2

Construction Planning and Scheduling

2.1 Introduction

One of the most important responsibilities of construction project management is the planning and scheduling of construction projects. The key to successful profit making in any construction company is to have successful projects. Therefore, for many years, efforts have been made to plan, direct, and control the numerous project activities to obtain optimum project performance. Because every construction project is a unique undertaking, project managers must plan and schedule their work utilizing their experience with similar projects and applying their judgment to the particular conditions of the current project.

Until just a few years ago, there was no generally accepted formal procedure to aid in the management of construction projects. Each project manager had a different system, which usually included the use of the Gantt chart, or bar chart. The bar chart was, and still is, quite useful for illustrating the various items of work, their estimated time durations, and their positions in the work schedule as of the report date represented by the bar chart. However, the relationship that exists between the identified work items is by implication only. On projects of any complexity, it is difficult, if not virtually impossible, to identify the interrelationships between the work items, and there is no indication of the criticality of the various activities in controlling the project duration. A sample bar chart for a construction project is shown in Fig. 2.1.

The development of the critical path method (CPM) in the late 1950s provided the basis for a more formal and systematic approach to project management. Critical path methods involve a graphical display (network diagram) of the activities on a project and their interrelationships and an arithmetic procedure.
that identifies the relative importance of each activity in the overall project schedule. These methods have been applied with notable success to project management in the construction industry and several other industries, when applied earnestly as dynamic management tools. Also, they have provided a much-needed basis for performing some of the other vital tasks of the construction project manager, such as resource scheduling, financial planning, and cost control. Today’s construction manager who ignores the use of critical path methods is ignoring a useful and practical management tool.

Planning and Scheduling

Planning for construction projects involves the logical analysis of a project, its requirements, and the plan (or plans) for its execution. This will also include consideration of the existing constraints and available resources that will affect the execution of the project. Considerable planning is required for the support functions for a project, material storage, worker facilities, office space, temporary utilities, and so on. Planning, with respect to the critical path method, involves the identification of the activities for a project, the ordering of these activities with respect to each other, and the development of a network logic diagram that graphically portrays the activity planning. Figure 2.2 is an I-J CPM logic diagram.

The planning phase of the critical path method is by far the most difficult but also the most important. It is here that the construction planner must actually build the project on paper. This can only be done by becoming totally familiar with the project plans, specifications, resources, and constraints, looking at various plans for feasibly performing the project, and selecting the best one.

The most difficult planning aspect to consider, especially for beginners, is the level of detail needed for the activities. The best answer is to develop the minimum level of detail required to enable the user to schedule the work efficiently. For instance, general contractors will normally consider two or three activities for mechanical work to be sufficient for their schedule. However, to mechanical contractors, this would be totally inadequate because they will need a more detailed breakdown of their activities in order to schedule their work. Therefore, the level of activity detail required depends on the needs of the user of the plan, and only the user can determine his or her needs after gaining experience in the use of critical path methods.
Once the activities have been determined, they must be arranged into a working plan in the network logic diagram. Starting with an initial activity in the project, one can apply known constraints and reason that all remaining activities must fall into one of three categories:

1. They must precede the activity in question.
2. They must follow the activity in question.
3. They can be performed concurrently with the activity in question.

The remaining planning function is the estimation of the time durations for each activity shown on the logic diagram. The estimated activity time should reflect the proposed method for performing the activity, plus consider the levels at which required resources are supplied. The estimation of activity times is always a tough task for the beginner in construction because it requires a working knowledge of the production capabilities of the various crafts in the industry, which can only be acquired through many observations of actual construction work. Therefore, the beginner will have to rely on the advice of superiors for obtaining time estimates for work schedules.

Scheduling of construction projects involves the determination of the timing of each work item, or activity, in a project within the overall time span of the project. Scheduling, with respect to the critical path methods, involves the calculation of the starting and finishing times for each activity and the project duration, the evaluation of the available float for each activity, and the identification of the critical path or paths. In a broader sense, it also includes the more complicated areas of construction project management such as financial funds, flow analyses, resource scheduling and leveling, and inclement weather scheduling.

The planning and scheduling of construction projects using critical path methods have been discussed as two separate processes. Although the tasks performed are different, the planning and scheduling processes normally overlap. The ultimate objective of the project manager is to develop a working plan with a schedule that meets the completion date requirements for the project. This requires an interactive process of planning and replanning, and scheduling and rescheduling, until a satisfactory working plan is obtained.

### Controlling

The controlling of construction projects involves the monitoring of the expenditure of time and money in accordance with the working plan for the project, as well as the resulting product quality or performance. When deviations from the project schedule occur, remedial actions must be determined that will allow the project to be finished on time and within budget, if at all possible. This will often require replanning the order of the remaining project activities.
If there is any one factor for the unsuccessful application of the critical path method to actual construction projects, it is the lack of project monitoring once the original schedule is developed. Construction is a dynamic process; conditions often change during a project. The main strength of the critical path method is that it provides a basis for evaluating the effects of unexpected occurrences (such as delivery delays) on the total project schedule. The frequency for performing updates of the schedule depends primarily on the job conditions, but updates are usually needed most as the project nears completion. For most projects, monthly updates of the schedule are adequate. At the point of 50% completion, a major update should be made to plan and schedule the remaining work. The control function is an essential part of successful CPM scheduling.

Critical Path Methods

The critical path technique was developed from 1956 to 1958 in two parallel but different problems of planning and control in projects in the U.S.

In one case, the U.S. Navy was concerned with the control of contracts for its Polaris missile program. These contracts compromised research and development work as well as the manufacture of component parts not previously made. Hence, neither cost nor time could be accurately estimated, and completion times, therefore, had to be based upon probability. Contractors were asked to estimate their operational time requirements on three bases: optimistic, pessimistic, and most likely dates. These estimates were then mathematically assessed to determine the probable completion date for each contract, and this procedure was referred to as the program evaluation and review technique (PERT). Therefore, it is important to understand that the PERT systems involve a probability approach to the problems of planning and control of projects and are best suited to reporting on works in which major uncertainties exist.

In the other case, the E.I. du Pont de Nemours Company was constructing major chemical plants in America. These projects required that time and cost be accurately estimated. The method of planning and control that was developed was originally called project planning and scheduling (PPS) and covered the design, construction, and maintenance work required for several large and complex jobs. PPS requires realistic estimates of cost and time and, thus, is a more definitive approach than PERT. It is this approach that was developed into the critical path method, which is frequently used in the construction industry. Although there are some uncertainties in any construction project, the cost and time required for each operation involved can be reasonably estimated. All operations may then be reviewed by CPM in accordance with the anticipated conditions and hazards that may be encountered on this site.

There are several variations of CPM used in planning and scheduling work, but these can be divided into two major classifications: (1) activity-on-arrows, or I-J CPM; and (2) activity-on-nodes, especially the precedence version. The original CPM system was I-J system, with all others evolving from it to suit the needs and desires of the users. There is a major difference of opinion as to which of the two systems is the best to use for construction planning and scheduling. There are pros and cons for both systems, and the systems do not have a significant edge over the other. The only important thing to consider is that both systems be evaluated thoroughly before deciding which one to use. This way, even though both systems will do a fine job, you will never have to wonder if your method is inadequate.

The two CPM techniques used most often for construction projects are the I-J and precedence techniques. As mentioned earlier, the I-J CPM technique was the first developed. It was, therefore, the technique used most widely in the construction industry until recent years. It is often called activity-on-arrows and sometimes referred to as PERT. This last reference is a misnomer, because PERT is a distinctly different technique, as noted previously; however, many people do not know the difference. An example of an I-J CPM diagram is shown in Fig. 2.2, complete with calculated event times.

The other CPM technique is the precedence method; it is used most often today for construction planning and scheduling. It is actually a more sophisticated version of the activity-on-nodes system, initiated by John W. Fondahl of Stanford University. A diagram of an activity-on-nodes system is shown in Fig. 2.3. Notice that the activities are now the nodes (or circles) on the diagram, and the arrows simply
show the constraints that exist between the activities. The time calculations represent the activity's early and late start and finish times.

The precedence technique was developed to add flexibility to the activity-on-nodes system. The only constraint used for activity-on-nodes is the finish-to-start relationship, which implies that one activity must finish before its following activity can start. In the precedence system, there are four types of relationships that can be used; also, the activities are represented by rectangles instead of circles on the logic diagram. A complete precedence network plus calculations is shown in Fig. 2.4.

**Advantages of CPM**

The critical path methods have been used for planning and scheduling construction projects for over 20 years. The estimated worth of their use varies considerably from user to user, with some contractors feeling that CPM is a waste of time and money. It is difficult to believe that anyone would feel that detailed planning and scheduling work is a waste. Most likely, the unsuccessful applications of CPM resulted from trying to use a level of detail far too complicated for practical use, or the schedule was developed by an outside firm with no real input by the user, or the CPM diagram was not reviewed and updated during the project.
Regardless of past uses or misuses of CPM, the basic question is still the same: “What are the advantages of using CPM for construction planning and scheduling?” Experience with the application of CPM on several projects has revealed the following observations:

1. CPM encourages a logical discipline in the planning, scheduling, and control of projects.
2. CPM encourages more long-range and detailed planning of projects.
3. All project personnel get a complete overview of the total project.
4. CPM provides a standard method of documenting and communicating project plans, schedules, and time and cost performances.
5. CPM identifies the most critical elements in the plan, focusing management’s attention to the 10 to 20% of the project that is most constraining on the scheduling.
6. CPM provides an easy method for evaluating the effects of technical and procedural changes that occur on the overall project schedule.
7. CPM enables the most economical planning of all operations to meet desirable project completion dates.

An important point to remember is that CPM is an open-ended process that permits different degrees of involvement by management to suit their various needs and objectives. In other words, you can use CPM at whatever level of detail you feel is necessary. However, one must always remember that you only get out of it what you put into it. It will be the responsibility of the user to choose the best technique. They are all good, and they can all be used effectively in the management of construction projects; just pick the one best liked and use it.

### 2.2 I-J Critical Path Method

The first CPM technique developed was the I-J CPM system, and therefore, it was widely used in the construction industry. It is often called activity-on-arrows and sometimes referred to as PERT (which is a misnomer). The objective of this section is to instruct the reader on how to draw I-J CPM diagrams, how to calculate the event times and activity and float times, and how to handle the overlapping work schedule.

#### Basic Terminology for I-J CPM

There are several basic terms used in I-J CPM that need to be defined before trying to explain how the system works. A sample I-J CPM diagram is shown in Fig. 2.5 and will be referred to while defining the basic terminology.

**Event (node)** — A point in time in a schedule, represented on the logic diagram by a circle, is an event. An event is used to signify the beginning or the end of an activity, and can be shared by several activities. An event can occur only after all the activities that terminate at the event have been completed. Each event has a unique number to identify it on the logic diagram.

**Activity** $(A_{ij})$ — A work item identified for the project being scheduled is an activity. The activities for I-J CPM are represented by the arrows on the logic diagram. Each activity has two events: a preceding event (i-node) that establishes its beginning and a following event (j-node) that establishes its end. It is the use of the i-node and j-node references that established the term I-J CPM.

In Fig. 2.5, activity A, excavation, is referred to as activity 1–3.

**Dummy** — A fictitious activity used in I-J CPM to show a constraint between activities on the logic diagram when needed for clarity is called a dummy. It is represented as a dashed arrow and has a duration of zero. In Fig. 2.5, activity E cannot start until activity A is finished.

**Activity duration** $(T_{ij})$ — Duration of an activity is expressed in working days, usually eight-hour days, based on a five-day workweek.
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This is the earliest possible occurrence time for event $i$, expressed in project workdays, cumulative from the beginning of the project.

LET$_i$ — This is the latest permissible occurrence time for event $i$, expressed in project workdays, cumulative from the end of the project.

Developing the I-J CPM Logic Diagram

The initial phase in the utilization of CPM for construction planning is the development of the CPM logic diagram, or network model. This will require that the preparer first become familiar with the work to be performed on the project and constraints, such as the resource limitations, which may govern the work sequence. It may be helpful to develop a list of the activities to be scheduled and their relationships to other activities. Then, draw the logic diagram. This is not an exact science but an interactive process of drawing and redrawing until a satisfactory diagram is attained.

A CPM diagram must be a closed network in order for the time and float calculations to be completed. Thus, there is a single starting node or event for each diagram and a single final node or event. In Fig. 2.5, the starting node is event 1, and the final node is event 11. Also, notice in Fig. 2.5 that event 11 is the only event which has no activities following it. If any other event in the network is left without an activity following it, then it is referred to as a dangling node and will need to be closed back into the network for proper time calculations to be made.

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>DESCRIPTION</th>
<th>DURATION</th>
<th>PREDECESSOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>EXCAVATION</td>
<td>2</td>
<td>----</td>
</tr>
<tr>
<td>B</td>
<td>BUILD FORMS</td>
<td>3</td>
<td>----</td>
</tr>
<tr>
<td>C</td>
<td>PROCUREMENT REINF. STEEL</td>
<td>1</td>
<td>----</td>
</tr>
<tr>
<td>D</td>
<td>FINE GRADING</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>E</td>
<td>ERECT FORMWORK</td>
<td>2</td>
<td>A, B</td>
</tr>
<tr>
<td>F</td>
<td>SET REINF. STEEL</td>
<td>2</td>
<td>D, E, C</td>
</tr>
<tr>
<td>G</td>
<td>PLACE/FINISH CONCRETE</td>
<td>1</td>
<td>F</td>
</tr>
</tbody>
</table>
The key to successful development of CPM diagrams is to concentrate on the individual activities to be scheduled. By placing each activity on the diagram in the sequence desired with respect to all other activities in the network, the final logic of the network will be correct. Each activity has a variety of relationships to other activities on the diagram. Some activities must precede it, some must follow it, some may be scheduled concurrently, and others will have no relationship to it. Obviously, the major concern is to place the activity in a proper sequence with those that must precede it and those that must follow it. In I-J CPM, these relationships are established via the activity’s preceding event (i-node) and following event (j-node).

The key controller of logic in I-J CPM is the event. Simply stated, all activities shown starting from an event are preceded by all activities that terminate at that event and cannot start until all preceding activities are completed. Therefore, one of the biggest concerns is to not carelessly construct the diagram and needlessly constrain activities when not necessary. There are several basic arrangements of activities in I-J CPM; some of the simple relationships are shown in Fig 2.6. Sequential relationships are the name of the game — it is just a matter of taking care to show the proper sequences.

The biggest problem for most beginners in I-J CPM is the use of the dummy activity. As defined earlier, the dummy activity is a special activity used to clarify logic in I-J CPM networks, is shown as a dashed line, and has a duration of zero workdays. The dummy is used primarily for two logic cases: the complex
logic situation and the unique activity number problem. The complex logic situation is the most important use of the dummy activity to clarify the intended logic. The proper use of a dummy is depicted in Fig. 2.7, where it is desired to show that activity $A_{rs}$ needs to be completed before both activities $A_{st}$ and $A_{jk}$, and the activity $A_{ij}$ precedes only $A_{jk}$. The incorrect way to show this logic is depicted in Fig. 2.8. It is true that this logic shows that $A_{rs}$ precedes both $A_{st}$ and $A_{jk}$, but it also implies that $A_{ij}$ precedes both $A_{st}$ and $A_{rs}$, which is not true. Essentially, the logic diagram in Fig. 2.7 was derived from the one in Fig. 2.8 by separating event $j$ into two events, $j$ and $s$, and connecting the two with the dummy activity $A_{st}$.

The other common use of the dummy activity is to ensure that each activity has a unique $i$-node and $j$-node. It is desirable in I-J CPM that any two events may not be connected by more than one activity. This situation is depicted in Fig. 2.9. This logic would result in two activities with the same identification number, $i-j$. This is not a fatal error in terms of reading the logic, but it is confusing and will cause
problems if utilizing a computer to analyze the schedule. This problem can be solved by inserting a dummy activity at the end of one of the activities, as shown in Fig. 2.10. It is also possible to add the dummy at the front of the activity, which is the same logic.

Each logic diagram prepared for a project will be unique if prepared independently. Even if the same group of activities is included, the layout of the diagram, the number of dummy activities, the event numbers used, and several other elements will differ from diagram to diagram. The truth is that they are all correct if the logic is correct. When preparing a diagram for a project, the scheduler should not worry about being too neat on the first draft but should try to include all activities in the proper order. The diagram can be fine-tuned after the original schedule is checked.

I-J Network Time Calculations
An important task in the development of a construction schedule is the calculation of the network times. In I-J CPM, this involves the calculation of the event times, from which the activity times of interest are then determined. Each event on a diagram has two event times: the early event time (EET) and the late event time (LET), which are depicted in Fig. 2.11. Each activity has two events: the preceding event, or the i-node, and the following event, or the j-node. Therefore, each activity has four associated event times: EET, LET, EET, and LET. A convenient methodology for determining these event times involves a forward pass to determine the early event times and a reverse pass to determine the late event times.

**FIGURE 2.10** Correct nodes for parallel activities.

\[
\begin{align*}
A_{ip} &= \text{OLD } A_{ij}^1 \\
A_{ij} &= \text{A}_{ij}^2 \\
A_{ij} &= \text{DUMMY ACTIVITY}
\end{align*}
\]

**FIGURE 2.11** Terminology for I-J CPM activities.
Forward Pass

The objective of the forward pass is to determine the early event times for each of the events on the I-J diagram. The process is started by setting the early event time of the initial event on the diagram (there is to be only one initial event) equal to zero (0). Once this is done, all other early event times can be calculated; this will be explained by the use of Fig. 2.12. The early event time of all other events is determined as the maximum of all the early finish times of all activities that terminate at an event in question. Therefore, an event should not be considered until the early finish times of all activities that terminate at the event have been calculated. The forward pass is analogous to trying all the paths on a road network, finding the maximum time that it takes to get each node. The calculations for the forward pass can be summarized as follows:

1. The earliest possible occurrence time for the initial event is taken as zero \[ \text{EET}_i = 0 = \text{EST}_{ij} \] (\( i \) = initial event).
2. Each activity can begin as soon as its preceding event (i-node) occurs (\( \text{EST}_{ij} = \text{EET}_i \), \( \text{EFT}_{ij} = \text{EET}_i + T_{ij} \)).
3. The earliest possible occurrence time for an event is the largest of the early finish times for those activities that terminate at the event \[ \text{EET}_j = \text{max} \ E\text{FT}_{pj} \ (p = \text{all events that precede event } j) \].
4. The total project duration is the earliest possible occurrence time for the last event on the diagram \[ \text{TPD} = \text{EET}_j \ (j = \text{terminal event on diagram}) \].

The early event time of event 1 in Fig. 2.12 was set equal to 0; i.e., \( \text{EET}(1) = 0 \). It is then possible to calculate the early finish times for activities 1–5, 1–3, and 1–11, as noted. Activity early finish times are not normally shown on an I-J CPM diagram but are shown here to help explain the process. Since both events 3 and 11 have only a single activity preceding them, their early event times can be established as five and eight, respectively. Event 5 has two preceding activities; therefore, the early finish times for both activities 1–5 (4) and 3–5 (5) must be found before establishing that its early event time equals 5. Note that dummy activities are treated as regular activities for calculations. Likewise, the early finish time for event 15 cannot be determined until the early finish times for activities 3–15 (9) and 13–15 (13) have been calculated. \( \text{EET}(15) \) is then set as 13. The rest of the early event times on the diagram are, thus, similarly calculated, resulting in an estimated total project duration of 24 days.

Reverse Pass

The objective of the reverse pass is to determine the late event time for each event on the I-J diagram. This process is started by setting the late event time of the terminal, or last, event on the diagram (there
is to be only one terminal event) equal to the early event time of the event; i.e., LET\(_j\) = EET\(_j\). Once this
is done, then all other late event times can be calculated; this will be explained by the use of Fig. 2.13.
The late event time of all other events is determined as the minimum of all the late start times of all
activities that originate at an event in question. Therefore, an event should not be considered until the
late event times of all activities that originate at the event have been calculated. The calculations for the
reverse pass can be summarized as follows:

1. The latest permissible occurrence time for the terminal event is set equal to the early event time
   of the terminal event. This also equals the estimated project duration [LET\(_j\) = EET\(_j\) = TPD (j =
terminal event on diagram)].
2. The latest permissible finish time for an activity is the latest permissible occurrence time for its
   following event (j-node) (LFT\(_{ij}\) = LET\(_j\); LST\(_{ij}\) = LET\(_j\) – T\(_{ij}\)).
3. The latest permissible occurrence time for an event is the minimum (earliest) of the latest start
   times for those activities that originate at the event [LET\(_i\) = min LST\(_{ip}\) (p = all events that follow
   event i)].
4. The latest permissible occurrence time of the initial event should equal its earliest permissible
   occurrence time (zero). This provides a numerical check [LET\(_i\) = EET\(_i\) = 0 (i = initial event on
diagram)].

The late event time of event 21 in Fig. 2.13 was set equal to 24. It is then possible to calculate the late
start times for activities 9–21, 19–21, and 17–21, as noted. Activity late start times are not normally
shown on I-J CPM diagram but are shown here to help explain the reverse pass process. Since both events
17 and 19 have only a single activity that originates from them, their late event times can be established
as 23 and 20, respectively. Event 9 has two originating activities; therefore, the late start times for activities
9–17 (23) and 9–21 (19) must be found before establishing that its late event time equals 19. Note that
dummy activities are treated as regular activities for calculations. Likewise, the late event time for event
3 cannot be determined until the late start times for activities 3–5 (6) and 3–15 (9) have been calculated.
LET(3) is then set as 6. The rest of the late event times on the diagram are thus calculated, resulting in
the late event time of event 1 checking in as zero.

**Activity Float Times**

One of the primary benefits of the critical path methods is the ability to evaluate the relative importance
of each activity in the network by its calculated float, or slack, time. In the calculation procedures for
CPM, an allowable time span is determined for each activity; the boundaries of this time span are
established by the activity’s early start time and late finish time. When this bounded time span exceeds the activity’s duration, the excess time is referred to as float time. Float time can exist only for noncritical activities. Activities with zero float are critical activities and make up the critical path(s) on the network. There are three basic float times for each activity: total float, free float, and interfering float. It should be noted that once an activity is delayed to finish beyond its early finish time, then the network event times must be recalculated for all following activities before evaluating their float times.

**Total Float**

The total float for an activity is the total amount of time that the activity can be delayed beyond its early finish time, before it delays the overall project completion time. This delay will occur if the activity is not completed by its late finish time. Therefore, the total float is equal to the time difference between the activity’s late finish time and its early finish time. The total float for an activity can be calculated by the following expression:

\[
TF_{ij} = LET_j - EET_i - T_{ij}
\]

Since the \(LET_j\) for any activity is its late finish time, and the \(EET_i\) plus the duration, \(T_{ij}\), equals the early finish time, then the above expression for the total float of an activity reduces to:

\[
TF_{ij} = LFT_i - EFT_j
\]

The calculation of the total float can be illustrated by referring to Fig. 2.14, where the total float and free float for each activity are shown below the activity. For activity B, the total float = 15 – 5 – 9 = 1, and for activity K, the total float = 23 – 13 – 3 = 7. The total float for activities G, H, I, and J is zero; thus, these activities make up the critical path for this diagram. Float times are not usually noted on dummy activities; however, dummies have float because they are activities. Activity 13–15 connects two critical activities and has zero total float; thus, it is on the critical path and should be marked as such.

One of the biggest problems in the use of CPM for scheduling is the misunderstanding of float. Although the total float for each activity is determined independently, it is not an independent property but is shared with other activities that precede or follow it. The float value calculated is good only for the event times on the diagram. If any of the event times for a diagram change, then the float times must be recalculated for all activities affected. For example, activity B has a total float = 1; however, if activity A or E is not completed until CPM day 6, then the EET(5) must be changed to 6, and the total float for activity B then equals zero. Since activity B had one day of float originally, then the project duration is not affected. However, if the EET(5) becomes greater than 6, then the project duration will be increased.
A chain of activities is a series of activities linked sequentially in a CPM network. Obviously, there are many different possible chains of activities for a given network. Often, a short chain will have the same total float, such as the chain formed by activities B, C, and D in Fig. 2.14. The total float for each of these activities is 1 day. Note that if the total float is used up by an earlier activity in a chain, then it will not be available for following activities. For instance, if activity B is not finished until day 15, then the total float for both activities C and D becomes zero, making them both critical. Thus, one should be very careful when discussing the float time available for an activity with persons not familiar with CPM. This problem can be avoided if it is always a goal to start all activities by their early start time, if feasible, and save the float for activities that may need it when problems arise.

**Free Float**

Free float is the total amount of time that an activity can be delayed beyond its early finish time, before it delays the early start time of a following activity. This means that the activity must be finished by the early event time of its \( j \)-node; thus, the free float is equal to the time difference between the \( EET_j \) and its early finish time. The free float can be calculated by the following expressions:

\[
FF_{ij} = EET_j - EET_i - T_{ij} \quad \text{or} \quad FF_{ij} = EET_j - EFT_{ij}.
\]

The calculation of free float can be illustrated by referring to Fig. 2.14, where the total float and free float for each activity are shown below the activity. For activity A, the free float = 14 – 5 – 9 = 0, and for activity D, the free float = 24 – 18 – 5 = 1.

The free float for most activities on a CPM diagram will be zero, as can be seen in Fig. 2.14. This is because free float occurs only when two or more activities merge into an event, such as event 5. The activity that controls the early event time of the event will, by definition, have a free float of zero, while the other activities will have free float values greater than zero. Of course, if two activities tie in the determination of the early event time, then both will have zero free float. This characteristic can be illustrated by noting that activities 1–5 and 3–5 merge at event 5, with activity 3–5 controlling the \( EET = 5 \). Thus, the free float for activity 3–5 will be zero, and the free float for activity 1–5 is equal to one. Any time you have a single activity preceding another activity, then the free float for the preceding activity is immediately known to be zero, because it must control the early start time of the following activity. Free float can be used up without hurting the scheduling of a following activity, but this cannot be said for total float.

**Interfering Float**

Interfering float for a CPM activity is the difference between the total float and the free float for the activity. The expression for interfering float is:

\[
IF_{ij} = LET_j - EET_j \quad \text{or} \quad IF_{ij} = T_{ij} - FF_{ij}.
\]

The concept of interfering float comes from the fact that if one uses the free float for an activity, then the following activity can still start on its early start time, so there is no real interference. However, if any additional float is used, then the following activity’s early start time will be delayed. In practice, the value of interfering float is seldom used; it is presented here because it helps one to better comprehend the overall system or float for CPM activities. The reader is encouraged to carefully review the sections on activity float, and refer to Figs. 2.14 and 2.15 for graphic illustrations.

**Activity Start and Finish Times**

One of the major reasons for the utilization of CPM in the planning of construction projects is to estimate the schedule for conducting various phases (activities) of the project. Thus, it is essential that one know how to determine the starting and finishing times for each activity on a CPM diagram. Before explaining
how to do this, it is important to note that any starting or finish time determined is only as good as the CPM diagram and will not be realistic if the diagram is not kept up to date as the project progresses. If one is interested only in general milestone planning, this is not as critical. However, if one is using the diagram to determine detailed work schedules and delivery dates, then updating is essential. This topic will be discussed in “Updating the CPM Network” later in this chapter.

The determination of the early and late starting and finishing times for I-J CPM activities will be illustrated by reference to Fig. 2.14. There are four basic times to determine for each activity: early start time, late start time, early finish time, and late finish time. Activity F in Fig. 2.14, as for all other activities on an I-J CPM diagram, has four event times:

EET\(_i\) = 5, LET\(_i\) = 6, EET\(_j\) = 13, LET\(_j\) = 13

A common mistake is to refer to these four times as the early start time, late start time, early finish time, and late finish time for activity F, or activity 3–15. Although this is true for all critical activities and may be true of some other activities, this is not true of many of the activities on an I-J diagram, and this procedure should not be used.

The basic activity times can be determined by the following four relationships:

- Early start time, \(EST_{ij} = EET_i\) (5 for activity F)
- Late start time, \(LST_{ij} = LET_i - t_{ij}\) (13 – 4 = 9 for activity F)
- Early finish time, \(EFT_{ij} = EST_{ij} + t_{ij}\) (5 + 4 = 9 for activity F)
- Late finish time, \(LFT_{ij} = LET_j\) (13 for activity F)

As can be seen, the early finish time for activity F is 9, not 13, and the late start time is 9, not 6. The four basic activity times can be found quickly and easily but cannot be read directly off the diagram. For

![FIGURE 2.15 Graphic representation of I-J CPM float.](image-url)
many construction projects today, the starting and finishing times for all activities are shown on a computer printout, not only in CPM days, but in calendar days also. As a further example, the EST, LST, EFT, and LFT of activity A in Fig. 2.14 are 0, 2, 4, and 6, respectively. These times are in terms of CPM days; instructions will be given later for converting activity times in CPM days into calendar dates.

**Overlapping Work Items in I-J CPM**

One of the most difficult scheduling problems encountered is the overlapping work items problem. This occurs often in construction and requires careful thought by the scheduler, whether using I-J CPM or the precedence CPM technique (precedence will be discussed in the following section). The overlapping work situation occurs when two or more work items that must be sequenced will take too long to perform end to end, and thus, the following items are started before their preceding work items are completed. Obviously, the preceding work items must be started and worked on sufficiently in order for the following work items to begin. This situation occurs often with construction work such as concrete wall (form, pour, cure, strip, finish) and underground utilities (excavate, lay pipe, test pipe, backfill). Special care must be taken to show the correct logic to follow on the I-J diagram, while not restricting the flow of work, as the field forces use the CPM schedule.

The overlapping work item problem is also encountered for several other reasons in construction scheduling. A major reason is the scheduling required to optimize scarce or expensive resources, such as concrete forms. It is usually too expensive or impractical to purchase enough forms to form an entire concrete structure at one time; therefore, the work must be broken down into segments and scheduled with the resource constraints identified. Another reason for overlapping work items could be for safety or for practicality. For instance, in utilities work, the entire pipeline could be excavated well ahead of the pipe-laying operation. However, this would expose the pipe trench to weather or construction traffic that could result in the collapse of the trench, thus requiring expensive rework. Therefore, the excavation work is closely coordinated with the pipe-laying work in selected segments to develop a more logical schedule.

The scheduling of overlapping work items will be further explained by the use of an example. Assume that a schedule is to be developed for a small building foundation. The work has been broken down into four separate phases: excavation, formwork, concrete placement, and stripping and backfilling. A preliminary analysis of the work has determined the following workday durations of the four work activities: 4, 8, 2, and 4, respectively. If the work items are scheduled sequentially, end to start, the I-J CPM diagram for this work would appear as depicted in Fig. 2.16. Notice that the duration for the completion of all the work items is 18 workdays.

A more efficient schedule can be developed for the work depicted in Fig. 2.16. Assume that the work is to be divided into two halves, with the work to be overlapped instead of done sequentially. A bar chart schedule for this work is shown in Fig. 2.17. The work items have been abbreviated as E1 (start excavation), E2 (complete excavation), and so on, to simplify the diagrams. Because there is some float available for some of the work items, there are actually several alternatives possible. Notice that the work scheduled on the bar chart will result in a total project duration of 13 workdays, which is five days shorter than the CPM schedule of Fig. 2.16.

An I-J CPM schedule has been developed for the work shown on the bar chart of Fig. 2.17 and is depicted in Fig. 2.18. At first glance, the diagram looks fine except for one obvious difference: the project duration is 14 days, instead of 13 days for the bar chart schedule. Closer review reveals that there are

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**FIGURE 2.16** I-J CPM for sequential activities.
serious logic errors in the CPM diagram at events 7 and 11. As drawn, the second half of the excavation (E2) must be completed before the first concrete placement (CP1) can start. Likewise, the first wall pour cannot be stripped and backfilled (S/BF1) until the second half of the formwork is completed (F2). These are common logic errors caused by the poor development of I-J activities interrelationships. The diagram shown in Fig.2.19 is a revised version of the I-J CPM diagram of Fig. 2.18 with the logic errors at events 7 and 11 corrected. Notice that the project duration is now 13 days, as for the bar chart.

Great care must be taken to show the correct logic for a project when developing any CPM diagram. One should always review a diagram when it is completed to see if any unnecessary or incorrect constraints have been developed by improper drawing of the activities and their relationships to each other. This is especially true for I-J CPM diagrams where great care must be taken to develop a sufficient number of
events and dummy activities to show the desired construction work item sequences. The scheduling of overlapping work items often involves more complicated logic and should be done with care. Although beginning users of I-J CPM tend to have such difficulties, they can learn to handle such scheduling problems in a short time period.

2.3 Precedence Critical Path Method

The critical path method used most widely in the construction industry is the precedence method. This planning and scheduling system was developed by modifying the activity-on-node method discussed earlier and was depicted in Fig. 2.3. In activity-on-node networks, each node or circle represents a work activity. The arrows between the activities are all finish-to-start relationships; that is, the preceding activity must finish before the following activity can start. The four times shown on each node represent the early start time/late start time and early finish time/late finish time for the activity. In the precedence system (see Fig. 2.20), there are several types of relationships that can exist between activities, allowing for greater flexibility in developing the CPM network.

The construction activity on a precedence diagram is typically represented as a rectangle (see Fig. 2.21). There are usually three items of information placed within the activity’s box: the activity number, the activity description, and the activity time (or duration). The activity number is usually an integer, although alphabetical characters are often added to denote the group responsible for management of the activity’s work scope. The activity time represents the number of workdays required to perform the activity’s work scope, unless otherwise noted.

There are two other important items of information concerning the activity shown on a precedence diagram. First, the point at which the relationship arrows touch the activity’s box is important. The left edge of the box is called the start edge; therefore, any arrow contacting this edge is associated with the
activity's start time. The right edge of the box is called the finish edge; therefore, any arrow contacting this edge is associated with the activity’s finish time. Second, the calculated numbers shown above the box on the left represent the early start time and the late start time of the activity, and the numbers above the box on the right represent the early finish time and the late finish time of the activity. This is different from I-J CPM, where the calculated times represent the event times, not the activity times.

**Precedence Relationships**

The arrows on a precedence diagram represent the relationships that exist between different activities. There are four basic relationships used, as depicted in Fig. 2.22. The **start-to-start** relationship states that
activity B cannot start before activity A starts; that is, EST(B) is greater than or equal to EST(A). The greater-than situation will occur when another activity that precedes activity B has a greater time constraint than EST(A).

The finish-to-start relationship states that activity B cannot start before activity A is finished; that is, EST(B) is greater than or equal to EFT(A). This relationship is the one most commonly used on a precedence diagram. The finish-to-finish relationship states that activity B cannot finish before activity A finishes; that is, EFT(B) is greater than or equal to EFT(A). This relationship is used mostly in precedence networks to show the finish-to-finish relationships between overlapping work activities.

The fourth basic relationship is the lag relationship. Lag can be shown for any of the three normal precedence relationships and represents a time lag between the two activities. The lag relationship shown in Fig. 2.22 is a start-to-start (S-S) lag. It means that activity B cannot start until X days of work are done on activity A. Often when there is an S-S lag between two activities, there is a corresponding F-F lag, because the following activity will require X days of work to complete after the preceding activity is completed. The use of lag time on the relationships allows greater flexibility in scheduling delays between activities (such as curing time) and for scheduling overlapping work items (such as excavation, laying pipe, and backfilling). A precedence with all three basic relationships and three lags is shown in Fig. 2.23.
Precedence Time Calculations

The time calculations for precedence are somewhat more complex than for I-J CPM. The time calculation rules for precedence networks are shown in Fig. 2.24. These rules are based on the assumption that all activities are continuous in time; that is, once started, they are worked through to completion. In reality, this assumption simplifies interpretation of the network and the activity float times. It ensures that the EFT equals the EST plus the duration for a given activity.

The time calculations involve a forward pass and a reverse pass, as in I-J CPM. However, for precedence, one is calculating activity start and finish times directly and not event times as in I-J. In the forward pass, one evaluates all activities preceding a given activity to determine its EST.

For activity F in Fig. 2.23, there are three choices: C-to-F (start-to-start), EST(F) = 4 + 3 = 7; C-to-F (finish-to-finish), EST(F) = 10 + 1 – 5 = 6; D-to-F (finish-to-start), EST(F) = 2 + 3 = 5. Since 7 is the largest EST, the C-to-F (S-S) relationship controls. The EFT is then determined as the EST plus the duration; for activity F, the EFT = 12.

For the reverse pass in precedence, one evaluates all activities following a given activity to determine its LFT. For activity F, the only following activity is activity J; therefore, the LFT(F) is 2 + 0 = 2. For activity D, there are two choices for LFT: D-to-F (start-to-start, with lag), LFT(D) = 19 – 3 + 7 = 23; D-to-G (finish-to-start), LFT(D) = 9 – 0 = 9. Since 9 is the smallest LFT, the D-to-G relationship controls. The LST is then determined as the LFT minus the duration; for activity D, the LST is 2.

A major advantage of the precedence system is that the times shown on a precedence activity represent actual start and finish times for the activity. Thus, less-trained personnel can more quickly read these times from the precedence network than from an I-J network. As for I-J CPM, the activity times represent
I. EARLIEST START TIME
   A. EST of first Work Item (W.I.) is zero (by definition).
   B. EST of all other W.I.'s is the greater of these times:
      1) EST of a preceding W.I. if start-start relation.
      2) EFT of a preceding W.I. if finish-start relation.
      3) EFT of a preceding W.I., less the duration of the W.I. itself, if finish-finish relation.
      4) EST of a preceding W.I., plus the lag, if there is a lag relation.

II. EARLIEST FINISH TIME
   A. For first Work Item, EFT = EST + Duration.
   B. EFT of all other W.I.'s is the greater of these times:
      1) EST of W.I. plus its duration.
      2) EFT of preceding W.I. if finish-finish relation.

III. LATEST FINISH TIME
   A. LFT for last Work Item is set equal to its EFT.
   B. LFT for all other W.I.'s is the lesser of these items:
      1) LST of following W.I. if finish-start relation.
      2) LFT of following W.I. if finish-finish relation.
      3) LST of following W.I., plus the duration of the W.I. itself, if there is a start-start relation.
      4) LST of following W.I., less the lag, plus the duration of the W.I. itself, if there is a lag relation.

IV. LATEST START TIME
   A. LST of first Work Item = LFT - Duration.
   B. LST of all other W.I.'s is the lesser of these items:
      1) LFT of W.I. less its duration.
      2) LST of following W.I. if start-start relation.
      3) LST of following W.I. if less the lag, if there is a lag relation.

EST = Early Start Time  LST = Late Start Time
EFT = Early Finish Time  LFT = Late Finish Time

Lag = Number of days of lag time associated with a relationship.

FIGURE 2.24 Precedence activity times calculation rules.

CPM days, which relate to workdays on the project. The conversion from CPM days to calendar dates will be covered in the next section.

Precedence Float Calculations

The float times for precedence activities have the same meaning as for I-J activities; however, the calculations are different. Before float calculations can be made, all activity start and finish times must be calculated as just described. Remember again that all activities are assumed to be continuous in duration. The float calculations for precedence networks are depicted in Fig. 2.25.

The total float of an activity is the total amount of time that an activity can be delayed before it affects the total project duration. This means that the activity must be completed by its late finish time; therefore, the total float for any precedence activity is equal to its LFT minus its EFT. For activity F in Fig. 2.23, its total float is 24 − 12 = 12.

The free float of an activity is the total amount of time that an activity can be delayed beyond its EFT before it delays the EST of a following activity. In I-J CPM, this is a simple calculation equal to the EET of its j-node minus the EET of its i-node minus its duration. However, for a precedence activity, it is necessary to check the free float existing between it and each of the activities that follows it, as depicted in Fig. 2.25. The actual free float for the activity is then determined as the minimum of all free float options calculated for the following activities. For most precedence activities, as for I-J, the free float
time is normally equal to zero. For activity C in Fig. 2.23, there are three choices: C-to-F (start-to-start), FF = 7 – 4 – 3 = 0; C-to-F (finish-to-finish), FF = 12 – 10 – 1 = 1; C-to-I (finish-to-start), FF = 20 – 10 = 10. Since the smallest is 0, then the C-to-F (S-S) relationship controls, and the FF = 0.

**Overlapping Work Items**

A major reason that many persons like to use the precedence CPM system for construction scheduling is its flexibility for overlapping work items. Figure 2.26 depicts the comparable I-J and precedence diagrams necessary to show the logic and time constraints shown in the bar chart at the top of the figure. Although the precedence version is somewhat easier to draw, one has to be careful in calculating the activity times. There is also a tendency for all of the precedence activities to be critical, due to the continuous time constraint for the activities. If one understands how to use either CPM system, the network development will not be difficult; therefore, it is mostly a matter of preference.
2.4 CPM Day to Calendar Day Conversion

All CPM times on the logic diagrams are noted in CPM days, which are somewhat different from project workdays and decidedly different from calendar days or dates. Because most persons utilizing the activity times from a CPM diagram need to know the starting and finishing time requirements in calendar dates, one needs to know how to convert from CPM days to calendar dates. To illustrate this relationship, refer to Fig. 2.27 that depicts a typical activity from an I-J CPM activity, plus a CPM day to CAL day conversion chart.

The CPM/CAL conversion table represents CPM days on the left and regular calendar days on the right. For the sample project shown, the project start date is February 3, 1993. Accordingly, the first CPM
day is 0 and is shown on the left side. CPM days are then noted consecutively, skipping weekends, holidays, and other nonworkdays for the project. CPM days are referenced to the morning of a workday; therefore, CPM day 0 is equal to the morning of project workday 1 and also equal to the morning of February 3, 1993.

Activity start dates are read directly from the conversion table, because they start in the morning. For instance, if an activity has an early start on CPM day 5, then it would start on February 10, 1993. This is also the morning of workday 6. Finish times can also be read directly from the table, but one must remember that the date is referenced to the morning of the day. For instance, if an activity has an early finish of CPM day 8, then it must finish on the morning of February 13. However, most persons are familiar with finish times referenced to the end of the day; therefore, unless the project crew is working 24-hour days, one must back off by one CPM day to give the finish date of the evening of the workday before. This means the finish time for the activity finishing by the morning of February 12 would be given as February 12, 1993. This process is followed for the early finish time and the late finish time for an activity.

### FIGURE 2.27 CPM/CAL conversion chart.

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<th>CAL</th>
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</table>

**NOTE:** CPM Day (X) = Work Day (X + 1)
(i.e. CPM Day 0 = Project Work Day 1)
The activity shown in Fig. 2.27 has the following activity times:

- Early start time = CPM day 5
- Late start time = 15 – 5 = CPM day 10
- Early finish time = 5 + 5 = CPM day 10 (morning) or CPM day 9 (evening)
- Late finish time = 15 = CPM day 15 (morning) or CPM day 14 (evening)

The activity time in calendar dates can be obtained for the activity depicted in Fig. 2.27 using the CPM/CAL conversion table:

- Early start time = February 10, 1993
- Late start time = February 17, 1993
- Early finish time = February 17 (morning) or February 14 (evening) (February 14 would be the date typically given)
- Late finish time = February 24 (morning) or February 21 (evening) (February 21 would be the date typically given)

The conversion of CPM activity start and finish times to calendar dates is the same process for I-J CPM and precedence CPM. The CPM/CAL conversion table should be made when developing the original CPM schedule, because it is necessary to convert all project constraint dates, such as delivery times, to CPM days for inclusion into the CPM logic diagram. The charts can be made up for several years, and only the project start date is needed to show the CPM days.

2.5 Updating the CPM Network

Updating the network is the process of revising the logic diagram to reflect project changes and actual progress on the work activities. A CPM diagram is a dynamic model that can be used to monitor the project schedule if the diagram is kept current, or up to date. One of the major reasons for dissatisfaction with the use of CPM for project planning occurs when the original schedule is never revised to reflect actual progress. Thus, after some time, the schedule is no longer valid and is discarded. If it is kept up to date, it will be a dynamic and useful management tool.

There are several causes for changes in a project CPM diagram, including the following:

1. Revised project completion date
2. Changes in project plans, specifications, or site conditions
3. Activity durations not equal to the estimated durations
4. Construction delays (e.g., weather, delivery problems, subcontractor delays, labor problems, natural disasters, owner indecision)

In order to track such occurrences, the project schedule should be monitored and the following information collected for all activities underway and those just completed or soon to start:

1. Actual start and finish dates, including actual workdays completed
2. If not finished, workdays left to complete and estimated finish date
3. Reasons for any delays or quick completion times
4. Lost project workdays and the reasons for the work loss

Frequency of Updating

A major concern is the frequency of updates required for a project schedule. The obvious answer is that updates should be frequent enough to control the project. The major factor is probably cost, because monitoring and updating are expensive and cause disturbances, no matter how slight, for the project staff. Other factors are the management level of concern, the average duration of most activities, total project duration, and the amount of critical activities. Some general practices followed for updating frequencies include the following:
1. Updates may be made at uniform intervals (daily, weekly, monthly).
2. Updates may be made only when significant changes occur on the project schedule.
3. Updates may be made more frequently as the project completion draws near.
4. Updates may be made at well-defined milestones in the project schedule.

In addition to keeping up with the actual project progress, there are other reasons that make it beneficial to revise the original project network:

1. To provide a record for legal action or for future schedule estimates
2. To illustrate the impact of changes in project scope or design on the schedule
3. To determine the impact of delays on the project schedule
4. To correct errors or make changes as the work becomes better defined

Methods for Revising the Project Network

If it is determined that the current project network is too far off the actual progress on a project, then there are three basic methods to modify the network. These methods will be illustrated for a small network, where the original schedule is as shown in Fig. 2.28, and the project’s progress is evaluated at the end of CPM day 10.

I. Revise existing network (see Fig. 2.29).
   A. Correct diagram to reflect actual duration and logic changes for the work completed on the project schedule.
   B. Revise logic and duration estimates on current and future activities as needed to reflect known project conditions.

II. Revise existing network (see Fig. 2.30).
   A. Set durations equal to zero for all work completed and set the EET (first event) equal to the CPM day of the schedule update.
   B. Revise logic and duration estimates on current and future activities as needed to reflect known project conditions.

III. Develop a totally new network for the remainder of project work if extensive revisions are required of the current CPM schedule.

FIGURE 2.28 I-J CPM diagram for updating example.
2.6 Other Applications of CPM

Once the CPM schedule has been developed for a construction project (or any type of project, for that matter), there are several other applications that can be made of the schedule for management of the project. Since complete coverage of these applications is beyond the scope of this handbook, the applications are only mentioned here. The methodologies for using these applications are covered in most textbooks on construction planning and scheduling, if the reader is interested. Major applications include the following:

Funds flow analysis — The flow of funds on a construction project (expenditures, progress billings and payments, supplier payments, retainages, etc.) are of great concern to contractors and owners for their financing projections for projects. CPM activities can be costed and used, along with other project cost conditions, to predict the flow of funds over the life of the project.

Resource allocation and analysis — The efficient utilization of resources is an important problem in construction project management, especially for the scheduling of scarce resources. By identifying the resource requirements of all activities on a CPM network, the network provides the basis for

![FIGURE 2.29 Updated I-J CPM diagram (Version I).](image1)

![FIGURE 2.30 Updated I-J CPM diagram (Version II).](image2)
evaluating the resource allocation needs of a project. If the demand is unsatisfactory over time, then several methods are available with which to seek a more feasible project schedule to minimize the resource problem. The controlling factor in most cases is the desire to minimize project cost.

**Network compression** — This process is sometimes referred to as the *time-cost trade-off problem*. In many projects, the need arises to reduce the project duration to comply with a project requirement. This can be planned by revising the CPM network for the project to achieve the desired date. This is accomplished by reducing the durations of critical activities on the network and is usually a random process with minimal evaluation of the cost impact. By developing a cost utility curve for the network’s activities, especially the critical or near-critical activities, the network compression algorithm can be used to seek the desired reduced project duration at minimal increased cost.

### 2.7 Summary

Construction project planning and scheduling are key elements of successful project management. Time spent in planning prior to a project start, or early in the project, will most always pay dividends for all participants on the project. There are several methods available to utilize for such planning, including the bar chart and the critical path methods. Key information on these methods has been presented in this chapter of the *Handbook*. Use of any of the methods presented will make project planning an easier and more logical process. They also provide the basis for other management applications on the project. The reader is encouraged to seek more information on the methods presented and investigate other methods available. Finally, there are many computer software packages available to facilitate the planning process. The use of these systems is encouraged, but the reader should take care to purchase a system that provides the services desired at a reasonable cost. Take time to investigate several systems before selecting one, and be sure to pick a reliable source that is likely to be in business for some time in the future.

**Defining Terms**

**Activity** — A distinct and identifiable operation within a project that will consume one or more resources during its performance is an activity. The concept of the distinct activity is fundamental in network analysis. The level of detail at which distinct activities are identified in planning depends largely on the objectives of the analysis. An activity may also be referred to as an operation, or work item. A dummy activity, which does not consume a resource, can be used to identify a constraint that is not otherwise apparent.

**Activity duration** — The estimated time required to perform the activity and the allocation of the time resource to each activity define activity duration. It is customary to express the activity duration in work-time units; that is, workday, shift, week, and so on. An estimate of activity duration implies some definite allocation of other resources (labor, materials, equipment, capital) necessary to the performance of the activity in question.

**Constraints** — Limitations placed on the allocation of one or several resources are constraints.

**Critical activities** — Activities that have zero float time are critical. This includes all activities on the critical path.

**Critical path** — The connected chain, or chains, of critical activities (zero float), extending from the beginning of the project to the end of the project make up the critical path. Its summed activity duration gives the minimum project duration. Several may exist in parallel.

**Float (slack)** — In the calculation procedures for any of the critical path methods, an allowable time span is determined for each activity to be performed within. The boundaries of this time span for an activity are established by its early start time and late finish time. When this bounded time span exceeds the duration of the activity, the excess time is referred to as float time. Float can be classified according to the delayed finish time available to an activity before it affects the starting time of its following activities. It should be noted that once an activity is delayed to
finish beyond its early finish time, then the network calculations must be redone for all following activities before evaluating their float times.

**Free float** — The number of days that an activity can be delayed beyond its early finish time without causing any activity that follows it to be delayed beyond its early start time is called free float. The free float for many activities will be zero, because it only exists when an activity does not control the early start time of any of the activities that follow it.

**Management constraints** — Constraints on the ordering of activities due to the wishes of management are management constraints. For instance, which do you install first, toilet partitions or toilet fixtures? It does not usually matter, but they cannot be easily installed at the same time. Therefore, one will be scheduled first and the other constrained to follow; this is a management constraint.

**Monitoring** — The periodic updating of the network schedule as the project progresses is called monitoring. For activities already performed, estimated durations can be replaced by actual durations. The network can then be recalculated. It will often be necessary to replan and reschedule the remaining activities, as necessary, to comply with the requirement that the project duration remain the same.

**Network model** — The graphical display of interrelated activities on a project, showing resource requirements and constraints or a mathematical model of the project and the proposed methods for its execution. A network model is actually a logic diagram prepared in accordance with established diagramming conventions.

**Physical constraints** — Constraints on the ordering of activities due to physical requirements are termed physical constraints. For instance, the foundation footings cannot be completed until the footing excavation work is done.

**Planning** — The selection of the methods and the order of work for performing the project is planning. (Note that there may be feasible methods and, perhaps, more than one possible ordering for the work. Each feasible solution represents a plan.) The required sequence of activities (preceding, concurrent, or following) is portrayed graphically on the network diagram.

**Project** — Any undertaking with a definite point of beginning and a definite point of ending, requiring one or more resources for its execution is a project. It must also be capable of being divided into interrelated component tasks.

**Project duration** — The total duration of the project, based on the network assumptions of methods and resource allocations. It is obtained as the linear sum of activity durations along the critical path.

**Resource constraints** — Constraints on the ordering of activities due to an overlapping demand for resources that exceeds the available supply of the resources. For instance, if two activities can be performed concurrently but each requires a crane, and only one crane is available, then one will have to be done after the other.

**Resources** — These are things that must be supplied as input to the project. They are broadly categorized as manpower, material, equipment, money, time, and so on. It is frequently necessary to identify them in greater detail (draftsmen, carpenters, cranes, etc.).

**Scheduling** — The process of determining the time of a work item or activity within the overall time span of the construction project. It also involves the allocation of resources (men, material, machinery, money, time) to each activity, according to its anticipated requirements.

**Total float** — The total time available between an activity’s early finish time and late finish time as determined by the time calculations for the network diagram. If the activity’s finish is delayed more than its number of days of total float, then its late finish time will be exceeded, and the total project duration will be delayed. Total float also includes any free float available for the activity.
References


Further Information

There are hundreds of books, papers, and reports available on the subject of construction planning and scheduling in the U.S. The two references cited above are only two such publications often used by the author. In addition, there are many computer software packages available that give in-depth details of basic and advanced applications of planning and scheduling techniques for construction project management. Some of the commonly used packages are Primavera, Open Plan, Harvard Project Manager, and Microsoft Project. Another excellent source of information on new developments in scheduling is the ASCE Journal of Construction Engineering and Management, which is published quarterly.