PART THREE

Construction Management

16

Planning and Scheduling

16–1 INTRODUCTION

Planning and Scheduling

As you already know, some planning must be done in order to perform any function with a minimum of wasted time and effort. This is true whether the function is getting to work on time or constructing a multimillion dollar building. A schedule is nothing more than a time-phased plan. Schedules are used as guides during the performance of an operation in order to control the pace of activities and to permit completion of the operation at the desired or required time.

Scheduling is utilized for many different phases of the construction process, from master planning through facility construction to facility operation and maintenance. In the construction phase itself, schedules are useful for a number of purposes before starting a project and after completion of the project as well as during the actual conduct of construction work. Some of the principal uses for schedules during each of these phases of construction are listed below.

Before Starting

1. Provides an estimate of the time required for each portion of the project as well as for the total project.
2. Establishes the planned rate of progress.
3. Forms the basis for managers to issue instructions to subordinates.
4. Establishes the planned sequence for the use of personnel, materials, machines, and money.

During Construction

1. Enables the manager to prepare a checklist of key dates, activities, resources, and so on.
2. Provides a means for evaluating the effect of changes and delays.

3. Serves as the basis for evaluating progress.
4. Aids in the coordination of resources.

After Completion of Construction

1. Permits a review and analysis of the project as actually carried out.
2. Provides historical data for improving future planning and estimating.

Scheduling Principles

There are a number of different forms of schedules that may be used, including written schedules, bar graph schedules, network schedules, and others. In this chapter, we will consider only bar graph, network, and linear scheduling methods. Regardless of the scheduling method employed, the following general principles of scheduling should be observed.

1. Establish a logical sequence of operations.
2. Do not exceed the capabilities of the resources that are available.
3. Provide for continuity of operations.
4. Start project controlling (or critical) activities early.

It must be recognized that the accuracy or validity of scheduling depends on the validity of the work quantity and productivity estimates used. The accuracy of an estimate of the time it will take to perform a construction operation is a function of the kind of work involved and prior experience in doing that sort of work. For example, one expects a more accurate estimate of the time required to install a wastewater line in a residential structure than of the time required to install a cooling line in a nuclear power plant. Methods for dealing with the uncertainty associated with activity-time estimates will be discussed later in this chapter.

In addition to valid time estimates for activities, the planner must have a thorough understanding of the nature of the work to be performed and the relationships between the various work items making up the project. One of the major deficiencies of the bar graph schedule described in the following section is the fact that the bar graph fails to show relationships between work items. That is, what activities must be started or completed before other activities can be started or completed?

16–2 BAR GRAPH METHOD

The Bar Graph Schedule

The *bar graph* or *bar chart schedule* is a graphical schedule relating progress of items of work to a time schedule. The bar schedule traces its origin to a chart developed by Henry L. Gantt, a pioneer in the application of scientific management methods to industrial production. These charts, referred to as *Gantt charts*, took several different forms, depending on their application. Because of their origin, all forms of bar graph schedules are sometimes called Gantt charts. In spite of the advent of network planning methods, the bar graph schedule is still the most widely used schedule form found in construction work. Its continued popularity in the face of the significant deficiencies that are described in the next section is undoubtedly due to its very graphic and easily understood format. A simple bar graph schedule for a construction project is shown in Figure 16–1. The major work items, or activities, making up the project are listed on the left side of the schedule with a time scale across the top. The column headed "Hours" indicates the estimated number of labor-hours required for each activity. The column headed "Weight" indicates the portion of the total project effort accounted for by each activity. For example, "Clearing and Stripping" requires 750 labor-hours of work, which represents 4.7% of the 15,900 labor-hours required for the entire project. While a weighting column is not always present on a bar chart, its presence is very useful when calculating cumulative project progress. Activities may be weighted on any desired basis. However, dollar value and labor-hours are most frequently used as a weighting basis.

Notice that two horizontal blocks are provided opposite each activity. The upper block (SCH) represents scheduled progress and the lower block (ACT) is used to record actual progress as work proceeds. For each block, a bar extends from starting to ending times. The numbers above each bar indicate percentage of activity completion at each major time division. Again such a system greatly simplifies calculation of scheduled cumulative progress and its comparison with actual progress. To aid in the evaluation of progress, it is suggested that the actual progress of each activity be inserted at the end of each major time period, as shown in Figure 16–1.

Cumulative Project Progress

Figure 16–2 shows a cumulative progress-versus-time curve for the bar graph of Figure 16–1. The vertical scale represents cumulative project progress in percent and the horizontal scale indicates time. Once the bar graph schedule has been prepared and weighting factors calculated for each activity, scheduled cumulative progress can be calculated and plotted as shown on the figure. Actual cumulative progress is calculated and plotted as work progresses. To construct the scheduled cumulative progress curve, scheduled cumulative progress must be calculated and plotted for a sufficient number of points to enable a smooth curve to be drawn. In Figure 16–2 scheduled cumulative progress for the bar graph schedule of Figure 16–1 has been calculated and plotted at the end of each week. Cumulative progress may be calculated as follows:

$$\text{Cumulative progress} = \sum_{i=1}^{n} (\text{Activity progress})_i \times (\text{Weight})_i \qquad \textbf{(16–1)}$$

Example calculations for the scheduled cumulative progress for the first 3 weeks of the project whose bar graph schedule appears in Figure 16–1 follow.

End of First Week

[Activity 1]

$$\text{Progress} = (0.20 \times 4.7) = 0.9\%$$

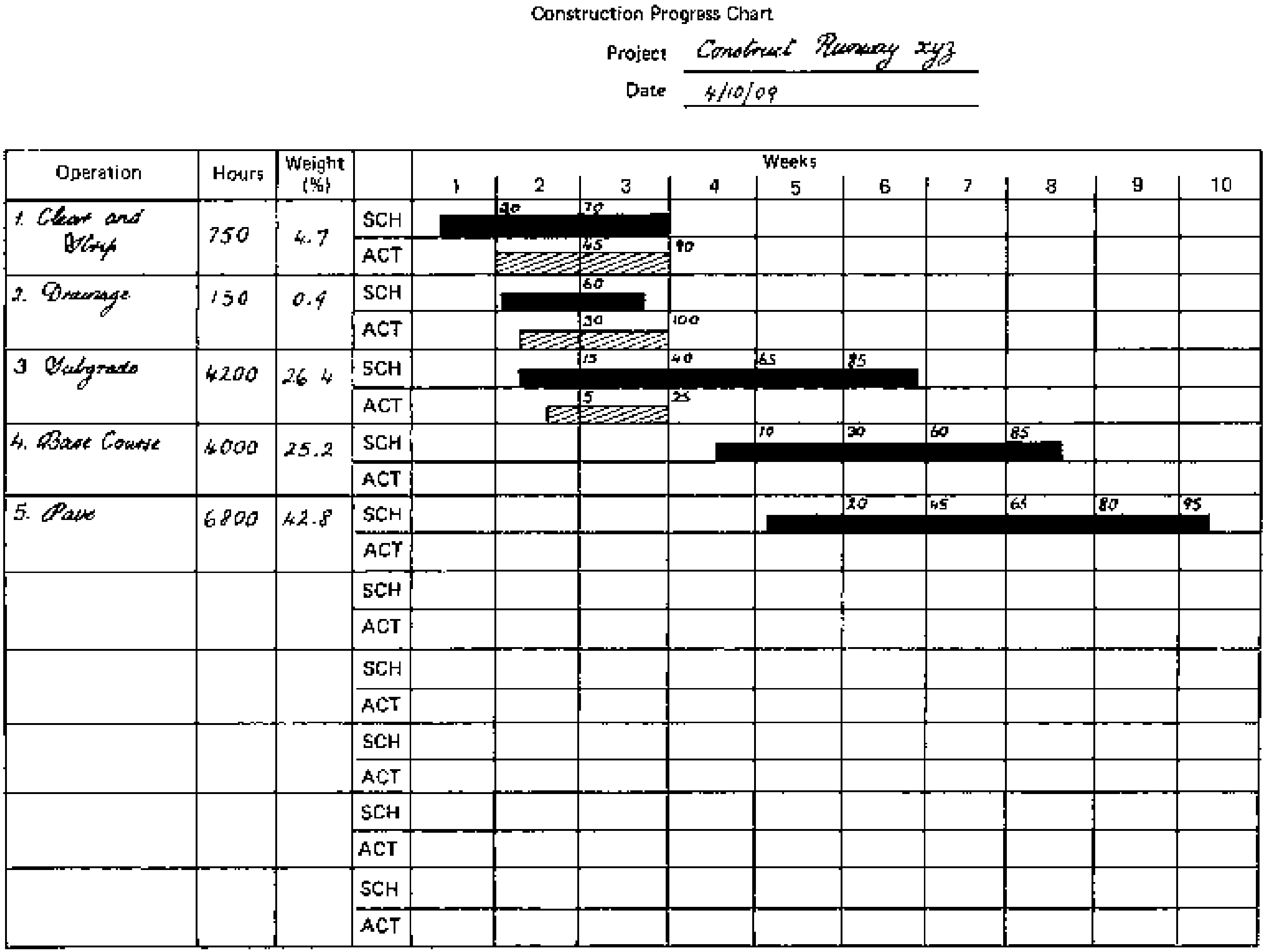


Figure 16–1 Bar graph schedule for construction project.

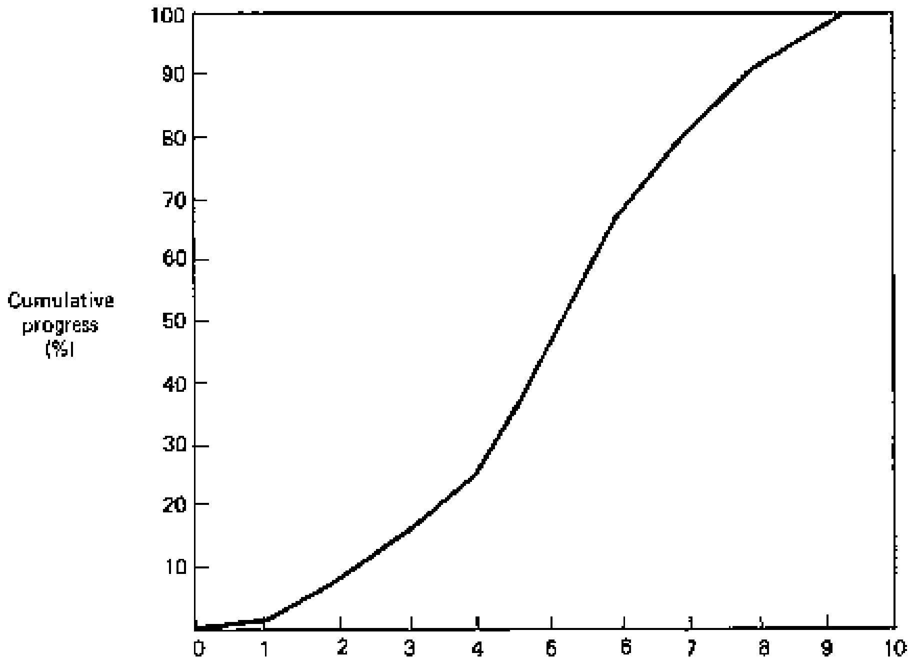


Figure 16–2 Scheduled cumulative progress.

End of Second Week

[Activity 1] [Activity 2] [Activity 3]

$$\text{Progress} = (0.70 \times 4.7) + (0.60 \times 0.9) + (0.15 \times 26.4) = 7.8\%$$

End of Third Week

[Activity 1] [Activity 2] [Activity 3]

$$\text{Progress} = (1.00 \times 4.7) + (1.00 \times 0.9) + (0.40 \times 26.4) = 16.2\%$$

Frequently, cumulative progress curves for a project are superimposed on the project's bar graph schedule as illustrated in Figure 16–3.

The Normal Progress Curve

At this point, let us consider the probable shape of a cumulative progress-versus-time curve. Observation of a large number of projects indicates that the usual shape of the curve is that shown in Figure 16–4. As the curve indicates, progress is slow at the beginning of a project as work is organized and workers become familiar with work assignments and procedures. Thus, only about 15% of the project is completed in the first 25% of project time. After that, progress is made at a rather constant rate until 85% of the work is completed at

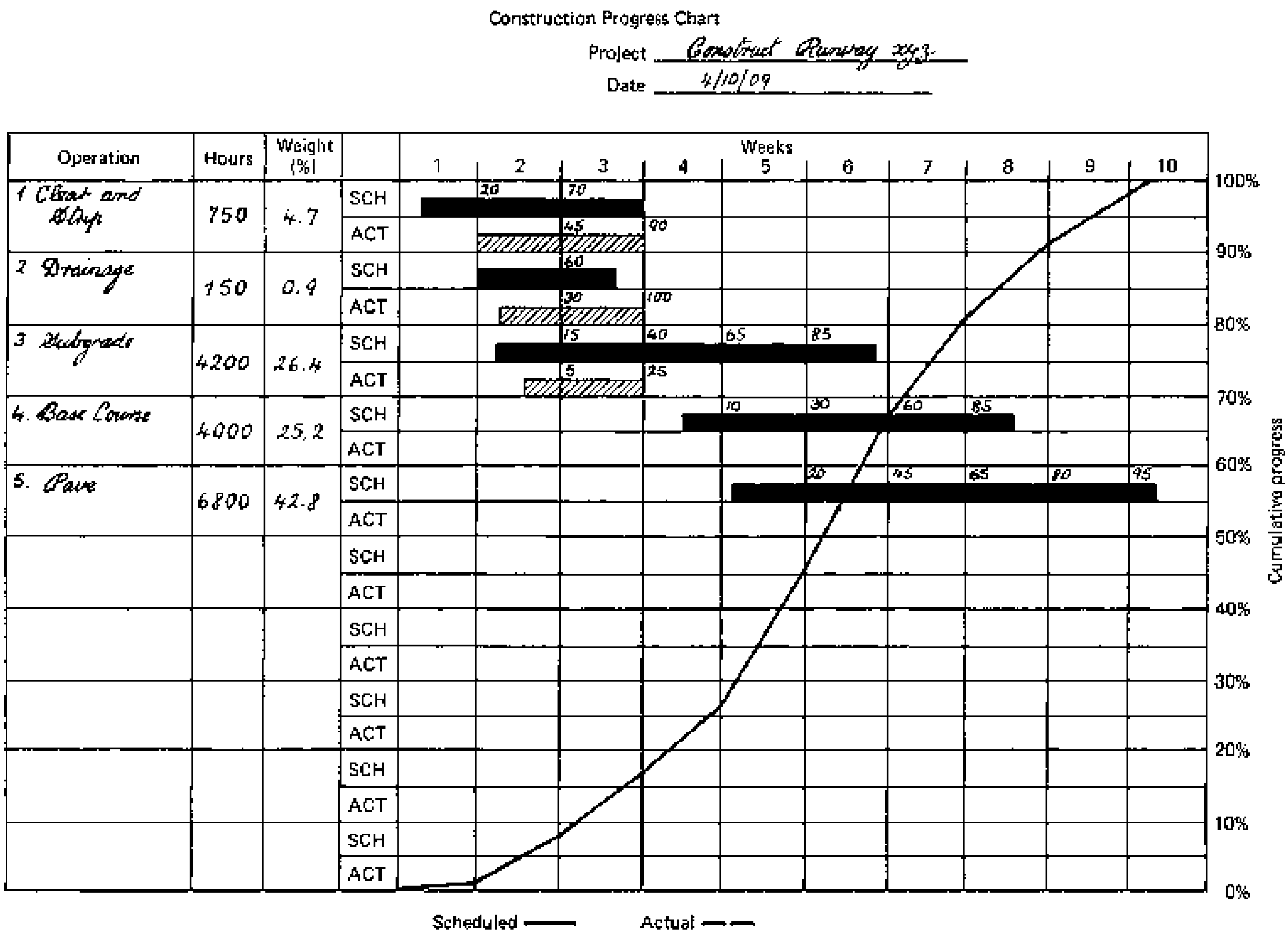


Figure 16–3 Bar graph with cumulative progress curve.

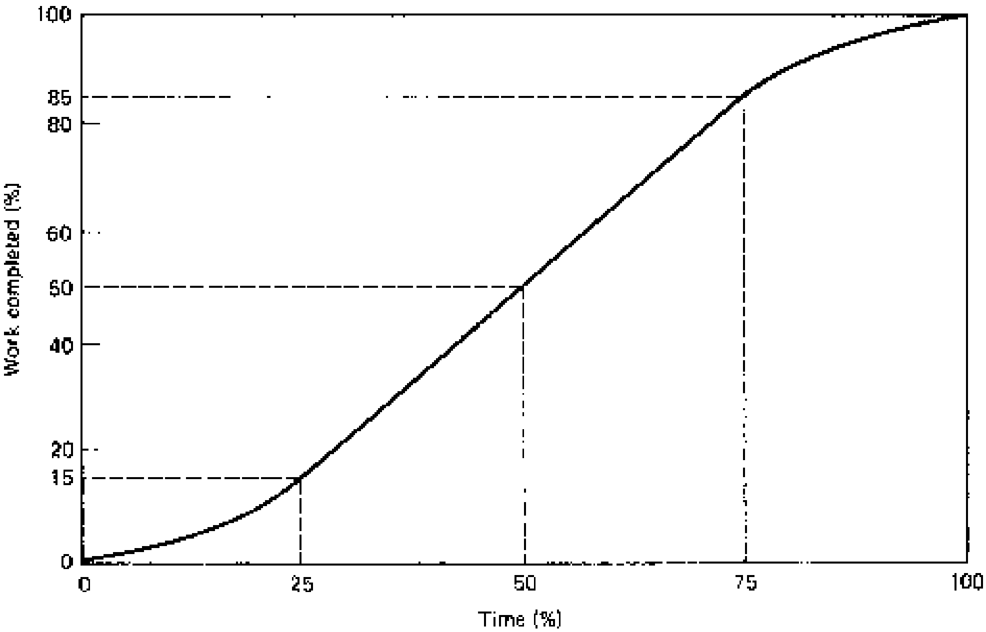


Figure 16–4 Normal progress curve.

the end of 75% of project time. Progress again slows as finishing work and project demobilization take place. The progress curve illustrated in Figure 16–4 is referred to as a *normal progress curve* or *S-curve* and will generally apply to any type of nonrepetitive work. If you find that the shape of a scheduled cumulative progress curve deviates substantially from the curve of Figure 16–4, you should carefully investigate the reason for this deviation. If progress is based on dollar value, the presence of a few high-dollar-value items may cause the curve to assume an abnormal shape. Otherwise, it is likely that a mistake has been made and that the planned rate of progress is unrealistic.

16–3 CPM—THE CRITICAL PATH METHOD

Deficiencies in Bar Graph Schedules

As indicated earlier, a major deficiency of the bar graph schedule is its failure to show relationships between project activities. Thus there is no way to determine from a bar graph schedule whether the person preparing the schedule was, in fact, aware of these relationships. A related weakness of the bar graph schedule is its failure to identify those activities which actually control the project duration. We will refer to such duration-controlling activities as *critical activities.* As a result of its failure to identify activity relationships and critical activities, the bar graph schedule also fails to show the effect of delay or change in one activity on the entire project. Recognizing these weaknesses in bar graph schedules, planners have for a number of years attempted to devise improved planning and scheduling methods.

However, it was not until the development of network planning methods in 1957 to 1958 that a major improvement in planning and scheduling methods took place. During this period the *Critical Path Method (CPM)* was developed jointly by the DuPont and Remington Rand Companies as a method for planning and scheduling plant maintenance and construction projects utilizing computers. At almost the same time, the Special Projects Office of the U.S. Navy, with Booz, Hamilton, and Allen as consultants, was developing the *Program Evaluation and Review Technique (PERT)* for planning and controlling weapons systems development. Successful application of both CPM and PERT by their developers soon led to widespread use of the techniques on both governmental and industry projects.

Both CPM and PERT use a network diagram to graphically represent the major activities of a project and to show the relationships between activities. The major difference between CPM and PERT is that PERT utilizes probability concepts to deal with the uncertainty associated with activity-time estimates, whereas CPM assigns each activity a single fixed duration.

The Network Diagram

As indicated, a network graphically portrays major project activities and their relationships. There are basically two methods of drawing such networks: the *activity-on-arrow diagram* and the *activity-on-node diagram.* Special forms of activity-on-node diagram, such as *precedence diagrams,* will be discussed later in the chapter. While activity-on-node diagrams have certain advantages, activity-on-arrow format will be utilized to illustrate network construction and time calculations.

In the activity-on-arrow format, each activity is represented by an arrow that has an associated description and expected duration. Each *activity,* as illustrated in Figure 16–5, must start and terminate at an *event* (represented by a circle). Events are numbered for identification purposes and event numbers are also utilized to identify activities on the diagram. That is, activities are identified by citing the event number at the tail of the arrow (I number) followed by the event number at the head of the arrow (J number). Thus activity 10-11 refers to the activity starting at event 10 and ending at event 11, as seen in Figure 16–5. This activity numbering system is referred to as the *I–J numbering system.* An event is simply a point in time and, as used in network diagramming, is assumed to occur instantaneously when all activities leading into the event have been completed. Similarly, all activities leading out of an event *may* start immediately upon the occurrence of an event. Figure 16–6 shows a simple network diagram for a construction project. As mentioned earlier, the diagram graphically indicates the relationships between activities. These relationships are *precedence* (what activities must precede the activity?), *concurrence* (what activities can go on at the same time?), and *succession* (what activities must follow the activity?). In Figure 16–6, activity 1–2 must precede activity 2–5, activities 1–2 and 1–3 are concurrent, and activity 2–5 succeeds activity 1–2. Activities progress in the direction shown by the arrows. Good diagramming practice requires that diagrams present a clear picture of the project logic and generally flow from left to right. Arrows should not point backward, although they may point straight up or down.

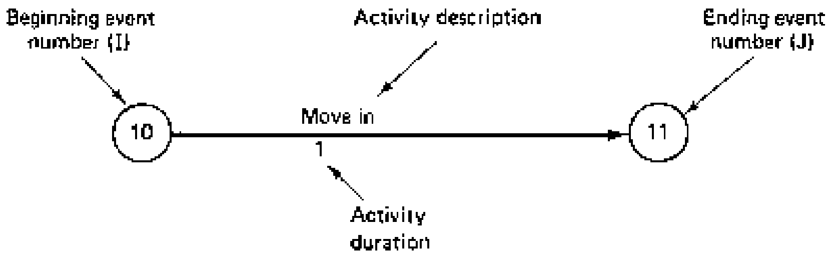


Figure 16–5 Activity-on-arrow notation.

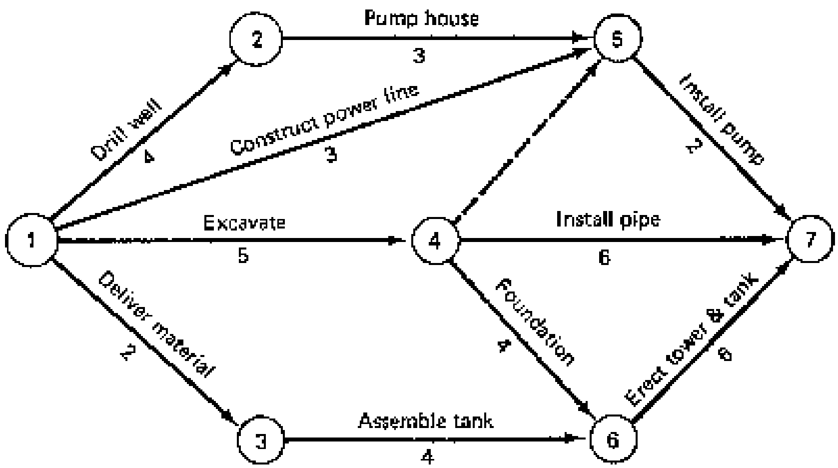


Figure 16–6 Example network diagram.

Notice the dashed arrow in Figure 16–6. This is called a *dummy activity* or simply a *dummy.* Dummies are used to impose logic constraints and prevent duplication of activity I–J numbers. They do not represent any work and, hence, always have a duration of zero.

Event-Time Calculations

Once a network diagram has been drawn that represents the required relationships between activities, network time calculations may be made. The first step is to calculate the earliest time at which each event may occur based on an arbitrary starting time of zero. This earliest event occurrence is referred to as *early event time,* commonly abbreviated *EET.* It is usually placed above the event circle as shown in Figure 16–7. Calculations then proceed from left to right, starting with 0 at the first event. This calculation is referred to as the forward pass through the network. At each event the early event time is found as the early event time of the previous event plus the duration of the activity connecting the two events. Thus the early event time of event 2 is found as the sum of the early event time at event 1 plus the duration of activity 1–2 (0 + 4 = 4). When two or more activity arrows meet at an event,

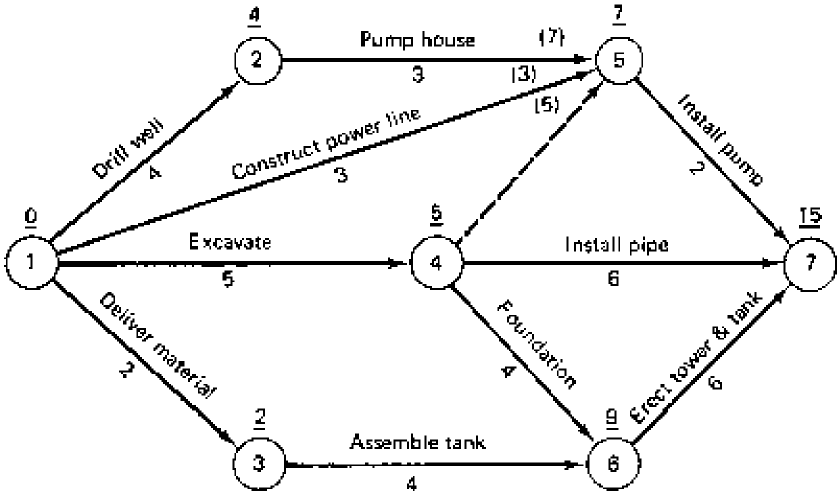


Figure 16–7 Example network—early event times.

the largest value of possible early event times is chosen as the early event time because, by definition, the event cannot occur until all activities leading into the event have been completed. In Figure 16–7, note the activity early completion times of 3, 5, and 7 at event 5, leading to the proper early event-time value of 7. The early event time at the last event is, of course, the minimum time required to complete the project.

When all early event-time values have been calculated and entered on the network, a backward pass is made to compute the latest possible time at which each event may occur without changing the project duration. As a starting point, the *late event time (LET)* of the last event is set equal to the early event time of the event. Starting with the assigned late event time at the last event, work backward through the network, calculating each late event time as the late event time of the previous event minus the duration of the activity connecting the events. The results are illustrated in Figure 16–8. The late event time of event 6 is found as the late event time of event 7 minus the duration of activity 6–7 ($15 - 6 = 9$). When two or more activities meet at an event, the lower of possible times is chosen as the late event time because, by definition, the event must occur before any activity leading out of the event may start. In order for all activities to be completed within the allotted time, the event must occur at the earliest of the possible time values. In Figure 16–8, note the possible late times at event 4 of 5, 9, and 13, leading to a late event time of 5.

The Critical Path

That path through the network which establishes the minimum project duration is referred to as the *critical path.* This path is the series of activities and events that was used to determine the project duration (or early event time of the final event) in the forward pass. However, it is usual to wait until all early and late event times have been calculated to mark the critical path. Notice in Figure 16–9 that the critical path passes through all events whose

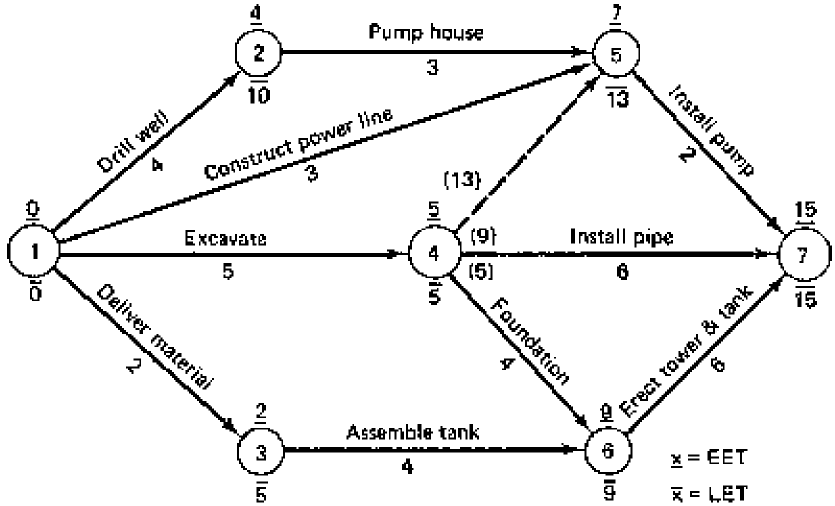


Figure 16–8 Example network—late event times.

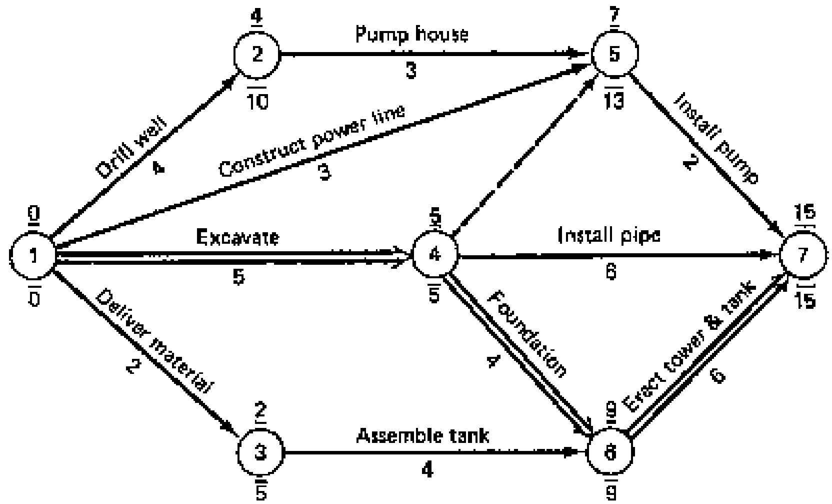


Figure 16–9 Example network—critical path.

early event times are equal to their late event times. Critical activities are those which make up the critical path and, of course, connect critical events. Where parallel activities connect critical events, however, only the activities whose duration equals the difference between event times at the ends of the arrow are critical. Thus in Figure 16–9, activities 4–7, as well as activities 4–6 and 6–7, connect the critical events 4 and 7. However, the time difference between event times at event 7 and event 4 is 10 units, while the duration of activity 4–7 is only 6 units. Hence activity 4–7 is *not* critical. When the critical path has been identified, it should be clearly indicated on the network by color, double arrow (as used in Figure 16–9), or similar means.

Activity Times

Up to this point, we have determined the minimum duration of our project and identified the critical path. The next step is to calculate the earliest and latest starting and finishing time and the total float (scheduling leeway) for each activity based on the event times already calculated. These time values are used as the basis for scheduling and resource allocation. Two of these values, early start and late finish, may be read directly off the network while the remaining values must be calculated. The following relations may be used to determine activity times

$$\text{Early start (ES)} = \text{Early event time of preceding (I) event} \quad \textbf{(16–2)}$$

$$\text{Early finish (EF)} = \text{Early start} + \text{Activity duration} \quad \textbf{(16–3)}$$

$$\text{Late finish (LF)} = \text{Late event time of following (J) event} \quad \textbf{(16–4)}$$

$$\text{Late start (LS)} = \text{Late finish} - \text{Activity duration} \quad \textbf{(16–5)}$$

$$\text{Total float (TF)} = \text{Late finish} - \text{Early finish} \quad \textbf{(16–6)}$$

or

$$\text{Total float (TF)} = \text{Late start} - \text{Early start} \quad \textbf{(16–7)}$$

Activity-time values for the example network are given in Figure 16–10. Note that activity times are not usually calculated for dummy activities. *Float* (*slack* in PERT terminology) is the amount of scheduling leeway available to an activity. While several different types of float have been defined, *total float* is the most useful of these values and is the only type of float that will be used here. Application of float to the scheduling process is covered in the following section.

Activity-on-Node Diagrams

As stated earlier, there are two principal formats used in drawing network diagrams. The activity-on-arrow format has been used up to this point. The second format is the activity-on-node format. This technique uses the same general principles of network logic and time calculations as does the activity-on-arrow technique. However, the activity-on-node network diagram looks somewhat different from the activity-on-arrow diagram because the node (which represented an event in the activity-on-arrow method) is now used to represent an activity. A simple form of the activity-on-node diagram is the *circle diagram* or *circle notation,* in which each activity is represented by a circle containing the activity description, an identifying number, and the activity duration.

Figure 16–11 illustrates a circle diagram for a five-activity construction project. In the activity-on-node technique, notice that arrows are used to represent logic constraints only. Thus all arrows act in the same manner as do dummies in the activity-on-arrow format.

	Act no.	Description	Duration	Early start	Early finish	Late start	Late finish	Total float
	1-2	Drill well	4	0	4	6	10	6
	1-3	Deliver material	2	0	2	3	5	3
*	1-4	Excavate	5	0	5	0	5	0
	1-5	Power line	3	0	3	10	13	10
	2-5	Pump house	3	4	7	10	13	6
	3-6	Assemble tank	4	2	6	5	9	3
*	4-6	Foundation	4	5	9	5	9	0
	4-7	Install pipe	6	5	11	9	15	4
	5-7	Install pump	2	7	9	13	15	6
*	6-7	Erect tower and tk	6	9	15	9	15	0

* = critical activity

Figure 16–10 Activity-time data for example network.

This feature has been found to make activity-on-node diagramming somewhat easier for beginners to understand. The principal disadvantage of activity-on-node diagramming has been the limited availability of computer programs for performing network time calculations. However, there are now a number of such programs available, and the use of the activity-on-node techniques is expected to increase.

Another form of activity-on-node diagram is illustrated in Figure 16–12. Here an enlarged node is used to provide space for entering activity time values directly on the node. This format is particularly well suited to manual network calculation, because activity times may be entered directly on the network as they are calculated. When time calculations are performed in this manner, it is suggested that calculations be performed independently by two individuals and the results compared as an error check.

The third form of activity-on-node diagram is the *precedence diagram.* Because of its special characteristics, it is described in greater detail in the following paragraphs.

Precedence Diagrams

The precedence diagram is an extension of the activity-on-node format that provides for incorporation of lag-time factors as well as permitting additional precedence relationships. The use of lag time is very useful when diagramming construction project relationships, where activities can often start as soon as a portion of a preceding activity is completed. In addition to the usual finish-to-start precedence relationship, this technique permits start-to-start and

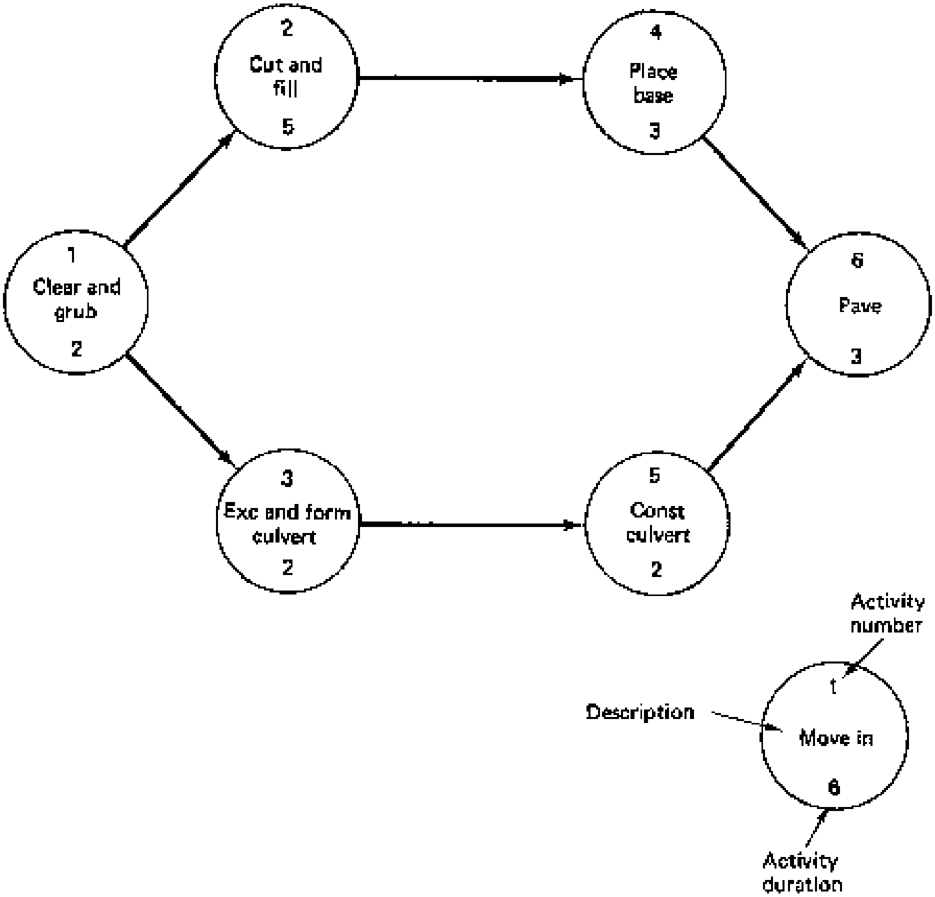


Figure 16–11 Circle diagram for a project.

finish-to-finish relationships. These relationships and the use of lag times are illustrated in Figure 16–13.

To appreciate the value of incorporating lag-time relationships, it is useful to consider how such relationships could be represented in the usual network diagramming techniques. For example, consider the network of Figure 16–12. The planner decides that activity 2, cut and fill, can start when activity 1, clear and grub, is 50% complete (equivalent to 1 day's work). Figure 16–14 illustrates how this situation would be represented in both conventional CPM and in a precedence diagram. To represent this situation in conventional CPM, it is necessary to split activity 1 into two activities, each having a duration of 1 day (Figure 16–14a). Using precedence diagram procedures, a 1-d lag time is simply inserted in a start-to-start relationship from activity 1 to activity 2 (Figure 16–14b).

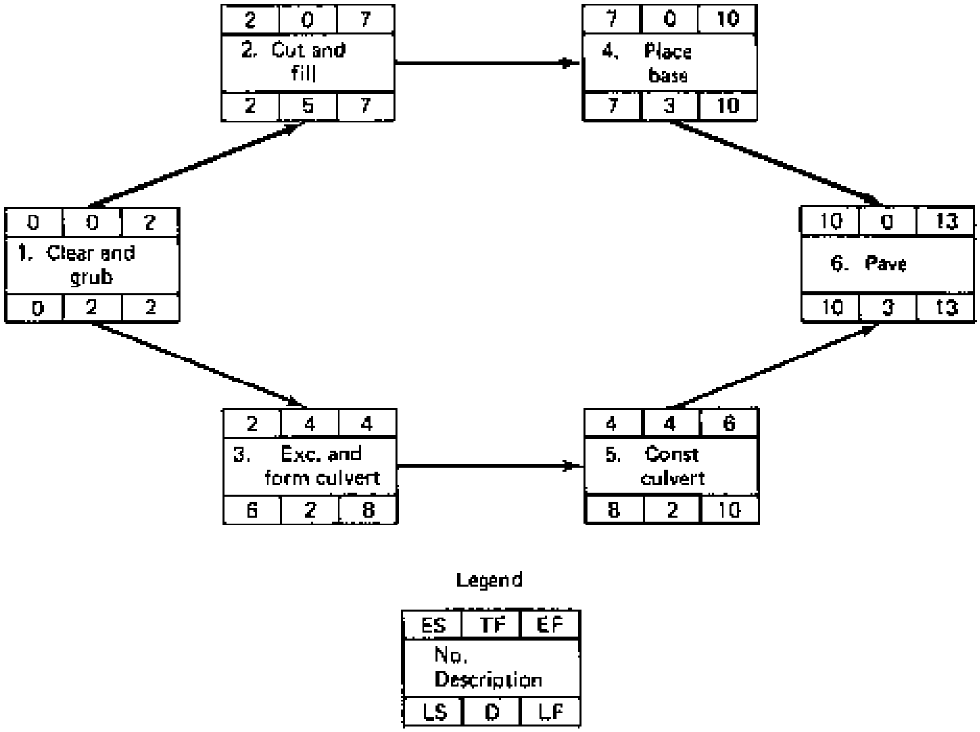


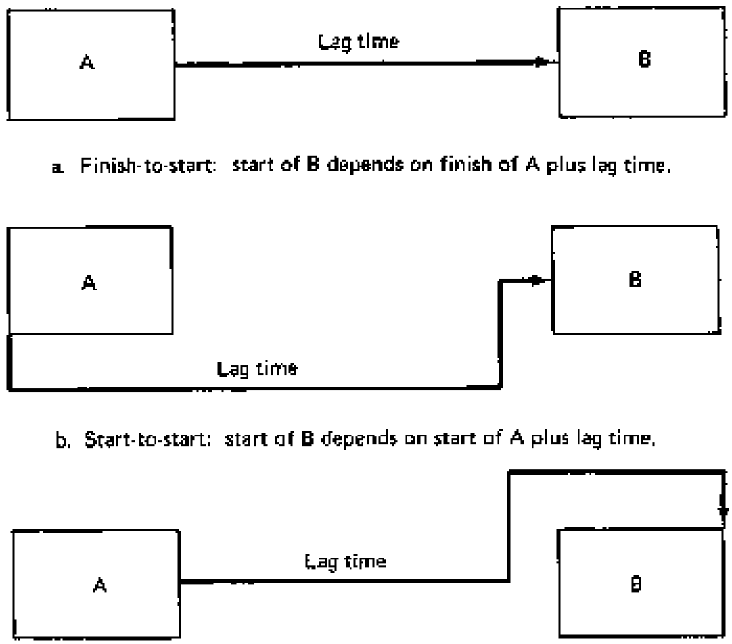
Figure 16–12 Expanded node diagram.

The precedence diagram for the example project is shown in Figure 16–15. Notice that this diagram is essentially the same as any other activity-on-node diagram for the project since only finish-to-start relationships are employed and no lag times are used.

Suppose that we now add the following logic constraints to the example project:

1. Erection of the tower and tank cannot begin until 3 d after completion of the foundation.
2. Installation of pump cannot be completed until 1 d after completion of pipe installation.
3. The foundation can start 3 d after start of excavation.

The precedence diagram for the revised project is shown in Figure 16–16. Notice that the early start of activity 8 (day 3) is the early start of activity 4 (day 0) plus a 3-d lag time. The early finish of activity 10 (day 12) is determined by the early finish of activity 7 (day 11) plus a 1-d lag time. The early start of activity 10 is, therefore, day 10 (early finish minus duration). The early start of activity 11 (day 10) is the early finish of activity 8 (day 7) plus a lag time of 3 d. As noted earlier, the increased flexibility of the precedence diagram comes at the cost of increased computational complexity.



a. Finish-to-start: start of B depends on finish of A plus lag time.

b. Start-to-start: start of B depends on start of A plus lag time.

c. Finish-to-finish: finish of B depends on finish of A plus lag time.

Figure 16–13 Precedence diagram relationships.

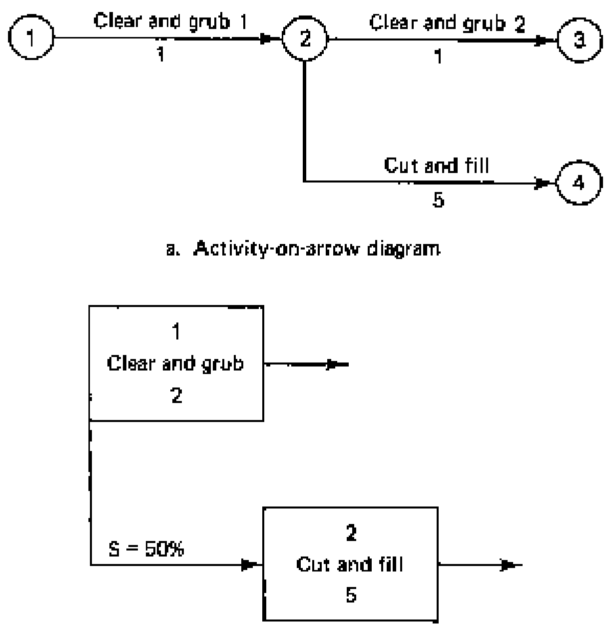


Figure 16–14 Comparison of CPM diagram and precedence diagram.

a. Activity-on-arrow diagram

b. Precedence diagram equivalent to (a)

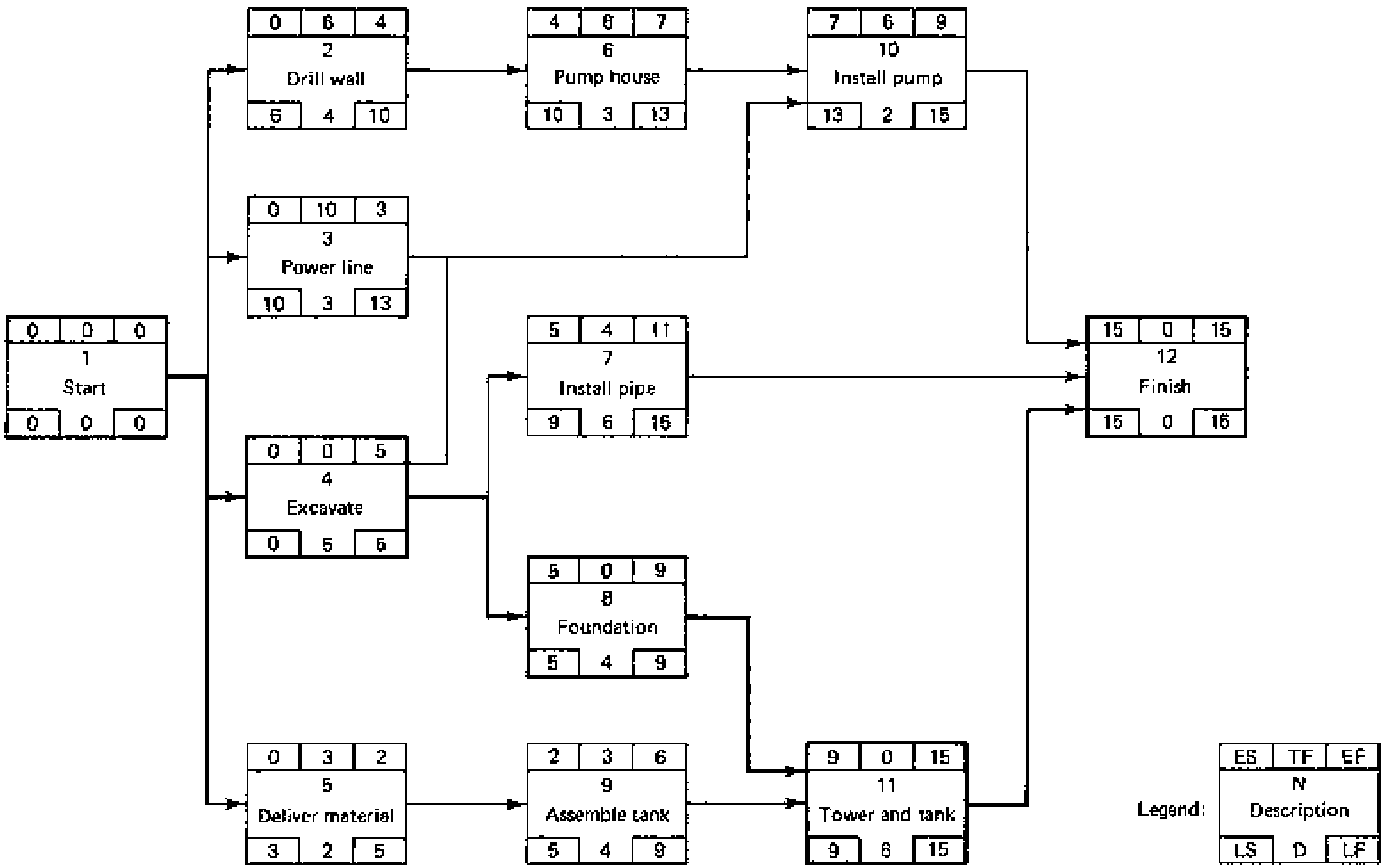


Figure 16–15 Precedence diagram for example project.

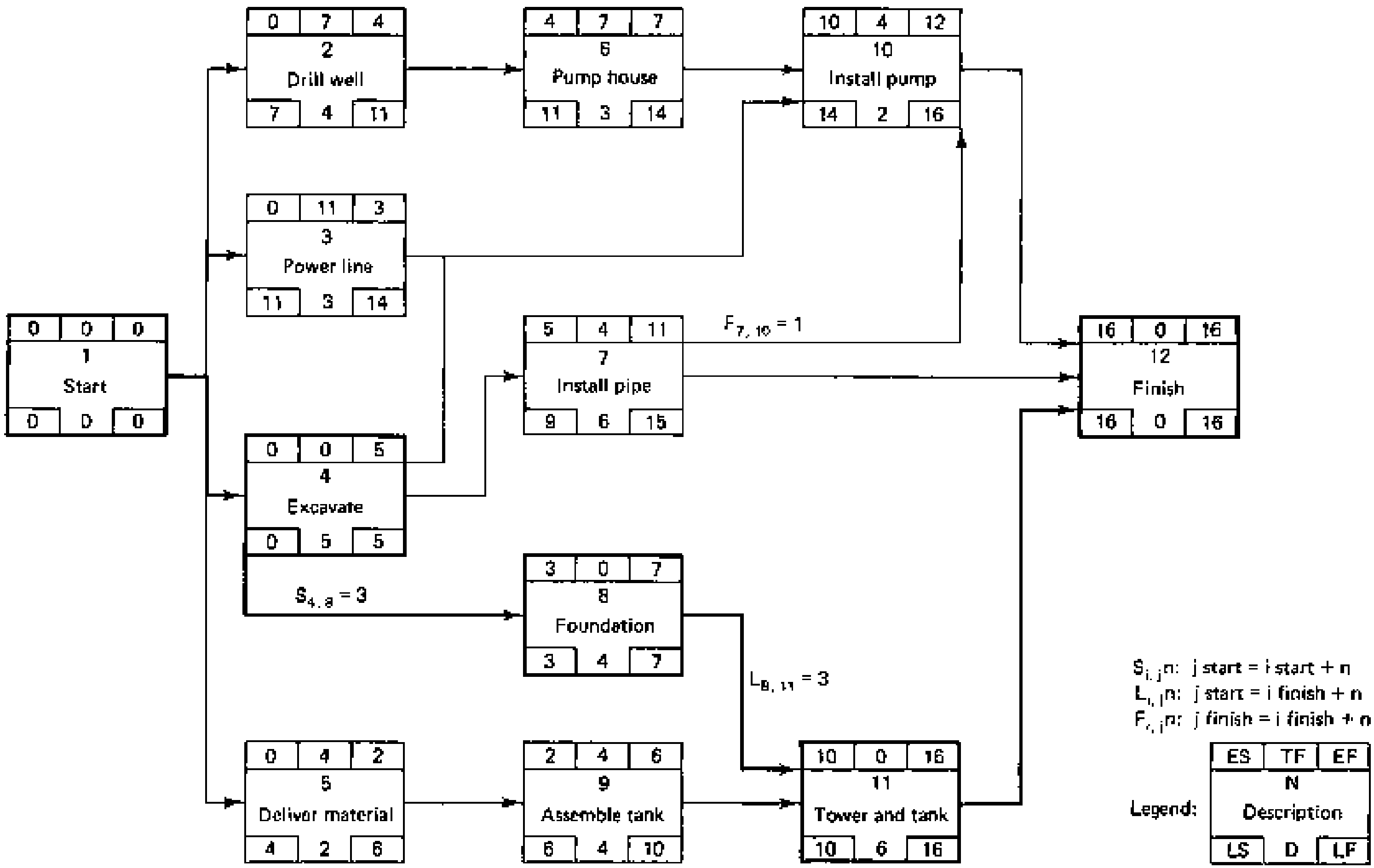


Figure 16–16 Revised example project.

16–4 SCHEDULING AND RESOURCE ASSIGNMENT USING CPM

The Early Start Schedule

The activity times calculated in Section 16–3 form the basis for a project schedule but in themselves do *not* constitute a schedule. For example, in Figure 16–10, activity 1–5, which has a duration of 3 d, has an early start time of 0 and a late finish time of 13 with 10 days of float. Thus activity 1-5 may be scheduled to occur on any 3 d between the beginning of day 1 and the end of day 13 without changing the project duration of 15 d.

When all activities are scheduled to start at the earliest allowable time, such a schedule is referred to as an *early start schedule.* To produce a schedule based on a calculated network, it is suggested that a time line first be drawn between the early start time and late finish time for each activity. Figure 16–17 illustrates this procedure applied to the example network of Figure 16–9. Note that the line starts at the end of the early start time tabulated in Figure 16–10 and extends to the end of the late finish time. For activity 1–2, the time line extends from time 0 (beginning of day 1) through time 10 (end of day 10). Notice also that the time has been filled in solid for activities on the critical path (activities 1–4, 4–6, and 6-7). This serves to warn the scheduler that these activities can be scheduled only at the time indicated unless the project duration is to be changed.

Each activity may now be scheduled at any position desired on the time line. If all activities are started at the beginning of their time line, the early start schedule of Figure 16–18 is produced. Here each workday is indicated by an asterisk while each day of float is represented by the letter F. Float may be used to rearrange the schedule as desired by the scheduler without changing project duration.

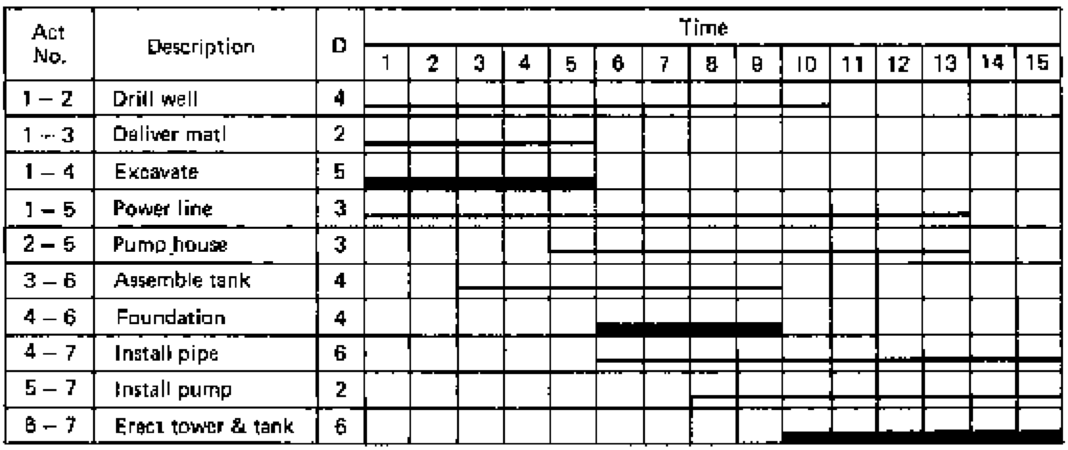


Figure 16–17 Allowable activity time span for example network.

Act No.	Description	D	Time														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 – 2	Drill well	4	*	*	*	*	F	F	F	F	F	F					
1 – 3	Deliver matl	2	*	*	F	F	F										
1 – 4	Excavate	5	*	*	*	*	*										
1 – 5	Power line	3	*	*	*	F	F	F	F	F	F	F	F	F	F		
2 – 5	Pump house	3					*	*	*	F	F	F	F	F	F		
3 – 6	Assemble tank	4			*	*	*	*	F	F	F						
4 – 6	Foundation	4						*	*	*	*						
4 – 7	Install pipe	6						*	*	*	*	*	*	F	F	F	F
5 – 7	Install pump	2								*	*	F	F	F	F	F	F
6 – 7	Erect tower & tank	6										*	*	*	*	*	*

* = work day F = float

Figure 16–18 Early start schedule for example network.

Some of the uses for float in scheduling are to incorporate preferential logic, to satisfy resource constraints, and to allow weather-sensitive activities to be scheduled when weather conditions are expected to be most favorable. *Preferential logic* is that network logic which is imposed by the planner solely because the planner prefers to conduct the operation in that sequence. In other words, it is not logic imposed by the fundamental nature of the process. An example would be the scheduling of all concreting activities in sequence so that only one concrete crew would be required for the project.

Late Start and Other Schedules

When all activities are started at their latest allowable starting time, a *late start schedule* is produced, as shown in Figure 16–19. Note that all float is used before the activity starts. An obvious disadvantage to the use of such a schedule is that it leaves no time cushion in the event that an activity requires longer than its estimated duration. In practice, the usual schedule is neither an early start nor a late start schedule. Rather, it is an intermediate schedule produced by delaying some activities to permit resource leveling or the incorporation of preferential logic while retaining as much float as possible.

When producing a schedule other than an early start schedule, care must be taken to ensure that no activity is scheduled to start before its predecessor event has occurred. This, of course, would be a violation of network logic. Such an error may be prevented by referring to the network diagram each time an activity is scheduled. However, a simple technique makes use of the activity numbers on the schedule to check logic constraints. Referring to Figures 16–17 and 16–9, we see activity 2–5 may be started as soon as all activities ending with event 2 (J number = 2) have been completed. In this case, this is only activity 1–2. In using this technique, some provision must be made for incorporating the

Act no.	Description		Time														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 – 2	Drill well	4	F	F	F	F	F	F	*	*	*	*					
1 – 3	Deliver mat'l	2	F	F	F	*	*										
1 – 4(5)	Excavate	5	*	*	*	*	*										
1 – 5	Power line	3	F	F	F	F	F	F	F	F	F	F	*	*	*		
2 – 5	Pump house	3					F	F	F	F	F	F	*	*	*		
3 – 6	Assemble tank	4			F	F	F	*	*	*	*						
4 – 6	Foundation	4						*	*	*	*						
4 – 7	Install pipe	6						F	F	F	F	*	*	*	*	*	*
5 – 7	Install pump	2								F	F	F	F	F	F	*	*
6 – 7	Erect tower & tank	6										*	*	*	*	*	*

* = work day F = float

Figure 16–19 Late start schedule for example network.

logic constraints imposed by dummies. This may be done by putting a third number in parentheses after the usual activity I–J number. The number in parentheses represents the event number at the end of the dummy. For example, in Figure 16–19, note that activity 1–4 has been identified as activity 1–4 (5). Here the number 5 indicates that activities starting with number 5 (I number = 5) cannot begin until activity 1–4 is completed. Reference to the network diagram of Figure 16–9 shows that this is the correct logic and is the result of the presence of dummy 4–5. Thus the real predecessors of activity 5-7 are activities 1–4, 1–5, and 2–5.

Resource Assignment

In planning the assignment of resources to a project, the planner is usually faced with two major considerations. For each type of resource, these are (1) the maximum number of resources available during each time period, and (2) the desire to eliminate peaks and valleys in resource requirements (i.e., resource leveling).

If the asterisk designating a workday in Figures 16–18 and 16–19 is simply replaced by a number representing the quantity of the resource required for the activity during that time period, it is a simple matter to determine the total quantity of the resource required for each time period for any particular schedule. Thus Figure 16–20 illustrates the number of workers needed on each day for the early start schedule (Figure 16–18) of the example network. The daily labor requirements are rather uneven, varying from 19 workers on the first 2 days to 8 workers on the twelfth day. Unless the contractor has other nearby projects that can utilize the excess labor produced by these fluctuations, labor problems would soon develop. A far better policy would be to attempt to level out the daily labor requirements. This can often be done by simply utilizing float to reschedule activities.

Act No.	Description	D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 – 2	Drill well	4	4	4	4	4											
1 – 3	Deliver matl	2	4	4													
1 – 4(5)	Excavate	5	5	5	5	5	5										
1 – 5	Power line	3	6	6	6												
2 – 5	Pump house	3					2	2	2								
3 – 6	Assemble tank	4			3	3	3	3									
4 – 6	Foundation	4						7	7	7	7						
4 – 7	Install pipe	6						4	4	4	4	4	4				
5 – 7	Install pump	2								5	5						
6 – 7	Erect tower & tank	6										8	8	8	8	8	8
	Total		19	19	18	12	10	16	13	16	16	12	12	8	8	8	8

Resources (Workers) Required by Activity

Activity	Number required
1 - 2	4
1 – 3	4
1 – 4	5
1 – 5	6
2 – 5	2
3 – 6	3
4 – 6	7
4 – 7	4
5 – 7	5
6 – 7	8

Figure 16–20 Resource assignment—early start schedule.

A quick calculation will indicate that the total resource requirement for the example network indicated in Figure 16–20 is 195 worker days. This yields an average requirement of about 13 workers per day. By utilizing float to reschedule activities, the revised schedule of Figure 16–21 may be obtained. The daily requirements of this schedule only vary between 12 and 15 workers. Similar procedures may be applied when maximum resource limits are established. However, it will often be necessary to extend the project duration to satisfy limited resource constraints. The daily requirements for each resource must be calculated separately, although several resources may be tabulated on the same schedule sheet by utilizing different colors or symbols for each resource. While the manual technique suggested above will be satisfactory for small networks, it is apparent that the procedure would become very cumbersome for large networks. Thus computer programs have been developed for both resource leveling and limited resource problems. Reference 1 identifies a number of such computer programs.

Act No.	Description	D	Time 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 – 2	Drill well	4	4	4	4	4											
1 – 3	Deliver mat'l	2	4	4													
1 – 4(5)	Excavate	5	5	5	5	5	5										
1 – 5	Power line	3			6	6	6										
2 – 5	Pump house	3					2	2	2								
3 – 6	Assemble tank	4						3	3	3	3						
4 – 6	Foundation	4						7	7	7	7						
4 – 7	Install pipe	6								4	4	4	4	4	4		
5 – 7	Install pump	2														5	6
6 – 7	Erect tower & tank	6										8	8	8	8	8	8
	Total		13	13	15	15	13	12	12	14	14	12	12	12	12	13	13

Figure 16–21 Improved level of resource assignment.

16–5 PRACTICAL CONSIDERATIONS IN NETWORK USE

When to Use Network Methods

The methodology involved in drawing a network diagram forces the planner to consider in some detail and to put down on paper the manner in which the project is to be carried out. In addition, the network diagram is an excellent communications device for transmitting this information to everyone involved in a project. For these reasons, preparation of a network diagram is useful for any project, regardless of size. The size of the network used will, of course, depend on the size and complexity of the project. Rules of thumb on network size and the need for a network diagram proposed by some experts are based on a particular method of operation and do not necessarily apply to your situation. Projects as large as a $3.5 million 25-story building have been successfully managed with a CPM network consisting of less than 90 activities. Where repetitive operations are involved, it may be worthwhile to draw a subnetwork to show each operation in some detail while using only a single activity to represent the operation on the major network.

Even prior to bid submittal, a summary or outline network can be very useful. For example, the network diagram can be used to determine whether the project can reasonably be completed within the time specified on the bid documents. Thus a decision can be made at this point whether a bid should even be submitted. If the decision is to proceed, the network diagram can then be used as a framework for developing the project's cost estimate for the bid. Upon award of the construction contract, a full network should be prepared to the level of detail considered necessary for carrying out the project. Some of the factors to be considered in determining the level of detail to be used include the dollar value, size, complexity, and duration of the project.

Preparing the Network

Regardless of the size of the planning group (which may be as small as the project manager alone) chosen to develop the network, it is important that input be obtained from the field personnel most familiar with the construction techniques to be applied. If specialty subcontractors are not represented in the planning group, it is important that they review the plan prior to its finalization to ensure that they can carry out their work in the manner contemplated.

Manual or Computer Techniques

One of the major factors that has sometimes led to dissatisfaction with network methods has been the excessive or inappropriate use of computers. Manual techniques have much to recommend them, particularly for personnel not well versed in network procedures. The manual preparation and calculation of a network is one of the best ways for a manager to really understand a project and to visualize potential problems and payoffs.

When it is necessary to utilize a network of more than several hundred activities, the use of computers for performing time calculations is advantageous. However, do not let yourself or your subordinates become inundated with unnecessary computer output. Output should be carefully selected to provide all levels of management with only the information they can effectively utilize.

An obvious advantage of the computer is its ability to rapidly update network calculations and to provide reports in any format and quantity desired. However, the preparation of reports too frequently or in an excessive quantity is simply a waste of paper and computer time. While the network diagram at the project site should always be kept current, computer reports should be produced on a more limited basis. For projects of average duration and importance an updating interval of 2 to 4 weeks should be satisfactory. As with all computer operations, the output is only as good as the input, so care must be taken to ensure that data are correctly entered before running a network program.

Advanced Network Techniques

There are a number of more sophisticated network-based management techniques that have been developed. Among these are selection of an optimum (lowest total cost) project duration based on project time-cost relations, minimizing project cost through financial planning and cost control techniques, and resource leveling over multiple projects. Although beyond the scope of this chapter, many of these techniques are described in the end-of-chapter references.

16–6 LINEAR SCHEDULING METHODS

Scheduling Repetitive Projects

Many in the construction industry feel that conventional network methods such as CPM are not well suited to highly repetitive work. Such projects include highways, airfields, pipelines, multiple housing units, and high-rise buildings. Highway projects whose

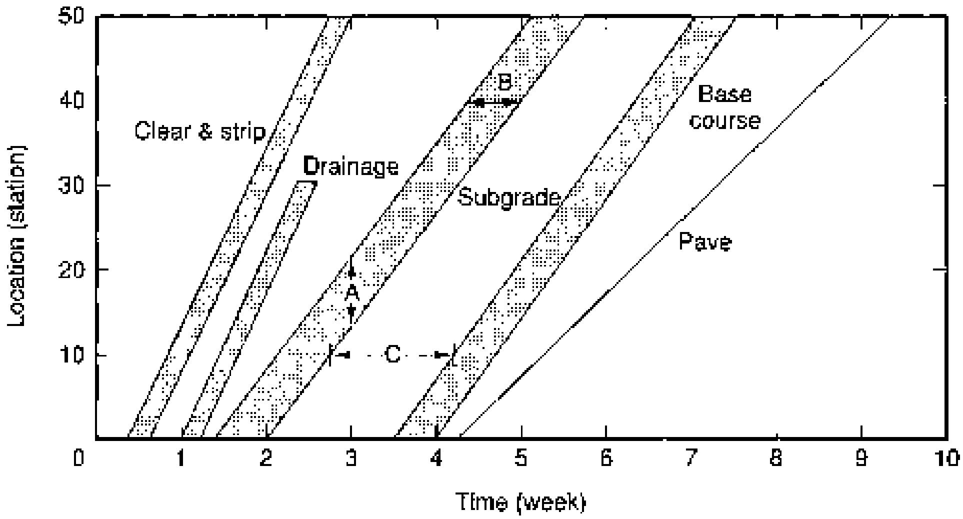


Figure 16–22 LSM diagram for project of Figure 16–1.

activities progress linearly from one end of the project to the other are particularly difficult to adequately represent in CPM. As a result, linear scheduling techniques are increasingly being employed on such projects.

The *Linear Scheduling Method (LSM)* is similar to the Line of Balance (LOB) scheduling technique developed in the early 1950s for industrial and aerospace projects and is sometimes identified by the same name. The objective of the LOB technique is to ensure that components or subassemblies are available at the time they are required to meet the production schedule of the final assembly. The objective of the LSM technique is to display and prevent interference between repetitive activities that progress linearly from one end of a project to the other. A brief explanation of the Linear Scheduling Method applied to a highway construction project is provided below.

A Linear Scheduling Method Diagram

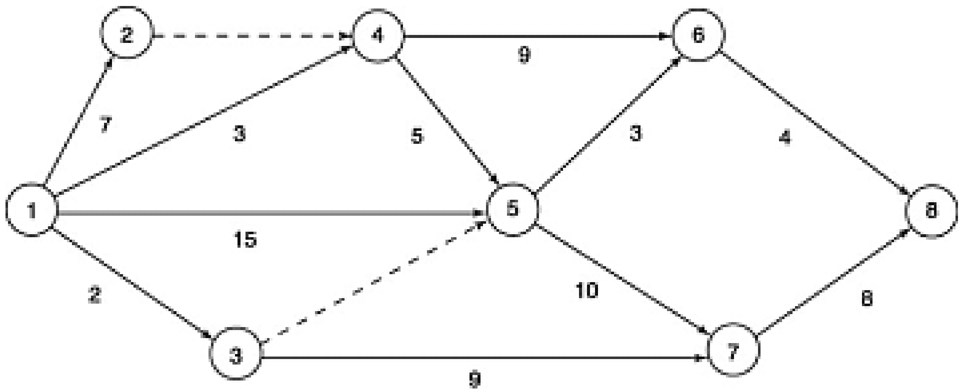
An LSM diagram of the highway construction project of Figure 16–1 is shown in Figure 16–22. The five activities involved are Clear and Strip, Drainage, Subgrade, Base Course, and Pave. Notice that activities are represented by a line or band representing time versus location.

The height (A) of an activity at a specific time represents the distance over which that activity is being carried out at that instant. Thus, Subgrade work extends from station 13 to station 21 at the start of week 3. The width (B) of an activity indicates the time from start to finish of that activity at a specific location. Hence, at station 40 Subgrade work starts at week 4.4 and continues to week 5.0. The horizontal distance between activities (C) represents the time lag or interval between the finish of one activity and the start of the succeeding activity at a specific location. Thus, the start of Base work at station 10 lags the completion of Subgrade work at that location by 1.4 weeks.

Notice that the Drainage activity follows Clear and Strip but extends only to station 30. That is, no drainage work is required from station 30 to station 50. The Drainage activity could also overlap the Clear and Strip activity if it were determined that the two activities could be carried out concurrently at the same location without interference between the two.

PROBLEMS

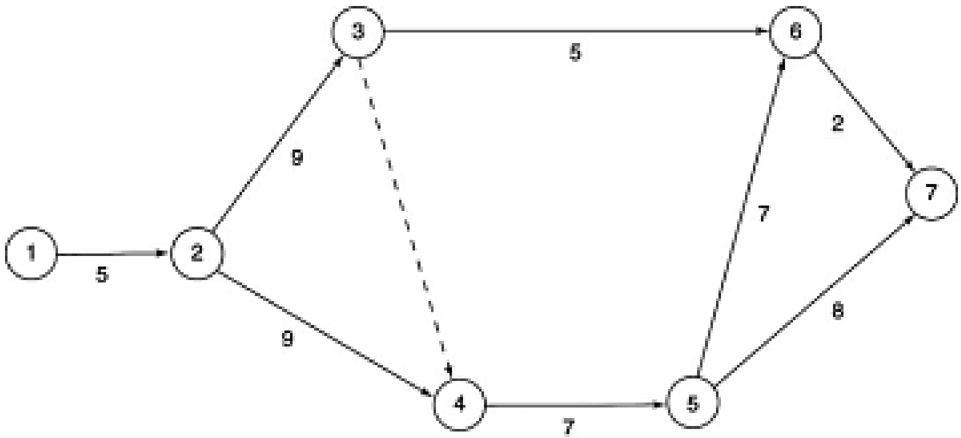
1. Redraw the accompanying network diagram, adding early and late event times to the diagram. Mark the critical path. Prepare an activity-time tabulation showing early start, late start, early finish, late finish, and total float.



2. What effect will the delays in Activities 1, 2, and 3 of Figure 16–1 have on project completion? Explain.
3. For the network of Problem 5, assign resources based on an early start schedule. Indicate the total resource requirements for each time period. Level the resource requirements as much as possible utilizing float. The resource requirements for each activity are as follows.

Activity	Workers Required
1–2	6
2–3	4
2–4	15
3–4	10
3–6	5
4–5	6
5–6	5
5–7	8
6–7	4

4. What advantages do CPM diagrams have over conventional bar graph schedules?
5. Redraw the accompanying network diagram, adding early and late event times to the diagram. Mark the critical path. Prepare an activity-time tabulation showing early start, late start, early finish, late finish, and total float.



6. How does the actual progress at the end of the second week in Figure 16–1 compare with the scheduled progress? Express your answer as the percentage of scheduled progress that has actually been achieved.
7. Draw an activity-on-arrow network diagram representing the following logical relationships.

Activity	Depends on Completion of Activity
A	—
B	—
C	—
D	A
E	B
F	C
G	B
H	D and G
I	B
J	—
K	I and F

8. For the LSM diagram of Figure 16–22, over what linear distance does the Base Course activity extend at any particular time?
9. Redraw the precedence diagram of Figure 16–15 adding the relationships given below. Enter the early start, late start, early finish, late finish, and total float times on the diagram. Mark the critical path.

Activity Relationships

Start to Start	Finish to Start	Finish to Finish	Lag Time
8 to 7			3
	7 to 10		2
		8 to 11	4

10. Utilizing a personal computer program, solve Problem 1.

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