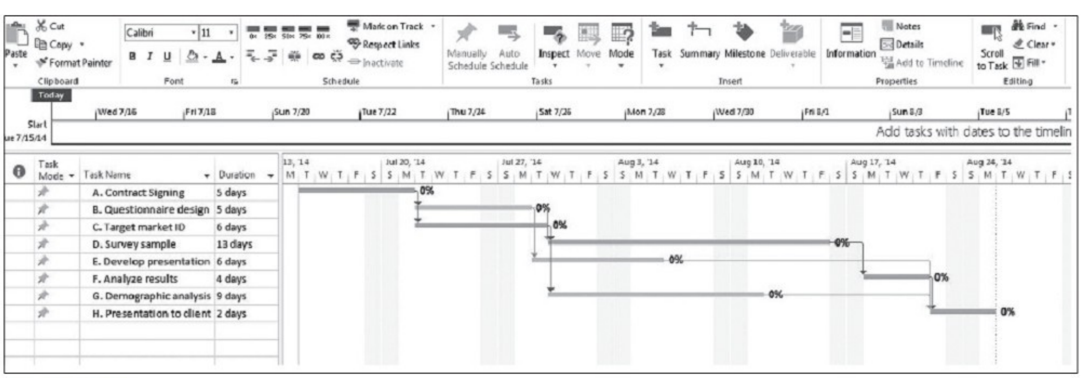

FIGURE 10.9 **Gantt Chart for Project Delta with Critical Path Highlighted**

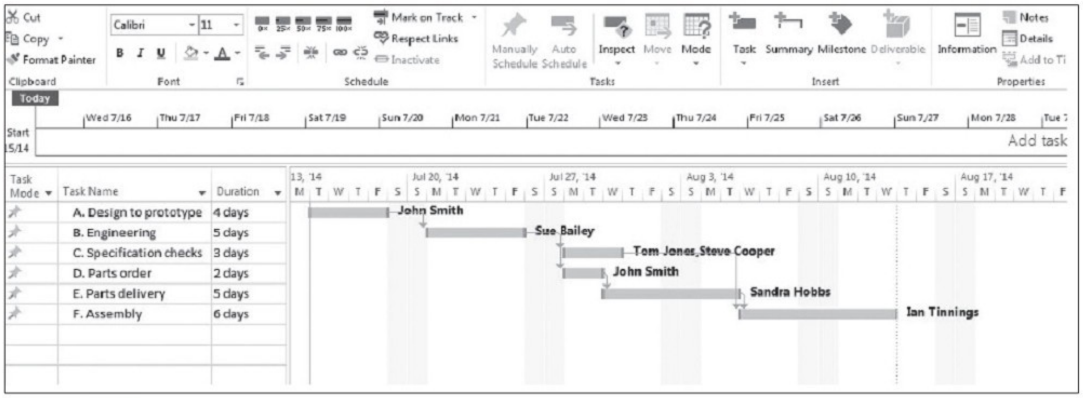

FIGURE 10.10 **Gantt Chart with Resources Specified**

Source: MS Project 2013, Microsoft Corporation.

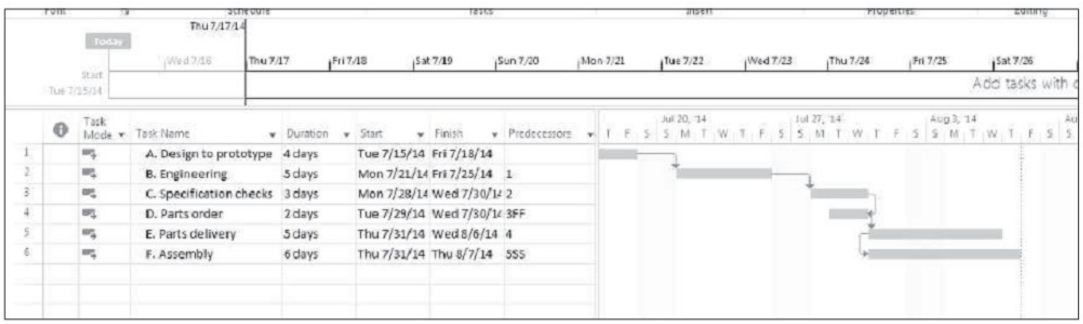

FIGURE 10.11 **Gantt Chart with Lag Relationships**

Source: MS Project 2013, Microsoft Corporation.

Incorporating Lags in Gantt Charts

Gantt charts can be adjusted when it is necessary to show lags, creating a visual image of the project schedule. Figure 10.11 is a Gantt chart with some alternative lag relationships specified. In this network, activities C (specification check) and D (parts order) are linked with a Finish to Finish relationship that has both ending on the same date. Activity E is a successor to activity D, and the final two activities, E and F, are linked with a Start to Start relationship. Similar to lag relationships in network construction, the key lies in developing a reasonable logic for the relationship between tasks. Once the various types of lags are included, the actual process of identifying the network's critical path and other pertinent information should be straightforward.

BOX 10.1

Project Managers in Practice

Christopher Fultz, Rolls-Royce Plc.

> *"A project manager is like the conductor of the orchestra. The conductor doesn't play an instrument, but understands how to balance the output of everyone to deliver the finished product. The conductor has to pay attention to all of the musicians and cannot focus too long on just one section. The PM is the same way, balancing the needs of multiple stakeholders and the team members to deliver the desired outcome. The project manager may not do the actual work, but makes sure all work is being completed to the schedule and is meeting the project requirements. The PM cannot focus on one specific area for long, or the rest of the project can quickly become out of control."*

Christopher Fultz holds a Master's Degree in Program Management from Penn State, an MBA from Indiana University, and an undergraduate degree from the School of Technology at Purdue University. He lives and works in Indianapolis, Indiana, at Rolls-Royce and is part of the Defense Business. His first formal project management role was leading a small engine modification program to support a new engine application for Bell broad exposure to the business and to project management. During the two-year program, they will work in different business units and locations on projects and programs in all phases of the product life cycle. At the end of their rotation, they will move into their first significant project management role with a solid background and good experience in project management."

Chris has accountability for developing and maintaining the Portfolio Management Process for Defense and works as part of a larger team to define and implement this process. "The focus of the process is to balance discretionary investment in projects to support program growth, customer satisfaction, and cost management. This portfolio balancing is an ongoing, continuous process as projects open and close and business and customer needs change."

Outside of work, Chris is a mentor in the FIRST Robotics program, a high school program that is focused on getting students interested in careers in science and engineering. One of the key elements of the program is to design and build a robot to play a specific new game challenge each year. These are big, remote-controlled machines, 24" × 36" × 60" tall, weighing 120 pounds. The program is "hands-on" and mentor based, where students and professionals work side by side. Chris believes it is a great project management experience for the students as well as an excellent development activity for mentors. "While there is much more to the program than just the robot, the project of building the robot provides all elements of the product life-cycle in a compressed, 6-week period. The game challenge provides several requirements and options of what to build and how to play. Teams must find the right balance of what they will design and build based on their skills, resources, budget, and schedule. The schedule is tight and there is no option to negotiate more time. Teams then move on to competition, where they see their robot in action and can evaluate their design, strategy, and final product against the 'competition.' Teams go from requirements to concepts to finished product to in-service in a span of a few months, providing immediate, and sometimes harsh, feedback on their work. Even though these are high school students, this is a great training ground for project managers."

10.3 CRASHING PROJECTS

At times it is necessary to expedite the project, accelerating development to reach an earlier completion date. The process of accelerating a project is referred to as **crashing**. Crashing a project directly relates to resource commitment. The more resources we are willing to expend, the faster we can push the project to its finish. There can be good reasons to crash a project, including:[2]

1. The initial schedule may be too aggressive. Under this circumstance, we may schedule the project with a series of activity durations so condensed they make the crashing process inevitable.
2. Market needs change and the project is in demand earlier than anticipated. Suppose, for example, your company discovered that the secret project you were working on was also being developed by a rival firm. Because market share and strategic benefits will come to the first firm to introduce the product, you have a huge incentive to do whatever is necessary to ensure that you are first to market.
3. The project has slipped considerably behind schedule. You may determine that the only way to regain the original milestones is to crash all remaining activities.
4. The contractual situation provides even more incentive to avoid schedule slippage. The company may realize that it will be responsible for paying more in late delivery penalties than the cost of crashing the activities.

Options for Accelerating Projects

A number of methods are available for accelerating or crashing projects. One key determinant of which method to use is how "resource-constrained" the project is; that is, whether there is additional budget or extra resources available to devote to the project. The issue of whether the project manager (and organization) is willing to devote additional resources to the project is a primary concern that will weigh in their choices. Depending on the level of resource constraint, certain options will be more attractive than others. Among the primary methods for accelerating a project are the following:

1. ***Improve the productivity of existing project resources***—Improving the productivity of existing project resources means finding efficient ways to do more work with the currently available pool of personnel and other material resources. Some ways to achieve these goals include improving the planning and organization of the project eliminating any barriers

to productivity such as excessive bureaucratic interference or physical constraints, and improving the motivation and productivity of project team members. Efforts should always be made to find ways to improve the productivity of project resources; however, these efforts are almost always better achieved during the down time *between* projects rather than in the midst of one.

2. ***Change the working method employed for the activity, usually by altering the technology and types of resources employed***—Another option for accelerating project activities is to promote methods intended to change the working method employed for the activity, usually by altering the technology and types of resources employed. For example, many firms have switched to computer-based project scheduling techniques and saved considerable time in the process. Changing working methods can also include assignment of senior personnel, or hiring contract personnel or subcontractors to perform specific project functions.
3. ***Compromise quality and/or reduce project scope***—These two options refer to conscious decisions made within the organization to sacrifice some of the original project specifications due to schedule pressure or a need to speed a project to completion. Compromising quality may involve a relatively simple decision to accept the use of cheaper materials or fewer oversight steps as the project moves forward. Rarely are decisions to lower quality beneficial for the project; in fact, the decision usually involves a sense of trying to limit or control the damage that could potentially occur. In some cases, it is impossible to even consider this as an option; construction firms hold safety (and hence, quality) as one of their highest concerns and would not consider deliberate steps to reduce quality.

   Reducing project scope, on the other hand, is a much more common response to critical pressure on the organization to deliver a project, particularly if it has been experiencing delays or if the benefits of being first to market seriously overshadow concerns about reduced scope. For example, suppose a television manufacturer in South Korea (Samsung) is working to devise a new product that offers 3D viewing, state-of-the-art sound quality, Internet connectivity, and a host of other features. While in the midst of development, the company becomes aware that a direct competitor is due to release its new television with a more modest set of features in time for the Christmas shopping season. Samsung might be tempted to limit work on their model to the advances that currently have been completed, scale back on other upgrades for a later model, and deliver their television with this reduced scope in order to maintain their market share.

   The decision to limit project scope is not one to be taken lightly, but in many cases, it may be possible to do so with limited negative impact on the company, provided the firm can prioritize and distinguish between the "must-have" features of the project and other add-on functions that may not be critical to the project's mission. Numerous projects have been successfully introduced with reduced scope because the organization approached these reductions in a systematic way, revisiting the work breakdown structure and project schedule and making necessary modifications. Approaching scope reduction in a proactive manner can have the effect of reducing scope while minimizing the negative effects on the final delivered project.
4. ***Fast-track the project***—Fast-tracking a project refers to looking for ways to rearrange the project schedule in order to move more of the critical path activities from sequential to parallel (concurrent) relationships. In some cases, the opportunities to fast-track a project only require creativity from the project team. For example, in a simple construction project, it may be possible to begin pouring the concrete foundation while the final interior design work or more detailed drawings are still being completed. That is, the design of cabinetry or the placement or doors and windows in the house will not be affected by the decision to start work on the foundation, and the net effect will be to shorten the project's duration. In Chapter 9, we discussed options to reduce the critical path. Fast-tracking can employ some of those methods as well as other approaches, including:

   a. Shorten the longest critical activities—Identify those critical activities with the longest durations and reduce them by some percentage. Shortening longer activities typically offers the most opportunity to affect the length of the overall project without incurring severe additional risks.

b. Partially overlap activities—Start the successor task before its predecessor is fully completed. We can use "negative lags" between activities to reschedule our critical activities and allow for one task to overlap another. For example, suppose we had two activities in sequence: (1) program function code, and (2) debug code. In many cases, it is possible to begin debugging code before the programmer has fully completed the assignment. We might indicate, for example, that the debugging activity has a negative lag of two weeks to allow the debugger to begin her task two weeks before the programming activity is scheduled to finish.

c. Employ Start to Start lag relationships—Standard predecessor/successor task relationships are characterized by Finish to Start relationships, suggesting that the successor cannot begin until its predecessor is fully completed. In Start to Start relationships, the assumption is that both activities can be undertaken at the same time; for example, instead of waiting for a city to issue a building permit approval, a local contractor may begin clearing the site for new construction or contacting other city departments to begin road and sewer applications. Not every set of activities can be redefined from a Finish to Start to a Start to Start lag relationship, but often there are places within the project schedule where it is possible to employ this fast-tracking technique.

5. ***Use overtime***—A common response to the decision to accelerate a project is to make team members work longer hours through scheduling overtime. On one level, the decision is an attractive one: If our workers are currently devoting 40 hours a week to the project, by adding another 10 hours of overtime, we have increased productivity by 20%. Further, for salaried employees, we can institute overtime regulations without the additional costs that would accrue from using hourly workers. Thus, the use of overtime appears on the surface to be an option with much to recommend it.

The decision to use overtime, however, comes with some important drawbacks that should be considered. The first is cost: For hourly workers, overtime rates can quickly become prohibitively expensive. The result is to seriously affect the project budget in order to gain time (part of what are referred to as "dollar-day" trade-offs). Another problem with overtime is possible effects on project team member productivity. Work by Ken Cooper offers some important points for project managers to consider when tempted to accelerate their projects through the use of overtime. Figure 10.13 shows the results of his research examining the effects of sustained overtime on project team members for two classes of employee: engineers and production staff. When real productivity and rework penalties (having to fix work incorrectly done the first time) are taken into account, the impact of overtime is worrisome: For only four hours of overtime worked each week, the project can expect to receive less than two hours of actual productivity from both engineers and production staff.

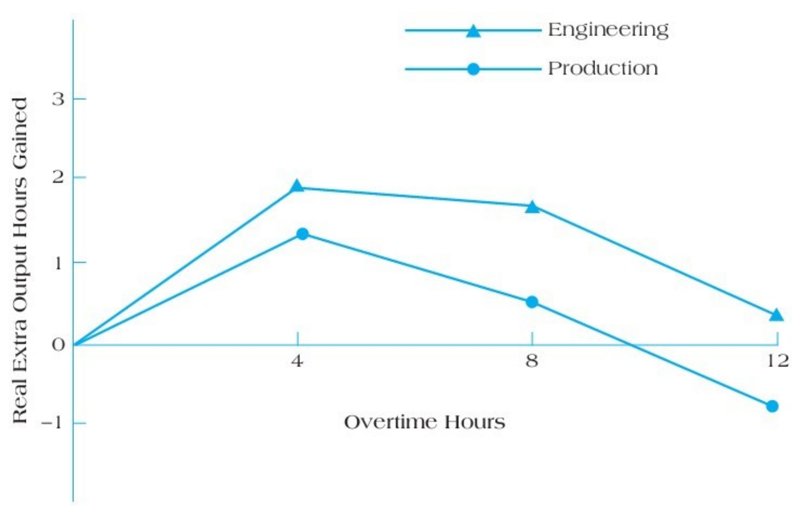

FIGURE 10.13 **Real Output Gained from Different Levels of Sustained Overtime**

The more overtime is used, the more this problem is exacerbated. Indeed, at 12 hours of sustained weekly overtime, the net output effect is negligible for engineering personnel and actually becomes negative for production resources! In effect, requiring additional overtime work in the hopes of accelerating the project's schedule often has the actual effect of increasing overtime-induced fatigue, adding to our budget while providing almost no real additional productivity.

6. ***Add resources to the project team***—Expected activity durations are based on using a set number of individuals to accomplish the task; however, when additional resources become available, they have the net effect of reducing the amount of time to complete the task. For example, suppose we originally assigned one programmer to complete a specific coding operation and determined that the task would take 40 hours. Now, we decide to shorten that task by adding two additional programmers. What is the new expected time to complete the activity? Certainly, we would anticipate it to be less than the original 40 hours, but how much less is not always clear, since the result may not be a simple linear function (e.g., 40/3 = 13.33 hours). Other variables can affect the completion time (e.g., communication delays or difficulty in coordinating the three programmers). In general, however, adding resources to activities can lead to a significant reduction in the expected duration of the programming activity.

    As with overtime, we need to carefully consider the impact of adding resources to a project, especially when some activities are already underway. In adding people to activities, for example, we need to consider "learning curve" effects. Suppose that our programmer has already begun working on the task when we decide to add two additional resources to help him. The effect of adding two programmers to this ongoing activity may actually backfire on the project manager, as was originally suggested by a former IBM executive named Fred Brooks. He suggested, in his famous **Brooks's Law**, that adding resources to ongoing activities only delays them further. His point was that the additional time and training needed to bring these extra resources up to speed on the task negates the positive impact of actually adding staff. It is much better, he suggested, to add extra resources to activities that have not yet started, where they can truly shorten the overall task durations. Although research has tended to confirm Brooks's Law in most situations, it is possible to realize schedule shrinkage provided sufficient time and current resources are available to train additional staff or they are added early enough into the activity to minimize the negative effects of Brooks's Law.[3]

Although the above discussion demonstrates that there are some important issues to consider when adding resources to a project, this alternative remains by far the most common method for shortening activity durations, and it is often useful as long as the link between cost and schedule is respected.

To determine the usefulness of crashing project activities, we must first be able to determine the actual cost associated with each activity in the project, both in terms of project fixed costs and variable costs. These concepts are discussed in greater detail in Chapter 8 on project budgeting. Let us assume that we have a reasonable method for estimating the total cost of project activities, both in terms of their normal development time and under a crashed alternative. Figure 10.14 illustrates the relationship between activity costs and duration. Note that the normal length of the duration for an activity reflects a calculated resource cost in order to accomplish that task. As we seek to crash activities, the costs associated with these activities increase sharply. The crash point on the diagram represents the fully expedited project activity, in which no expense is spared to complete the task. Because the line shows the slope between the normal and crash points, it is also understood that a project activity can be speeded up to some degree less than the complete crash point, relative to the slope of the crash line.

In analyzing crash options for project activities, the goal is to find the point at which time and cost trade-offs are optimized. We can calculate various combinations of time/cost trade-offs for a project's crash options by determining the slope for each activity using the following formula:

$$\text{Slope} = \frac{\text{crash cost} - \text{normal cost}}{\text{normal time} - \text{crash time}}$$

EXAMPLE 10.1 Calculating the Cost of Crashing

To calculate the cost of crashing project activities, suppose that for activity X, the normal activity duration is 5 weeks and the budgeted cost is $12,000. The crash time for this activity is 3 weeks and the expected cost is $32,000. Using the above formula, we can calculate the cost slope for activity X as:

$$\frac{32{,}000 - 12{,}000}{5 - 3} \text{ or } \frac{\$20{,}000}{2} = \$10{,}000 \text{ per week}$$

In this example, activity X is calculated to cost $10,000 for each week's acceleration to its original schedule. Is this a reasonable price? In order to answer that question, we need to consider:

a. ***What costs are associated with accelerating other project activities?*** It may be that activity X's unit cost of $10,000 per week is a genuine bargain. Suppose, for example, that an alternative activity would cost the project $25,000 for each week's acceleration.

b. ***What are the gains versus the losses in accelerating this activity?*** For example, does the project have excessive late penalties that would make crashing cheaper relative to late delivery? Alternatively, is there a huge potential payoff in being first to market with the project?

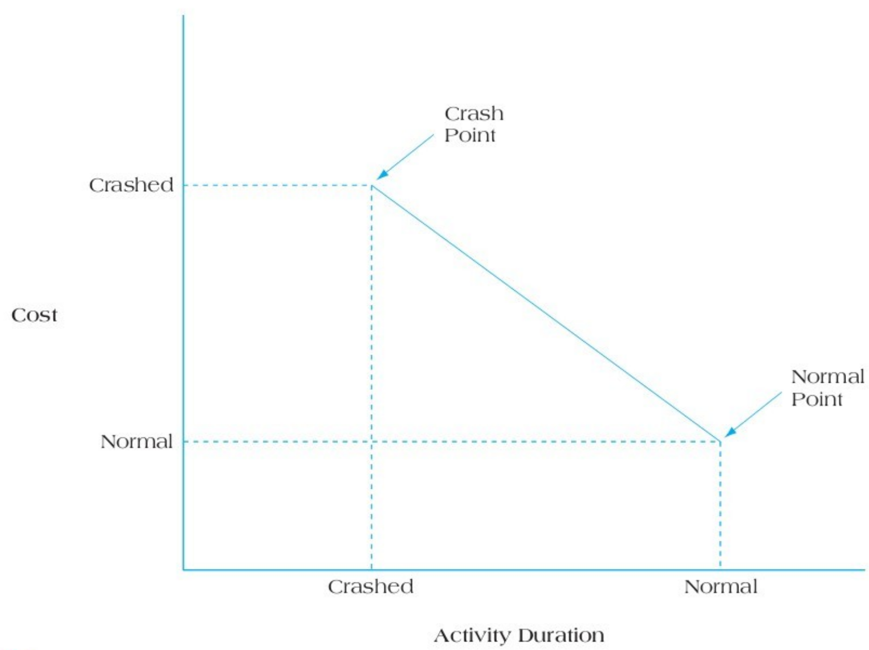

FIGURE 10.14 **Time/Cost Trade-Offs for Crashing Activities**

EXAMPLE 10.2 Crashing a Project

Suppose we have a project with only eight activities, as illustrated in Table 10.1. The table also shows our calculated normal activity durations and costs and crashed durations and their costs. We wish to determine which activities are the optimal candidates for crashing. Assume that the project costs listed include both fixed and variable costs for each activity. Use the formula provided earlier to calculate the per-unit costs (in this case, costs per day) for each activity. These costs are shown in Table 10.2.

The calculations suggest that the least expensive activities to crash would be first, activity A ($250/day), followed by activities B and G ($300/day). On the other hand, the project would incur the greatest cost increases through crashing activities H, E, and C ($2,000/day, $1,750/day, and

TABLE 10.1 Project Activities and Costs (Normal vs. Crashed)

		Normal		Crashed	
Activity	Predecessors	Duration	Cost	Duration	Cost
A	—	5 days	$ 1,000	3 days	$ 1,500
B	A	7 days	700	6 days	1,000
C	A	3 days	2,500	2 days	4,000
D	A	5 days	1,500	5 days	1,500
E	C, D	9 days	3,750	6 days	9,000
F	B	4 days	1,600	3 days	2,500
G	D	6 days	2,400	4 days	3,000
H	E, F, G	8 days	9,000	5 days	15,000
Total costs =			$22,450		$37,500

$1,500/day, respectively). Note that in this example, we are assuming that activity D cannot be shortened, so no crashing cost can be calculated for it.

Now let's transfer these crashing costs to a network that shows the precedence logic of each activity. We can form a trade-off between shortening the project and increasing its total costs by analyzing each alternative. Figure 10.15 shows the project network as a simplified AON example with only activity identification and crashed duration values included. The network also shows the critical path as A – D – E – H or 27 days. We determined that the initial project cost, using normal activity durations, is $22,450. Crashing activity A (lowest at $250) by 1 day will increase the project budget from $22,450 to $22,700. Fully crashing activity A will shorten the project duration to 25 days while increasing the cost to $22,950. Activities B and G are the next candidates for crashing at $300 per day each. Neither activity is on the project's critical path, however, so the overall benefit to the project from shortening these activities may be minimal. Activity D cannot be shortened. The per unit cost to crash E is $1,750, and the cost to crash H is higher ($2,000). Thus, crashing activity E by 1 day will increase the project budget from $22,950 to $24,700. The total costs for each day the project is crashed are shown in Table 10.3.

Note that in the fully crashed project network shown in Figure 10.15, the critical path is unchanged when all activities are fully crashed. The association of costs to project duration is graphed in Figure 10.16. As each project activity has been crashed in order, the overall project budget increases. Figure 10.16 demonstrates, however, that beyond crashing activities A, E, and H, there is little incentive to crash any of the other project tasks. The overall length of the project cannot shrink below 19 days, and additional crashing merely adds costs to the budget. Therefore, the optimal crash strategy for this project is to crash only activities A, E, and H for a total cost of $11,750 and a revised project cost of $34,200.

TABLE 10.2 Costs of Crashing Each Activity

Activity	Crashing Costs (per day)	On Critical Path?
A	$ 250	Yes
B	300	No
C	1,500	No
D	—	Yes
E	1,750	Yes
F	900	No
G	300	No
H	2,000	Yes

TABLE 10.3 Project Costs by Duration

Duration	Total Costs
27 days	$22,450
26 days	22,700
25 days	22,950
24 days	24,700
23 days	26,450
22 days	28,200
21 days	30,200
20 days	32,200
19 days	34,200

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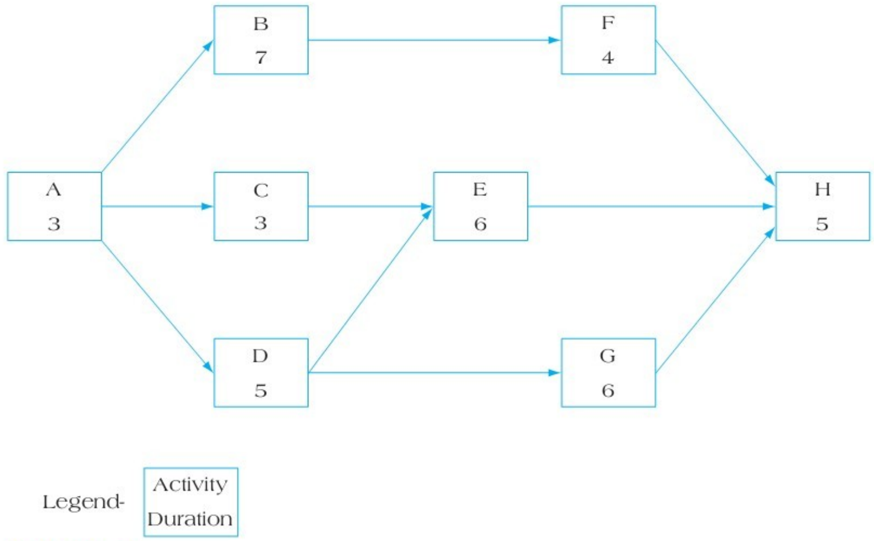

FIGURE 10.15 Fully Crashed Project Activity Network

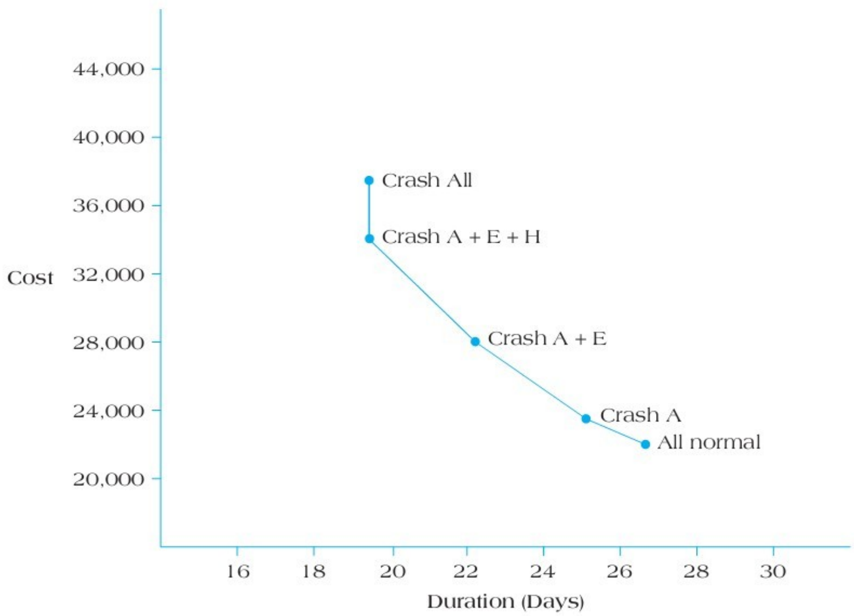

FIGURE 10.16 Relationship Between Cost and Days Saved in a Crashed Project

The decision to crash a project should be carefully considered for its benefits and drawbacks. Considering the relationship between activity duration and increased project costs is never a "painless" operation; there is always a significant cost associated with activity acceleration. However, if the reasons for crashing are sufficiently compelling, the overall project duration can often be shortened significantly.

Crashing the Project: Budget Effects

As we have seen, crashing is the decision to shorten activity duration times through adding resources and paying additional direct costs. There is a clear relationship between the decision to crash project activities and the effect of the crashing on the budget. As Figure 10.16 showed, the cost of crashing is always to be weighed against the time saved in expediting the activity's schedule.

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TABLE 10.4 Project Activities, Durations, and Direct Costs

	Normal		Crashed		
Activity	Cost	Duration	Extra Cost	Duration	Crash Cost
A	$2,000	10 days	$2,000	7 days	$ 667/day
B	1,500	5 days	3,000	3 days	1,500/day
C	3,000	12 days	1,500	9 days	500/day
D	5,000	20 days	3,000	15 days	600/day
E	2,500	8 days	2,500	6 days	1,250/day
F	3,000	14 days	2,500	10 days	625/day
G	6,000	12 days	5,000	10 days	2,500/day
H	9,000	15 days	3,000	12 days	1,000/day

To highlight this problem, consider the crashing table shown in Table 10.4. Let us assume that activities A, C, D, and H are on the critical path; therefore, the first decision relates to which of the critical activities we should crash. A simple side-by-side comparison of the activities and their crash costs reveals the following:

Activity	Crash Cost
A	$2,000
C	$1,500
D	$3,000
H	$3,000

Using Table 10.4, we find that in crashing activity C, the least expensive to crash, we save 3 days at a cost of $1,500 in extra expenses. The other candidates for crashing (A, D, and H) can also be evaluated individually in terms of schedule time gained versus cost to the project budget (assume all other paths are ≤48 days). Crashing Activity A saves the project 3 days at an additional cost of $2,000, raising the total cost of A to $4,000. Crashing Activities D and H represents a time savings of 5 and 3 days respectively at additional costs of $3,000 for each.

Indirect costs are affected by crashing as well. Table 10.5 illustrates the choices the project team is faced with as they continually adjust the cost of crashing the schedule against other project costs. Suppose the project is being charged overhead at a fixed rate, say, $200 per day. Also assume that a series of late penalties is due to kick in if the project is not completed within 50 days. The original 57-day schedule clearly leaves us at risk for penalties, and although we have improved the delivery date, we are still 4 days past the deadline. Now we discover that iterating the crashed schedule three times will take us from our original 57-day schedule to a new schedule of 48 days (crashing first activity C, then A, and then H). The schedule has shortened 9 days against a budget increase of $6,500.

We could make Table 10.5 more complete by following the costs for each successive crashed activity and linking them to total project costs. Intuitively, however, we can see that

TABLE 10.5 Project Costs over Duration

Project Duration (in days)	Direct Costs	Liquidated Damages Penalty	Overhead Costs	Total Costs
57	$32,000	$5,000	$11,400	$48,400
54	33,500	3,000	10,800	47,300
51	35,500	1,000	10,200	46,700
48	38,500	-0-	9,600	48,100

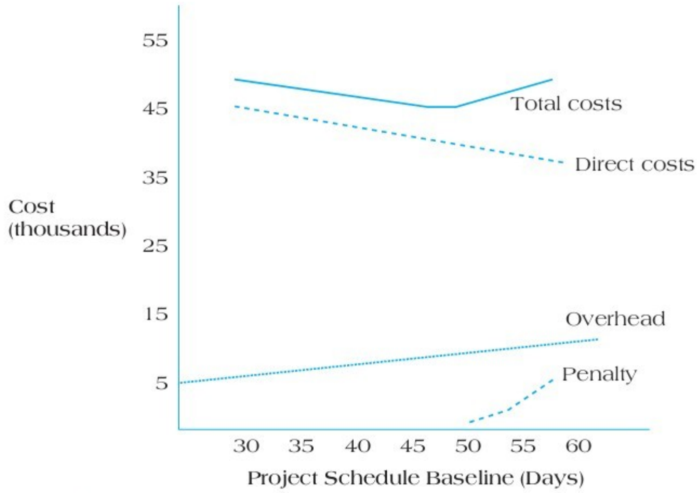

FIGURE 10.17 Project Costs over the Life Cycle

Source: A. Shtub, J. F. Bard, and S. Globerson. (1994). *Project Management: Processes, Methodologies, and Economics*, Second Edition. Copyright © 2005. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.

direct costs would continue to increase as we included the extra costs of more crashed activities. On the other hand, overhead charges and liquidated damages costs would decrease; in fact, at the 48-day mark, liquidated damages no longer factor into the cost structure. Hence, the challenge becomes deciding at what point it is *no longer* economically viable to continue crashing project activities.

Figure 10.17 depicts the choices the project team faces in balancing the competing demands of schedule and cost, with other intervening factors such as penalties for late delivery included. Direct costs are shown with a downward slope, reflecting the fact that the costs will rapidly ramp up as the schedule shrinks (the time-cost trade-off effect). With liquidated damage penalties emerging after the 50-day schedule deadline, we see that the project team is facing a choice of paying extra money for a crashed schedule at the front end versus paying out penalties upon project delivery for being late. The process the project team faces is a balancing act between competing costs—crashing costs and late completion costs.

10.4 ACTIVITY-ON-ARROW NETWORKS

So far this text has focused exclusively on the use of the **Activity-on-Node (AON)** convention for representing activity network diagrams. Among the reasons for this system's popularity is that it mirrors the standard employed in almost all project management scheduling software, it is visually easier to comprehend, and it simplifies many past standards and conventions in network diagrams. Nevertheless, *Activity-on-Arrow (AOA)* techniques are an alternative to AON methodology. Although no longer as popular as it once was, AOA is still used to some degree in various project management situations. Some AOA conventions are unique to its use and do not directly translate or integrate with AON approaches.

How Are They Different?

Both AON and AOA methods are used to create a project activity network. They simply differ in the means they employ and the graphical manner in which the network, once completed, is represented. AOA networks also employ arrows and nodes to build the activity network; however, with AOA, the arrow represents the activity with its duration time estimate, while the node is used only as an **event** marker, usually representing the completion of a task.

Consider the activity node shown in Figure 10.18. The AOA node is similar to AON nodes in that there is no set standard for the types of information that the node should contain however it

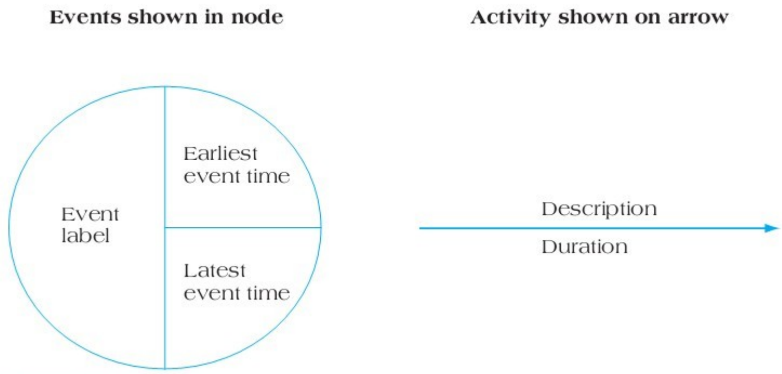

FIGURE 10.18 Notation for Activity-on-Arrow (AOA) Networks

should be sufficiently clear to convey understanding to the users. The convention in Figure 10.18 offers the major placement of network information for each activity arrow and node:

Arrow includes a short task description and the expected duration for the activity.

Node includes an event label, such as a number, letter, or code, and earliest and latest event times. These values correspond to early start and late finish times for the activity.

EXAMPLE 10.3 Activity-on-Arrow Network Development

The development of an AOA network follows a similar process to the one we apply to AON methodology, with some important distinctions. In order to make clear the differences, let us return to the sample network problem from earlier in this chapter: Project Delta. Table 10.6 gives us the relevant precedence information that we need to construct the AOA network.

We begin building a network in the same manner as with AON developed in Chapter 9. First, we can start with activity A and its immediate successors, activities B and C. Because the convention now is to indicate the activity on the arrow, it is common for AOA networks to have an initial "Start" event node that precedes the insertion of the activities. Figure 10.19 shows the process of beginning to add the project information to the network diagram. Note that activities B and C directly succeed activity A. The convention would be to draw two arrows, representing these activities, directly off event node 2.

The first problem with AOA networking becomes apparent once we have to enter activity D into the network. Note that both activities B and C are immediate predecessors for activity D. Representing this relationship with an AON network is easy; we simply draw two arrows connecting

TABLE 10.6 Project Information

Activity	Project Delta Description	Predecessors	Estimated Duration
A	Contract signing	None	5
B	Questionnaire design	A	5
C	Target market ID	A	6
D	Survey sample	B, C	13
E	Develop presentation	B	6
F	Analyze results	D	4
G	Demographic analysis	C	9
H	Presentation to client	E, F, G	2

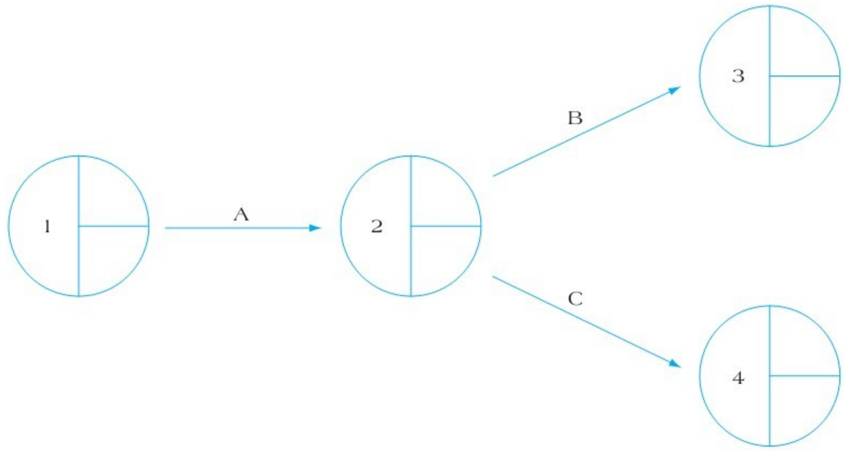

FIGURE 10.19 Sample Network Diagram Using AOA Approach

nodes B and C to the node for activity D (see Figure 9.10). However, with AOA networks we cannot employ the same process. Why not? Because each arrow is used not just to connect the nodes, but also to represent a separate task in the activity network. How can we show this precedence relationship in the network? Figure 10.20 offers several options, two of which are incorrect. The first option (Figure 10.20a) is to assign two arrows representing activity D and link activities B and C through their respective nodes (3 and 4) with node 5. This would be wrong because the AOA convention is to assign only one activity to each arrow. Alternatively, we could try to represent this precedence relationship by using the second option (Figure 10.20b), in which a double set of activity arrows for activities B and C jointly link node 2 to node 3. Again, this approach is incorrect because it violates the rule that each node represents a unique event, such as the completion of an individual activity. It can also become confusing when the convention is to employ multiple arrows between event nodes. It was in order to resolve just such a circumstance that the use of dummy activities was created.

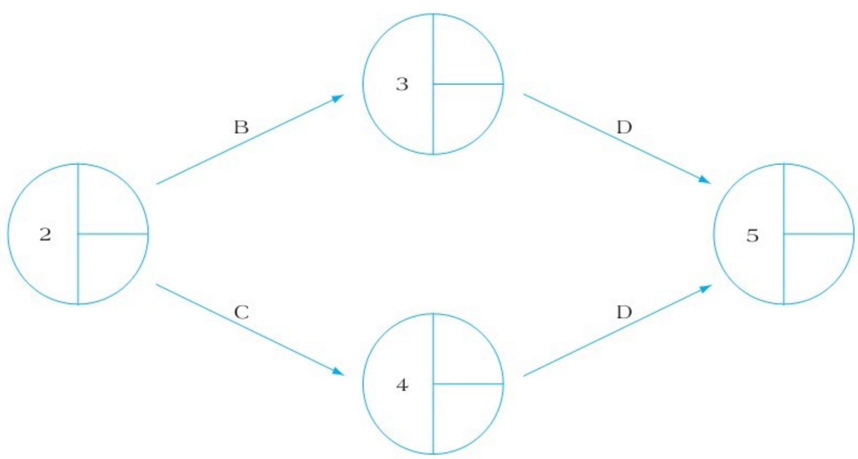

FIGURE 10.20a Representing Activities with Two or More Immediate Successors (Wrong)

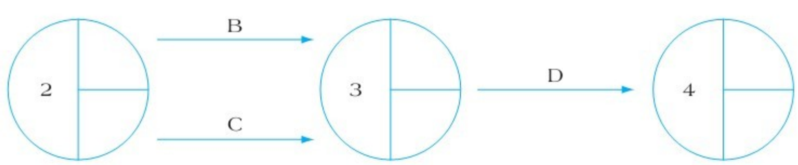

FIGURE 10.20b Alternative Way to Represent Activities with Two or More Immediate Successors (Wrong)

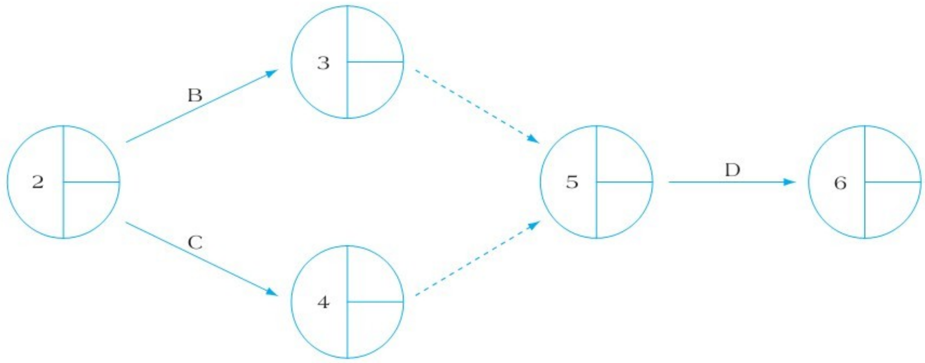

FIGURE 10.20c **Representing Activities with Two or More Immediate Successors Using Dummy Activities (Better)**

Dummy Activities

Dummy activities are used in AOA networks to indicate the existence of precedent relationships between activities and their event nodes. They do not have any work or time values assigned to them. They are employed when we wish to indicate a logical dependency such that one activity cannot start before another has been completed, but the activities do not lie on the same path through the network. Dummy activities are usually represented as dashed or dotted lines and may or may not be assigned their own identifiers.

Figure 10.20c shows the proper method for linking activities B and C with their successor, activity D, through the use of dummy activities. In this case, the dummy activities merely demonstrate that both activities B and C must be completed prior to the start of activity D. When using dummy activities in network diagramming, one good rule for their use is to try to apply them sparingly. The excessive use of dummy activities can add confusion to the network, particularly when it is often possible to represent precedence logic without employing the maximum possible number of dummy activities. To illustrate this point, consider Figure 10.21, in which we have reconfigured the partial activity network for Project Delta slightly. Note that this diagram has simply eliminated one of the dummy activities about to enter node 5 without changing the network logic.

Now that we have a sense of the use of dummy activities, we can construct the full AOA network for Project Delta. Activity E succeeds B and is entered on the network with its endpoint at node 6. Likewise, activity F, following D, is entered into the network with endpoint at node 6. Activity G can also be entered following the completion of C, and its endpoint node is also 6. Finally, activity H, which has activities E, F, and G as predecessors, is entered and completes the basic AOA network (see Figure 10.22).

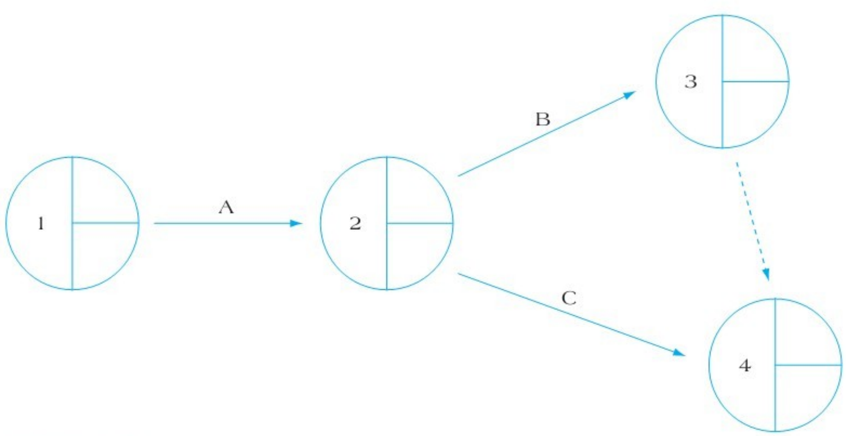

FIGURE 10.21 **Partial Project Delta Network Using AOA Notation**

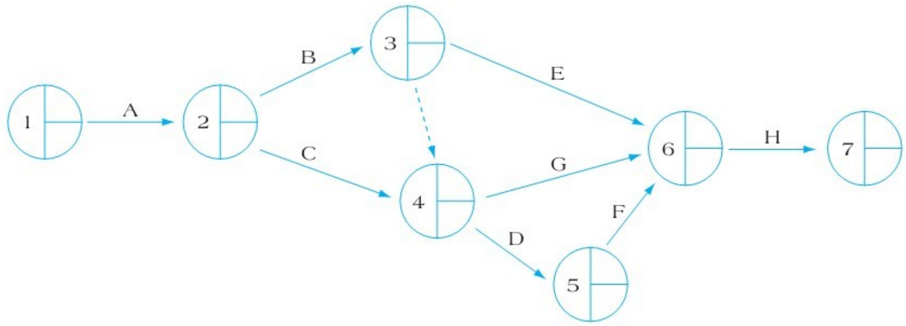

FIGURE 10.22 Completed Project Delta AOA Network

Forward and Backward Passes with AOA Networks

The actual information we seek to collect for these processes that determines early and late start dates is slightly different from that used in AON, as we are concerned with the early start (ES) values for each activity node in the forward pass. The decision rules still apply: Where we have nodes that serve as **merge** points for multiple predecessor activities, we select the largest ES. The only other point to remember is that dummy activities do not have any duration value attached to them.

Figure 10.23 shows the forward pass results for Project Delta. The nodes display the information concerning ES in the upper right quadrant. As with the AON forward pass, the process consists simply of adding duration estimates for each activity moving from left to right through the network. The only places in the network that require some deliberation regarding the ES value to apply are at the merge points represented by nodes 4 and 6. Node 4 is the merge point for activity C and the dummy activity represented by the dotted line. Because dummy activities do not have any value themselves, the ES for node 4 is the largest of the additive paths for activities A − C = 11 versus activities A − B = 10. Therefore, we find that the ES at node 4 should be 11. The other merge point, node 6, uses the same selection process. Because the path A − C − D − F = 28, which is the largest of the paths entering the node, we use 28 as the ES for node 6. Finally, after adding the duration for activity H, the overall length of the network is 30 weeks, just as it was in the AON network shown in the previous chapter (see Figure 9.18).

The backward pass is also similar in procedure to the earlier AON process. The backward pass starts at the far right or completion of the network at node 7 and, using the 30-week duration as its starting point, subtracts activity times along each path (LF − Duration = LS). When we reach a burst event, such as node 2 or 4, we select the smallest LS from the choice of activities. Thus, using Figure 10.24 as our reference, we can begin subtracting duration values as we move from right to left in the network. The LS values are included in the node in the bottom right-hand quadrant, right underneath the ES values.

The forward pass allowed us to determine that the expected duration for the project is 30 weeks. Using the backward pass, we can determine the individual activity slacks as well as the

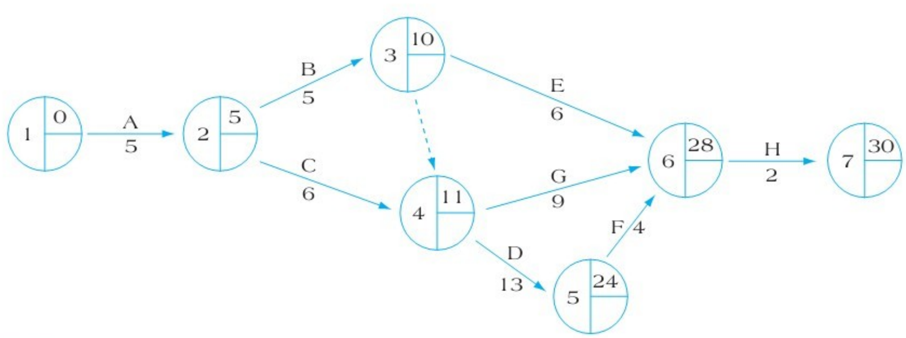

FIGURE 10.23 Partial Delta Forward Pass Using AOA Notation

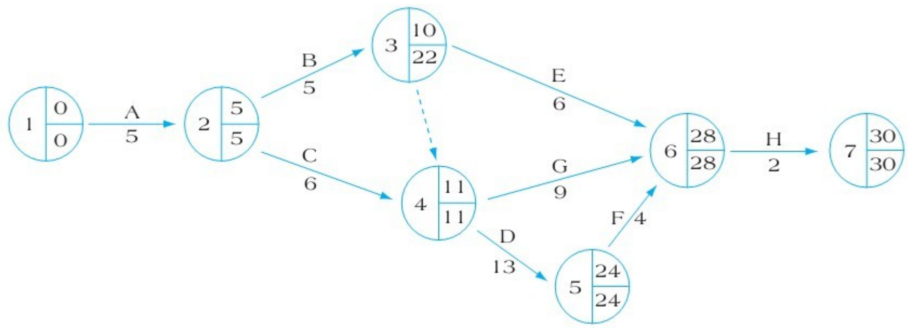

FIGURE 10.24 **Project Delta Backward Pass Using AOA Network**

critical path, similar to the AON process. The difference is that the labeling of ES and LS values lies within the event nodes; therefore, it is necessary to examine each activity path to determine the slack associated with it. We know, for example, that the ES for activity E is 10 weeks and the duration of the activity is 6 weeks. Therefore, when comparing the EF for activity E of 16 weeks with the ES value in node 6 of 28 weeks, we can see that the difference, 12 weeks, is the amount of slack for the activity. Likewise, activity G's ES is 11 weeks and its duration is 9. This EF value of 20 weeks is 8 weeks less than the ES for node 6, indicating that activity G's slack is 8. The same logic can be applied to each activity in the network to determine the critical path and the activities with slack time.

AOA Versus AON

Activity-on-Arrow and Activity-on-Node network diagramming are intended to do the same thing: create a sequential logic for all activities with a project and, once they are linked, determine the project's duration, critical path, and slack activities. One common question has to do with the efficacy of one network approach over the other; that is, what are the benefits and drawbacks of selecting either the AON format or the AOA approach? Consequently, in choosing to use either AOA or AON network methods, it is important to consider some of the strengths and weaknesses of each of these techniques.[4]

AON STRENGTHS AND WEAKNESSES The benefits of AON are centered primarily in the fact that it has become the most popular format for computer software packages, such as MS Project. Hence, as more and more companies use software-based project scheduling software, they are increasingly using the AON method for network diagrams. Another benefit of AON is that we place the activity within a node and use arrows merely as connection devices, thereby simplifying the network labeling. This convention makes AON networks very easy to read and comprehend, even for novice project managers. The primary drawback with AON networks occurs when the project is very complex with numerous paths through the model. The sheer number of arrows and node connections when multiple project activities are merging or bursting can make AON networks difficult to read.

AOA STRENGTHS AND WEAKNESSES The greatest benefit of AOA modeling lies in its accepted use in certain business fields, such as construction, where AON networks may be less widely used. Also, in the case of large, complex projects, it is often easier to employ the path process used in AOA. Finally, because the activity and node system is used for projects that have many significant milestones, such as supplier deliveries, AOA event nodes are very easy to identify and flag. On the other hand, there is no question that some conventions in AOA diagramming are awkward, particularly the use of dummy activities. The concept of dummy activities is not simple to master, and thus more training is required on the part of novice project managers to be able to use the concept easily. In addition, AOA networks can be "information-intensive" in that both arrows and nodes contain some important project information. Rather than centralizing all data into a node, as in the AON convention AOA networks use both arrows and nodes to label the network

Ultimately, the choice to employ AON or AOA network methodology comes down to individual preferences and the external pressures faced in work situations. For example, if the organization I work for has decided to adopt AON modeling because of the commonly used scheduling software, in all likelihood I will concentrate exclusively on AON network diagramming approaches. Regardless of the decision each of us makes regarding the use of AOA or AON methodology, it is extremely important that we all become comfortable with the basic theory and operation of both types of network models.

10.5 CONTROVERSIES IN THE USE OF NETWORKS

The **Program Evaluation and Review Technique**/Critical Path Method (PERT/CPM) is a well understood and much employed system for project planning and scheduling. Nevertheless, networks are abstract representations of events in which time is reduced to a numerical value. They may or may not be drawn to a scale that has a relationship to the ongoing pattern of events. Sometimes this abstraction can be misleading. In fact, there are several criticisms and caveats we need to bear in mind as we develop project activity networks, including:[5]

1. ***Networks can become too large and complex to be meaningful.*** Many projects are large and hugely complex. For example, the creation of an operating system for personal computers, construction of a sports arena, or development of a drug are all projects that can easily contain thousands of steps or individual activities. Many projects extend over years, and estimation of activity duration can become general guesses at best. As a result, when working with networks for large-scale or long-term projects, it is necessary to find ways to simplify the activity network calculations. One rule of thumb for large projects is to try to simplify network logic and reduce it to the most obvious or meaningful relationships. Rather than showing every possible path through the network and every activity sequence, a "meta-network" that shows only the key subroutines or network paths can be created. These subroutines can be further broken down by the project manager or administrator responsible for their completion, but the overall project network is streamlined to include only the most general or relevant project activities.

   A variably scaled time frame is another option for long-term projects. For example, activities scheduled to occur within the first nine months may be listed with durations scaled to the number of days necessary to complete them. Activities scheduled between the first and second year may be listed on the network with a scaling of weeks or even months, and activities included in the network beyond the second year may only be listed with durations indicated by months.
2. ***Faulty reasoning in network construction can sometimes lead to oversimplification or incorrect representations.*** Problems frequently occur when organizations attempt to manage their projects on the basis of these multiple layers of activity networks. Information going to different levels in the organization is often not easily understood or translatable between levels because they do not share a common project schedule. Hence, it is important that when simplifying a project network, steps must be taken to ensure that information is not lost through oversimplification or the creation of multiple networks with no integration processes.

   Complex schedules often require a combination "top-down, bottom-up" approach to controlling project activities. Top-down control means that there is a tiered system for project schedules. At the top is the most basic summary information, as in the case of simply listing work packages or summary "roll-ups" of numerous individual tasks. Top management then deals with top-tier summary information that aggregates and simplifies the schedule. Although it is much easier to understand, this top-tier summary network does not give top management a basis for understanding the actual development of the project because they are not privy to the status of individual tasks. On the other hand, those responsible for portions of the project, as well as project managers, need more "bottom-up" information to allow them to maintain hands-on control of the portion of the project network for which they are responsible. Project personnel need specific, lower-tier activity network information to allow for optimal scheduling and control.

   Figure 10.25 provides an example of a simplified tiered system for schedules. Top management would receive aggregated information from the top tier, middle-level management

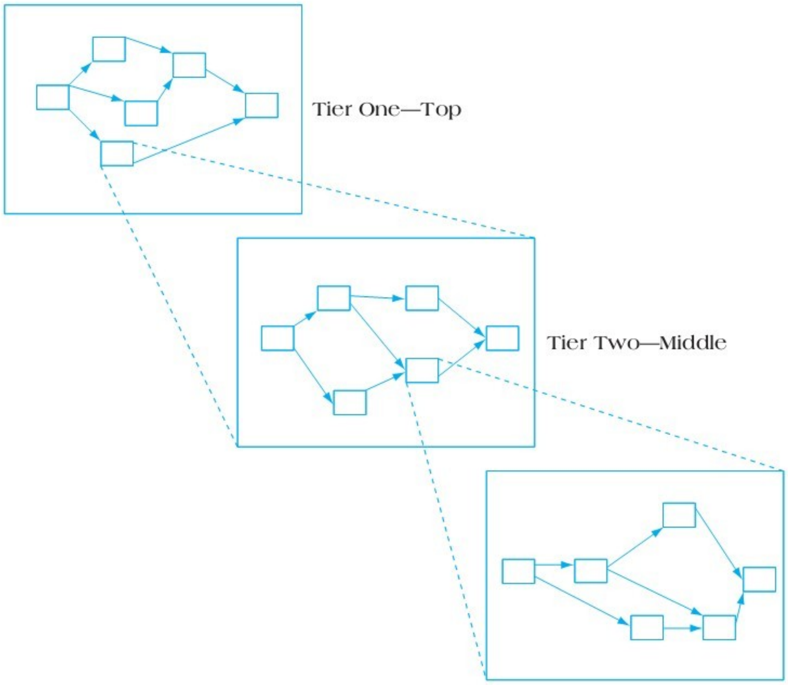

FIGURE 10.25 **Tiered System of Project Schedules**

(e.g., department heads) would get slightly more detailed information based on activities relevant to their departments or functions, and both the project manager and the project team would employ the full, detailed, and specific project schedule in the bottom tier.

3. ***Networks are sometimes used for tasks for which they are not well suited.*** Companies sometimes try to adopt project network scheduling to other scheduling activities in their organizations, but network activities are not useful for all scheduling challenges. Suppose, for example, that a manufacturing organization was having problems with its production scheduling. Under the mistaken notion that PERT can work just as well for manufacturing operations as it does for project planning, managers might mistakenly decide to employ PERT in situations for which it is not suited. In fact, although project network scheduling methodologies are an important technique in project management, they do not represent a panacea for all scheduling problems that organizations face.
4. ***Networks used to control the behavior of subcontractors have special dangers.*** Many projects involve the use of subcontractors. When the "prime contracting" organization employs multiple subcontractors, a common mistake is requiring them to develop independent activity plans without reference to or understanding the planning of other subcontractors with whom they may need to interface. If a firm is using multiple subcontractors, two important principles are needed to guide their use of networks: (1) All subcontractors must be privy to the prime contractor's overall network, which includes the schedules for each "sub," so that subcontractors can make scheduling decisions based not on assumptions, but rather on clear knowledge of the plans of other subcontractors; and (2) the networks of all subcontractors need to be merged—using a common set of network techniques, time-frame scaling, and so forth—and the network document must be mutually accessible, which is most likely to occur if all subcontractors are equally aware of the rules governing network creation.
5. ***There is a strong potential for positive bias in PERT estimations used in network construction.*** Research has demonstrated that most activity estimations using PERT methods lead to overly optimistic activity duration estimates. PERT analysis is based on probabilistic time estimates that, if unreasonably determined, can lead to inaccurate and misleading project schedules. The logic that drives duration estimates and the development of the PERT network must be demonstrated as reasonable for PERT scheduling to be meaningful.

Conclusions

Activity network development is the heart of the project management planning process. It requires us to make reasonable estimates of activity durations, and it expects us to develop the logic for activity sequencing and use this information to create meaningful project schedules. Only through the careful analysis of the steps in project scheduling can we turn project concepts into working realities. Scheduling allows us to determine the answers to the truly significant questions of project management: What needs to be accomplished? When does it need to be accomplished? How can it be accomplished? The scheduling techniques you select are not nearly as important to the final success of your projects as is your commitment to performing these operations carefully, methodically, and honestly. The schedule is our road map showing the route we must take to complete the project successfully. The care with which we create that map and the manner in which we follow it will go far to determining whether or not we will be successful in running our projects.

Summary

1. **Apply lag relationships to project activities.** Examples of developing network logic include determining how precedence relationships apply to each project activity; that is, do activities follow one another in a common manner in which the predecessor's early finish becomes the successor activity's early start, or are other relationships specified? Among these alternative relationships, referred to as lag relationships, are Finish to Start, Finish to Finish, Start to Start, and Start to Finish.
2. **Construct and comprehend Gantt charts.** An alternative method for developing the project network other than the use of PERT diagrams is Gantt charts. Gantt charts offer an important advantage over the early PERT diagrams in that they link the activities to a project schedule baseline based on actual calendar dates. Thus, we can see not only which activities have to occur in what order, but also when they are scheduled to begin and end. In recent years, Gantt charts have been used in conjunction with PERT charts, particularly with most project scheduling software.
3. **Recognize alternative means to accelerate projects, including their benefits and drawbacks.** The project schedule can be accelerated by a number of alternative means, including adding resources to the project team, fast-tracking, compromising quality, reducing the project's scope, and using overtime. Each of these options offers the means to accelerate a project, but not all are appropriate in every circumstance; for example, it may not be useful or helpful to deliberately compromise a project's quality. Some of these options can improve productivity in theory, but may not work as well in reality; for example, research suggests that use of sustained overtime for extended periods can actually have a detrimental effect on a project due to the effects of employee fatigue and rework costs. Finally, the choice of alternatives requires us to understand the resource constraints of the organization.
4. **Understand the trade-offs required in the decision to crash project activities.** When it has been determined that the project must be accelerated, due to either changes in the external environment or pressures from top management or customers, a method known as project crashing is employed. Crashing directly links all activities to their respective costs and allows us to calculate the cost for each day we choose to accelerate the project. The decision of whether or not to crash can therefore be directly linked to the cost implications for crashing, allowing project managers to make an informed decision on time/cost trade-offs.
5. **Develop activity networks using Activity-on-Arrow techniques.** Although AON network diagramming has become the more popular method, for many years AOA network diagramming was the technique of choice, and it is still widely applied in several project settings, such as construction. This chapter discusses in detail AOA networks and their unique properties, including the creation and use of dummy variables, and examines the steps necessary to construct an AOA network, as well as its advantages and disadvantages compared to AON notation.
6. **Understand the differences in AON and AOA and recognize the advantages and disadvantages of each technique.** The chapter concludes with a critical review of some of the controversies found in the development and use of network diagrams for project scheduling. Several drawbacks or concerns in diagramming are listed, including (1) networks can become too large and complex to be meaningful, (2) faulty reasoning can lead to oversimplification or incorrect representations, (3) networks can be used for tasks for which they are not well suited, and (4) network diagramming has special dangers when used to control subcontractor behavior.

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Key Terms

Activity-on-Arrow (AOA) (*p. 348*)
Activity-on-Node (AON) (*p. 348*)
Arrow (*p. 349*)
Brooks's Law (*p. 343*)
Crashing (*p. 340*)
Dummy activities (*p. 351*)
Event (*p. 348*)
Fast-tracking (*p. 334*)
Gantt chart (*p. 335*)
Lag (*p. 333*)
Merge (*p. 352*)
Node (*p. 349*)
Overtime (*p. 336*)
Program Evaluation and Review Technique (PERT) (*p. 354*)
Serial activities (*p. 333*)

Solved Problems

10.1 CRASHING PROJECT ACTIVITIES

Suppose you are considering whether or not to crash project activities in order to expedite your project. You have calculated the total costs per activity for both normal and crashed options. These are shown in the table below:

	Normal		Crashed	
Activity	**Duration**	**Cost**	**Duration**	**Cost**
A	6 days	$ 2,400	4 days	$ 3,600
B	7 days	3,500	5 days	5,000
C	5 days	3,000	4 days	3,800
D	3 days	2,700	2 days	4,500
E	4 days	800	3 days	1,500
F	5 days	1,200	3 days	2,100
G	8 days	2,400	5 days	4,200
H	3 days	4,500	2 days	7,000
Total costs	=	$20,500		$31,700

a. Which activities are the most likely candidates for crashing (i.e., which are the most cost-effective to crash)?
b. Refer back to Figure 10.24. Using the critical path from this activity network, consider A − C − D − F − H as the critical path and assume all other paths are less than a fully crashed A − C − D − F − H. Prioritize the candidates for crashing. How does the activity network change the decision rule?

SOLUTION

Remember that the formula to calculate crashing costs is based on the slope between the normal and crashed costs of each activity:

$$\text{Slope} = \frac{\text{crash cost} - \text{normal cost}}{\text{normal time} - \text{crash time}}$$

Using this equation, we can create a table showing the crashing costs per day:

Activity	Crashing Costs (per day)
A	$ 600
B	750
C	800
D	1,800
E	700
F	450
G	600
H	2,500

a. Prioritizing crashing choices, the most cost-effective activities to crash are (1) activity F, (2) activities A and G, and (3) activity E.
b. The choices for crashing should be prioritized first by those that are on the critical path. In this example, the critical path is made up of activities A − C − D − F − H. Therefore, the first activity to be crashed would be activity F, followed by activity A. Because neither activity G nor E is on the critical path, crashing them will not reduce the project length but will add to the overall costs.

10.2 COST OF CRASHING A PROJECT

Consider the following project activity table, identifying each activity, its normal duration and cost, and expedited durations and costs:

	Normal		Crashed	
Activity	**Duration**	**Cost**	**Duration**	**Cost**
A	3 days	$1,500	2 days	$2,000
B	5 days	3,500	4 days	5,000
C	4 days	6,800	3 days	7,500
D	5 days	2,500	3 days	6,000
E	7 days	4,200	6 days	5,400
F	4 days	2,000	3 days	2,700

a. What is the cost per day to crash each of the activities?
b. Assuming that only activities A, C, and E are part of the critical path, which activities should be crashed first?

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