CHAPTER FIVE

Project Scheduling Techniques

When a large engineering project is undertaken, there are many activities that have to be coordinated, and careful planning is needed if the project is to be completed on time and within budget. Scheduling techniques to assist in the planning of large projects, including the critical path method (CPM) and the Gantt Chart, are considered here. The use of these techniques assists in identifying and scheduling activities so that the project can be completed in the minimum feasible time. The rescheduling of activities taking account of limitations on certain critical resources is also discussed.

5.1 INTRODUCTION

Project scheduling deals with the timing and sequencing of the many activities that comprise a large project. It requires a comprehensive understanding of the project and informs other project management and control processes. Project scheduling will be used at different times within a project and will become more specific as the project progresses. For example, a schedule developed after the detailed design will be more comprehensive than the schedule developed during the preliminary design of the same project. Scheduling entails identification of the activities required within the project, estimation of the duration of each activity, identification of the precedence relations between activities (i.e. which ones need to precede others) and development of an organisational network or schedule that represents this information accurately. Such an organisational network can be used to provide the following information:

- the minimum time to complete the project if all activities run on time;
- the activities that are critical to ensure that the project is finished in the minimum time;
- the earliest start time and the latest finish time for each activity, if the project is to be finished in the minimum time; and
- the amount of time by which each activity can be delayed without delaying the project as a whole.

An organisational network can also be used to examine the times when resources (human resources, cash and equipment) need to be supplied and whether limits on these resources are likely to cause delays in the project completion. Furthermore, an organisational network can be used to identify which activities should be accelerated if the project needs to be completed in a shorter time than the current estimate.

This chapter serves as an introduction to project scheduling techniques. It provides a brief overview of their historical context and explains the steps required to develop and use the resultant organisational network and/or charts. Software is available to assist project managers and engineers develop and control project schedules. Such software is essential for large and complex projects, with potentially thousands of interconnected activities. However, it remains important for an engineer to develop an understanding of the underlying concepts and approaches upon which the software has been developed. This enables engineers to adapt their use of the software to suit the project being considered.

5.2 HISTORICAL BACKGROUND

Although project planning is sometimes considered as a recent development, the construction of structures such as the great Pyramids of Egypt and the Americas, Stonehenge and the statues on Easter Island undoubtedly required considerable organisational, resource management and scheduling skills. Unfortunately, there are no records of how these projects were planned, scheduled or managed.

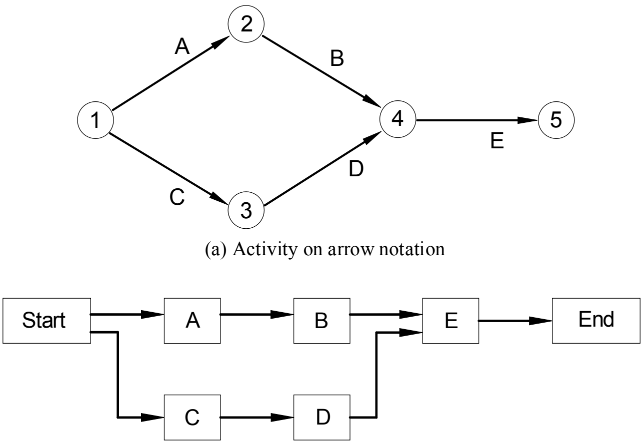
One of the first modern scheduling techniques developed to assist in project planning was the *Gantt Chart*. This was created in 1917 by Henry Laurence Gantt (1861–1919), an American mechanical engineer. The first Gantt Chart was developed for planning the building of ships during World War I. A Gantt Chart is a graph in which the horizontal axis represents time. All activities are listed down the page with each activity having a horizontal bar representing the planned timing of its completion. Gantt Charts can have varying levels of complexity and are discussed in Section 5.4.

In the late 1950s several techniques were developed to assist in the planning of complex projects. These include the critical path method (CPM) and the program evaluation and review technique (PERT). CPM was developed in the late 1950s by Morgan Walker of E.I. Du Pont and James E Kelly of Remington Rand Univac Corporation and was first used to schedule maintenance shutdowns in chemical processing plants. PERT was developed by Booz, Allen & Hamilton and the US Navy with the aim of coordinating the many thousands of contractors who were working on the Polaris missile program (Griffis and Farr, 2000; Shtub et al. 2005). Both techniques use a network of arrows and nodes to represent the activities in a project. Calculations can then be carried out to determine important information, such as that listed in Section 5.1. The basic difference between the two techniques is that CPM assumes that the durations of all activities are known, whereas PERT represents the durations of activities as random variables with optimistic, pessimistic and most likely estimates of their durations. In the 1980s, Gantt Charts were modified to include links between tasks so that they could also include certain attributes of CPM.

This chapter contains a description of CPM and Gantt Charts. As noted above, Gantt Charts were developed before CPM; however, they are introduced after CPM in this text to allow a more logical development of the concepts. It is these techniques, including PERT, which form the basis of modern project scheduling and control software. Progress can be tracked, assessed and updated at the task level, work package level or project level.

5.3 THE CRITICAL PATH METHOD

As already mentioned, CPM uses a network of arrows and nodes to represent all activities in a project. Two different types of notation are commonly used. These are called activity on node (AON) and activity on arrow (AOA). Either notation can be used to represent the precedence relationships between activities. To illustrate the two notations, consider a simple project consisting of five activities (A, B, C, D and E). Suppose that Activity A must be completed before Activity B can commence, Activity C must be complete before Activity D can commence and Activities B and D must be complete before Activity E can commence. An organisational network for the project using activity on arrow notation is shown in Figure 5.1 (a), while the network using activity on node notation is shown in Figure 5.1 (b).



(a) Activity on arrow notation

(b) Activity on node notation

Figure 5.1 Two types of network notation.

In the AOA notation in Figure 5.1 (a), the arrows represent the activities and the nodes are used to represent the precedence of activities. The nodes are arbitrarily numbered, so that each activity has a unique designation in terms of its start and end nodes. For example, Activity A is designated 1-2, Activity B is designated 2-4 and so on. Starting at node 1, Activities A and C have no preceding activities, so both may commence immediately. Activity B cannot commence until activity A is completed, so its start node is the end node of Activity A. For example, Activity A may represent the construction of footings for a house and Activity B the construction of the walls. In this case, Activity B cannot commence until Activity A is complete.

Similarly, Activity D has its start node (3) as the end node of Activity C. Now, why do both Activities B and D end at the same node? This is a notational convenience that also achieves a compact network, as Activity E requires them both to be completed before it can commence. There are other equally valid ways to draw this diagram that will be described later. Finally, as shown, Activity E can only start after both Activities B and D are complete and it finishes at Node 5. In this network, Node 5 also represents the completion of the project.

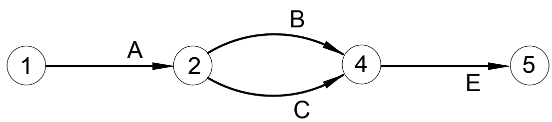
Figure 5.1 (b) shows an organisational network for the same project using AON notation. For this notation, a box represents an activity. There is also a box for the start and finish of the project. Arrows then represent the precedence relationship between activities. From the information provided above, Activities A and C do not need any activities to be completed before they can start. Therefore, they can both commence at the beginning of the project as shown in Figure 5.1 (b). Activity A must be completed before Activity B can commence, so an arrow goes from A to B. Similarly, Activity C must be completed before activity D, so an arrow runs from C to D. As both B and D must be completed before Activity E commences, they both have arrows running into Activity E. Finally the project can end once Activity E is finished.

AOA notation will be used for the remainder of this chapter, as it is more commonly used in practice.

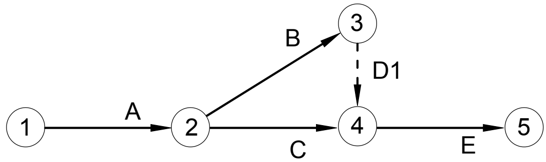
There are four basic rules to observe when constructing AOA organisational networks. These are:

1. the network must have one starting node and one finishing node representing the start and finish of the project, respectively;
2. each activity is represented by a single arrow in the network;
3. before an activity can start, all activities leading to its starting node must be complete; and
4. there can be, at most, one arrow between any pair of nodes in the network.

Rule 4 is required to ensure that each activity is uniquely defined by its starting and ending nodes. On occasions this may require the use of *dummy activities*. These are artificial activities of zero duration that are used purely to maintain the logic of the network. An example of the use of dummy activities is shown in Figure 5.2.



(a) Network that does not satisfy Rule 4



(b) Modified network using a dummy activity

Figure 5.2 Two ways of representing the same organisation network using AOA notation.

For the project shown in Figure 5.2, Activity A must be completed before both Activities B and C can commence. Activities B and C must both be completed before Activity E can commence. Figure 5.2(a) shows both Activities B and C passing from Node 2 to Node 4. This satisfies the precedence rule (Rule 3 above), but does not satisfy Rule 4. Figure 5.2 (b) shows an alternative representation in which a dummy activity, D1, has been introduced. This network satisfies all the given rules.

Dummy activities can also be used to represent the precedence logic in a network rather than specifically to satisfy Rule 4. An example is where there are four activities that form part of the project. These are designated A, B, C and E. Activity A must be complete before Activity C can commence, but Activity E requires both Activity A and B to be complete before it can commence. An organisational network for this project is shown in Figure 5.3. Note that a dummy activity, D1, has been introduced to satisfy the precedence logic.

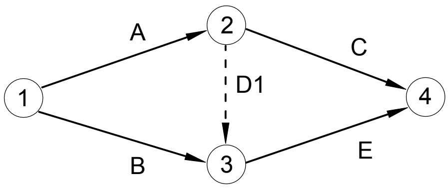


Figure 5.3 Use of a dummy activity to represent precedence logic

Application of the Critical Path Method

The CPM process for project planning involves the following steps:

1. list all activities that form part of the project;
2. estimate the time to complete each activity (called the *duration* of the activity);
3. identify the *precedence* relationships, i.e. for each activity, which other activities must be completed before it can commence;
4. construct the network;
5. analyse the network to identify the earliest start time (EST) and latest finish time (LFT) for each activity;
6. identify the critical path(s) for the network;
7. use the EST and LFT to estimate the latest start time (LST) and earliest finish time (EFT) for each activity;
8. use the EST, LST, EFT, LFT and duration for each activity to estimate its total float, free float and interfering float.

The critical path method will be demonstrated by applying it to a case study. This is the construction of a single span highway bridge over a creek. Simplified design drawings of the bridge are shown in Figure 5.4.

Step 1: List all activities that form part of the project.

An experienced engineer typically prepares the list of activities for the project. The complexity of the project and the level of control required will dictate how the list is provided. The activities can be presented as a sequential list or a hierarchical list. A hierarchical list is referred to as a *Work Breakdown Structure* (WBS) and is used to group similar tasks or activities undertaken by the same contractor. For example, all off-site activities may be grouped together and all on-site activities could also be grouped together. The hierarchical structure can provide added flexibility in relation to the level of detail presented and reported. A basic sequential list is used for this example, with the list of activities given in Table 5.1 The project involves fabricating the steel girders and handrails off-site and then transporting them for installation on site. Concrete will be produced off-site and delivered to the site ready to pour. All other activities will take place on-site.

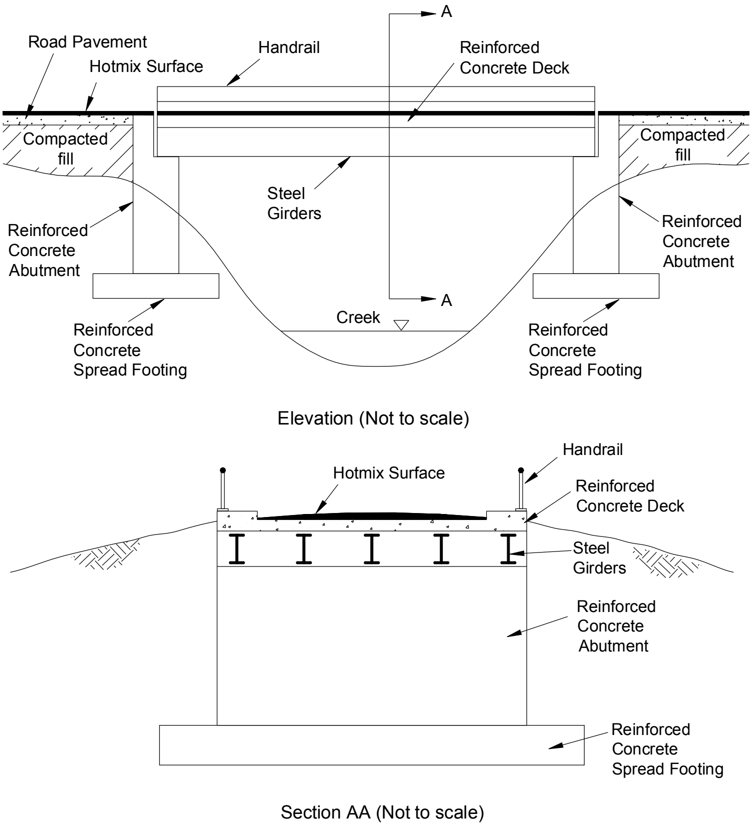


Figure 5.4 Simplified design drawings for a highway bridge.

Step 2: Estimate the duration of each activity.

The durations estimated are given in Table 5.1. These are based on the assumption that adequate equipment and human resources are available on-site to complete the activities without delays. In this simple example many simplifying assumptions have been made. For example, the construction of the foundations, abutments and embankments on each side of the creek would be considered as separate activities, as they may be scheduled to occur simultaneously or in sequence, depending on the available resources. In this case, these items are assumed to be undertaken on both sides of the creek simultaneously. A further practical consideration is the planning involved in transporting major items of equipment to the site and scheduling their usage. Such considerations have been ignored in this simple example in order to demonstrate how organisational networks are developed and analysed.

Table 5.1 Activities involved in the construction of a highway bridge.

Activity	Description	Duration (days)	Preceding Activities
A	Establish site office and transport equipment to site	3	None
B	Remove topsoil	4	A
C	Excavate foundations	3	B
D	Order reinforcement and have it delivered to the site	5	None
E	Place formwork and reinforcement for footings	2	C, D
F	Pour concrete footings	1	E
G	Cure concrete footings	7	F
H	Place formwork and reinforcement for abutments	2	G
I	Pour concrete abutments	2	H
J	Cure concrete abutments	14	I
K	Fabricate steel girders off-site and deliver to the site	21	None
L	Fabricate steel handrails off-site and deliver to the site	10	None
M	Place steel girders	3	J, K
N	Place formwork and reinforcement for concrete deck	3	M
O	Pour concrete deck	1	N
P	Cure concrete deck	14	O
Q	Install handrails	2	L, P
R	Place and compact fill on approaches	21	None
S	Construct pavement on approaches	10	R
T	Place hotmix on approaches and on the bridge deck	3	P, S
U	Replace topsoil and re-vegetate the embankments	5	R
V	Paint the handrails	3	Q
W	Clean up the site	7	T, U,V

Step 3: Identify the precedence relationships.

The relationships determined for this project are given in Table 5.1.

Step 4: Construct the network.

The construction of the network is a relatively straightforward task once steps 1-3 have been completed. However, steps 1-4 can involve several iterations as the process of drawing the network can facilitate thoughts about the activities involved and their inter-relationships and dependencies. The completed network is shown in Figure 5.5.

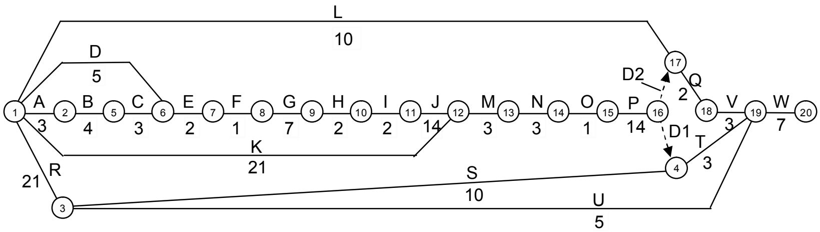


Figure 5.5 Organisational network for construction of the highway bridge.

The network satisfies the four basic rules given in Section 5.3 and includes two dummy activities. The dummy activity, D1, between Nodes 16 and 4 ensures that Activity T (place hotmix on approaches and on the bridge deck) cannot commence until Activity P (cure concrete deck) is complete. The other dummy activity, D2, between Nodes 16 and 17 ensures that Activity Q (install handrails) cannot commence until Activities P (cure concrete deck) and L (fabricate steel handrails off-site and deliver to the site) are complete. Two dummies are required in this instance because Activity Q does not depend on the completion of Activity S (construct pavement on approaches) being complete and Activity T does not depend on Activity L being complete. Some work can be undertaken on the abutments before the concrete of the foundations has reached its design strength so the duration for the curing of the concrete in the foundations has been set at 7 days.

Step 5: Analyse the network to identify the earliest start time (EST) and latest finish time (LFT) for each activity.

The earliest start time (EST) for an activity is the earliest time that it can commence assuming all preceding activities and the overall project starts on time. The latest finish time (LFT) for an activity is the latest time that it can finish without increasing the minimum completion time for the overall project. The EST and LFT are shown on Figure 5.6 with the EST shown in the left-hand box and the LFT in the right-hand box. Typically, the EST and LFT would be documented for each node. In Figure 5.6 this information is presented only at significant nodes for clarity.

The ESTs are calculated in the following way: Begin at the first node (i.e., the node that has no arrows leading into it). In this case this is Node 1. Set the EST at this node to be 0. For each subsequent node the EST is determined by examining all activities leading into the node. For each activity determine the sum of the EST

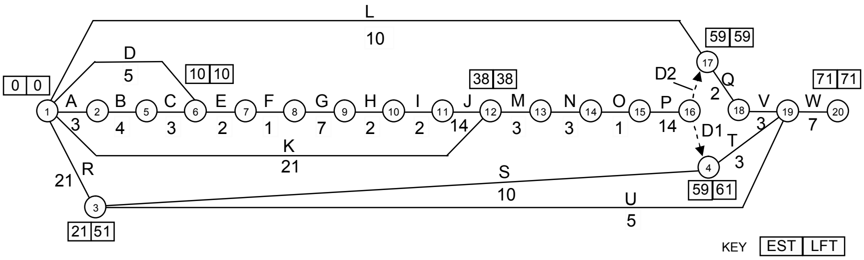


Figure 5.6 EST and LFT for activities involved in the highway bridge construction.

of its start node plus its duration. Take the largest of these values to give the EST at the new node.

For example, Node 2 has only 1 activity (A) leading into it. Clearly the EST at Node 2 is the EST at node 1 plus the duration of Activity A (3 days), thus giving an EST of 3 days at node 2. Similarly, the EST at Node 5 is the EST at Node 2 (3 days) plus the duration of Activity B (4 days) giving 7 days. Node 6 has 2 activities leading into it (C and D). The EST at Node 6 is the larger of the EST plus duration for these 2 Activities. For Activity C, its EST is 7 days and its duration is 3 days giving a total of 10 days. For Activity D, its EST is 0 days and its duration is 5 days, giving a total of 5 days. The larger of these two is 10 days which is, therefore, the EST at Node 6. This clearly must be the case, because no activities starting at Node 6 may commence until all activities feeding into this node have been completed. That is why it is the larger of the two times.

Mathematically, EST at Node j (EST_j) can be determined using the following equation:

$$EST_j = \max_i \{EST_i + D_{ij}\} \quad \text{all } i \in I_j \tag{5.1}$$

where, D_{ij} = the duration of Activity ij; and I_j is the set of all starting nodes that have activities that finish at node j.

The determination of ESTs requires the nodes to be considered in a certain order. For example, the EST at node 4 requires the EST at nodes 3 and 16 be determined first. This can be accomplished by starting at the node that has no activities leading into it and working one at a time to nodes that only have activities with known ESTs coming into them. This can be carried out by observation when working simple examples (such as this one) by hand and is programmed into software used for analysing more complex organisational networks.

Latest Finish Times (LFTs) are determined in a similar fashion by working backwards in time in the following manner: Start at the final node (the one with the largest EST. The LFT at this node is the same as the EST. Then work backwards one node at a time and considering all Activities that commence at the node. The LFT is the *smallest* of the LFT of any Activities that start at the node *minus* their duration. For example, the LFT at Node 20 equals its EST of 71 days. The LFT at Node 19 is the LFT of Activity W (71 days) minus its duration (7 days) and is therefore 64 days. The LFT at Node 4 is the LFT of Activity T (64 days) minus its duration (3 days). It is therefore 61 days.

There are two activities leading from Node 3. Therefore, the LFT at this node is the smaller of the LFT minus the duration for each of these activities. Activity S has a LFT of 61 days and a duration of 10 days and therefore a difference of 51 days. Activity U has a LFT of 64 days and a duration of 5 days and therefore a difference of 59 days. The smaller of the two (51 days) then becomes the LFT at Node 3. Mathematically, the LFT at Node *i* can be determined using the following equation:

$$LFT_i = \min_j \{LFT_j - D_{ij}\} \qquad \text{all } j \in J_i \tag{5.2}$$

where, J_i = the set of all ending nodes that have activities that commence at Node *i*.

As for the EST, the determination of the LFT involves careful selection of the sequence of nodes to be considered. A partial check on the calculations of EST and LFT is provided in that the LFT should be 0 at the first node. Although, if this value is obtained it does not necessarily mean that all values of EST and LFT are correct.

Step 6: Identify the critical path(s) for the network.

The *critical path* is the set of all activities that cannot be delayed without delaying the entire project. There is always at least one critical path from the first node to the last node. There may be more than one critical path in some cases. The minimum time to complete the project is given by the length of the critical path. This is also given by the EST and LFT at the last node.

In the example illustrated in Figure 5.6, the critical path consists of the following sequence of activities: A, B, C, E, F, G, H, I, J, M, N, O, P, Q, V, and W. The minimum time to complete the project is 71 days. It can also be seen that the EST and LFT are the same for all nodes on the critical path.

Step 7: Use the EST and LFT to estimate the latest start time (LST) and earliest finish time (EFT) for each activity.

The latest start time (LST) for an activity is the latest time that it can start without increasing the minimum completion time for the overall project. The earliest finish time (EFT) for an activity is the earliest time it can finish if it and all preceding activities start at their earliest start times.

It should be clear that the LST for each activity is simply its LFT minus its duration. Likewise the EFT for each activity is simply its EST plus its duration. LSTs unlike ESTs are not necessarily the same for all activities starting at the same node in the network. Likewise, EFTs are not necessarily the same for all activities that finish at the same node in the network. The EST, LST, EFT and LFT for all activities in the example are given in Table 5.2.

It should be clear from the definitions that the EST and LST are equal for all activities that are on the critical path. Similarly, the EFT and LFT are also equal for these activities. This is verified by the values given in Table 5.2.

Step 8: Use the EST, LST, EFT, LFT and duration for each activity to estimate its total float, free float and interfering float.

The *total float* (TF) for an activity is the amount of time that the activity can be delayed from its EST without affecting the time to complete the overall project. The total float must be zero for all activities on the critical path. For other activities, it may be determined by computing the difference between the LST and EST. Alternatively, the TF may be determined by computing the difference between the LFT and the EFT for each activity. The TFs for all activities in the example problem are shown in Table 5.2.

Table 5.2 Important times and floats for all activities.

Activity	Duration days	Critical (Y/N)	EST days	EFT days	LST days	LFT days	TF days	FF days	IF days
A	3	Y	0	3	0	3	0	0	0
B	4	Y	3	7	3	7	0	0	0
C	3	Y	7	10	7	10	0	0	0
D	5	N	0	5	5	10	5	5	0
E	2	Y	10	12	10	12	0	0	0
F	1	Y	12	13	12	13	0	0	0
G	7	Y	13	20	13	20	0	0	0
H	2	Y	20	22	20	22	0	0	0
I	2	Y	22	24	22	24	0	0	0
J	14	Y	24	38	24	38	0	0	0
K	21	N	0	21	17	38	17	17	0
L	10	N	0	10	49	59	49	49	0
M	3	Y	38	41	38	41	0	0	0
N	3	Y	41	44	41	44	0	0	0
O	1	Y	44	45	44	45	0	0	0
P	14	Y	45	59	45	59	0	0	0
Q	2	Y	59	61	59	61	0	0	0
R	21	N	0	21	30	51	30	0	30
S	10	N	21	31	51	61	30	28	2
T	3	N	59	62	61	64	2	2	0
U	5	N	21	26	59	64	38	38	0
V	3	Y	61	64	61	64	0	0	0
W	7	Y	64	71	64	71	0	0	0
D1	0	N	59	59	61	61	2	0	2
D2	0	Y	59	59	59	59	0	0	0

The *free float* (FF) for an activity is the amount of time that the activity can be delayed from its EST without affecting the starting times of subsequent activities. Once again, the FF is zero for all activities on the critical path. For non-critical activities, the FF is determined by subtracting its EST and its duration from the EST of its ending node. This can be calculated for all activities using the information contained in Figure 5.6. The FFs for all activities are given in Table 5.2. For example the FF for Activity K is based on the EST at Node 12 (38 days) and the EST at Node 1 (0 days). The FF is the difference between these (38 days) less the duration of the activity (21 days) giving 17 days.

The *interfering float* (IF) for an activity is simply the difference between its TF and FF. These values are also given in Table 5.2. The use of interfering float could delay subsequent activities, although it will not affect the time to complete the overall project.

The TF for Activity K is all FF, as the use of this time will not affect the timing of subsequent activities. On the other hand, the TF of Activity R (30 days) is all IF, as it will reduce the float available to Activities S, T and U if it is utilised by delaying Activity R.

Summary

The construction and analysis of an organisational network can provide very valuable information that is needed to manage major engineering projects. This information includes the following: The minimum total time required to complete the overall project, the activities that cannot be delayed without affecting the total time to complete the overall project, a summary of activities that need to be completed before any particular activity can be started, the earliest start, earliest finish, latest start and latest finish times for all activities and the float time for all non-critical activities (i.e., by how much time they can be delayed without affecting the time to complete the overall project or without affecting the timing of subsequent activities.

Because of its great value, it is common to use an organisational network for all major engineering projects. As previously discussed, CPM provides the basis for modern scheduling software packages.

5.4 GANTT CHARTS

As noted in Section 5.2, a Gantt Chart is an organisational network that represents the timing of activities that make up a project. In a Gantt Chart all activities are listed down the page with each activity having a horizontal bar representing the planned timing of its completion.

Figure 5.7 is a Gantt Chart for the construction of the highway bridge considered in Section 5.3. The shaded bars in Figure 5.7 represent the activities occurring over time (based on their EST), while open bars represent total floats for the corresponding activities. Each activity that has float can be rescheduled within the times represented by the open bar without delaying the overall project (assuming that all other activities run to schedule).

One advantage of a Gantt Chart compared to a critical path network is that the former shows which activities should be running at a particular time (by noting which shaded bars are intersected by a vertical line through the corresponding time). On the other hand it is not usually possible to draw the Gantt Chart without first analysing the relationships between activities using a critical path network in order to determine the EST, LFT and floats for all activities. Furthermore, it is not easy to depict the precedence relationship between activities in a Gantt Chart for complex projects. Although, in theory, vertical lines can be drawn from the end of preceding activities to subsequent activities, this can become very messy and hard

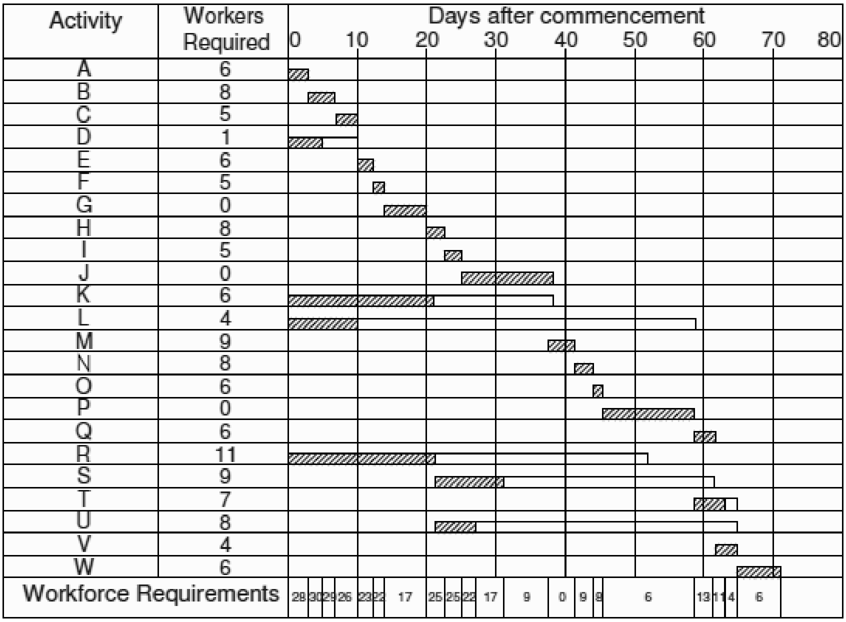


Figure 5.7 Gantt Chart for the construction of a single span highway bridge.

to follow for real projects. Nonetheless, Gantt Charts are commonly used to track the progress of projects (often in combination with critical path networks).

5.5 RESOURCE SCHEDULING

In drawing the organisational networks to date it has been assumed that the only factor that constrains the start and finish of activities is the precedence relationships, i.e., certain activities must be completed before a particular activity can commence. In practice, the availability of critical resources can constrain the timing of activities. These critical resources may be human resources such as the total workforce, skilled labour in particular areas (e.g. steel riggers or electricians) or critical items of equipment (e.g. cranes, bulldozers, graders). Project managers must schedule activities taking these critical resources into account, and, in appropriate cases acquire additional resources by purchase, lease, rent or redeployment from other projects.

A Gantt Chart can be used to indicate the allocation of critical resources on a project (or set of projects). A Gantt Chart together with a critical path network can be used to reschedule activities so that a project can be completed within the resource constraints.

Example

The example of the construction of the single highway bridge (considered earlier) will be used to demonstrate the use of a Gantt Chart to keep track of resources. The critical resource considered is the total labour force. For simplicity it is assumed that all workers on the project are interchangeable and have the same skill set. In reality, there are many different tradesmen and professionals employed on engineering projects. The principles demonstrated in this section can be used for projects with multiple resources.

Table 5.3 shows the estimated workforce requirements for the activities that make up the highway bridge project. Note that Activities G, J and P involve allowing the concrete to cure and do not require significant worker involvement.

The information given in Table 5.3 has been summarised in the bottom row of the Gantt Chart (Figure 5.7) to show the workforce requirements on each day of the project assuming that all activities start at their EST. From the bottom row in Figure 5.7 it can be seen that the workforce for the project (based on EST) starts at 28 workers and builds up to a peak of 30 workers but drops to 9 workers by day 26 and, in fact is 0 workers for some periods of the project. This is unlikely to be optimal. The company carrying out the construction would want to move its workers between projects so that all are fully employed and that no project runs overtime. A common approach is to attempt to "level" or smooth the resources required for any particular project. A trial-and-error process can be used by moving non-critical activities within their allowable times so as to smooth the workforce requirements as much as possible.

An alternative approach is to reschedule the activities so the workforce used on the project stays within a defined cap. For example, suppose that the maximum workforce available for this project is 20. It is desired to reschedule activities so that the workforce requirements stay within this limit and, if possible, the time to complete the overall project does not increase beyond the minimum 71 days. A heuristic approach to reschedule activities is presented by Meredith et al. (1985). The steps presented by Meredith et al. (1985) are as follows:

1. start with the first day and schedule all activities possible, then do the same for the second day and so on;
2. if several activities compete for the resource, then schedule first the one with the smallest float;
3. then, if possible, reschedule activities not on the critical path in order to free resources for the critical path activities.

This heuristic will be applied to the highway bridge project using the data contained within Table 5.3 and Figures 5.6 and 5.7. For simplicity it will be assumed that once an activity commences it cannot be interrupted in order to redeploy workers to other activities. The heuristic can be extended to the case where interruption of activities can occur, although there are usually inefficiencies in redeploying workers between activities due to the start-up time of activities and the need to re-familiarise the workers with the task.

Table 5.3 Workforce requirements for the activities involved in the construction of the highway bridge.

Activity	Description	Workers Required
A	Establish site office and transport equipment to site	6
B	Remove topsoil	8
C	Excavate foundations	5
D	Order reinforcement and have it delivered to the site	1
E	Place formwork and reinforcement for footings	6
F	Pour concrete footings	5
G	Cure concrete footings	0
H	Place formwork and reinforcement for abutments	8
I	Pour concrete abutments	5
J	Cure concrete abutments	0
K	Fabricate steel girders off-site and deliver to the site	6
L	Fabricate steel handrails off-site and deliver to the site	4
M	Place steel girders	9
N	Place formwork and reinforcement for concrete deck	8
O	Pour concrete deck	6
P	Cure concrete deck	0
Q	Install handrails	6
R	Place and compact fill on approaches	11
S	Construct pavement on approaches	9
T	Place hotmix on approaches and on the bridge deck	7
U	Replace topsoil and re-vegetate the embankments	8
V	Paint the handrails	4
W	Clean up the site	6

The process commences at the start of the first day. Five activities could start (Activities A, D, K, L and R). Activity A is on the critical path and so will be scheduled. The total floats for the remaining activities are given in Table 5.4.

Table 5.4 Total floats for non-critical activities that could start on day 1.

Activity	Workforce Requirement	Total Float (days)
D	1	5
K	6	17
L	4	49
R	11	30

As Activity A requires 6 workers, there are 14 available for other activities. The order of priority is Activity D, K, R and L. Activities D and K require a total of 7 workers thus leaving 7. This is not sufficient for Activity R so it will not be started at this time, but L can be, so the scheduled Activities on day 1 are A, D, K and L with a total workforce requirement of 17 workers as shown in Figure 5.8. This process has been set up in the first rows of Table 5.5 and will be repeated as we work through the time schedule of the project.

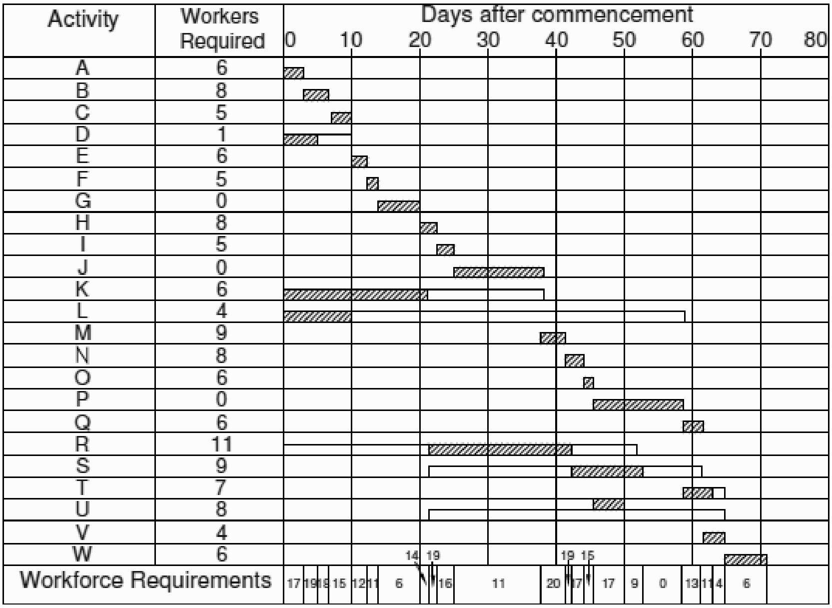


Figure 5.8 Revised Gantt Chart for construction of the highway bridge.

At the start of day 4, Activity A is completed and Activity B (a critical one) is due to start. Activities D, K and L are running and require a total of 11 workers. Activity B (requiring 8 workers) Activity R (11 workers) could be started. As Activity B is on the critical path it is scheduled to start immediately. The total workforce at this time is 19. This process has been continued for the total project. It is summarised in Table 5.5. The revised Gantt Chart is shown in Figure 5.8.

It should be noted that the project can still be completed in 71 days with a workforce of 20 workers compared with a peak of 30 workers using the EST (shown in Figure 5.7). Also note that the organisation network (Figure 5.6) needs to be considered when carrying out the scheduling, for example, Activity S cannot start until Activity R is complete.

Rather than blindly following the steps outlined above, some judgement has been applied in developing the above schedule. For example, Activity R could be scheduled to start at the end of day 13. However, it if did start then Activity H (which is on the critical path) could not start at the end of day 20 as only 3 workers would be available (Activity K and R would be active). This would delay the completion of the project as a whole. Therefore, Activity R has been delayed until the end of day 21.

Table 5.5 Scheduling of activities to match a resource constraint.

Time (end of day)	Activities in Progress	Workforce Committed (Available)	Possible New Activities	Workers Required	Total Float (days)	Activities Scheduled
0	None	0 (20)	A	6	0	A
			D	1	5	D
			K	6	17	K
			L	4	49	L
			R	11	30	
3	D, K, L	11 (9)	B	8	0	B
			R	11	27	
5	B, K, L	18 (2)	R	11	25	None
7	K, L	10 (10)	C	5	0	C
			R	11	23	
10	K	6 (14)	E	6	0	E
			R	11	20	
12	K	6 (14)	F	5	0	F
			R	11	18	
13	K	6 (14)	G	0	0	G
			R	11	17	
20	G	6 (14)	H	8	0	H
	K		R	11	10	
21	H	8 (12)	R	11	9	R
22	R	11 (9)	I	5	0	I
24	R	11 (9)	J	0	0	J
38	R	11 (9)	M	9	0	M
41	R	11 (9)	N	8	0	N
42	N	8 (12)	S	9	9	S
			U	8	17	
44	S	9 (11)	O	6	0	O
			U	8	15	
45	S	9 (11)	P	0	0	P
			U	8	14	U
50	P, S	9 (11)	None			None
52	P	0 (20)	None			None
59	None	0 (20)	Q	6	0	Q
			T	7	2	T
61	T	7 (13)	V	4	0	V
62	V	4 (16)	None			None
64	None	0 (20)	W	7	0	W

Resource Smoothing

In the above example, the peak workforce was limited to 20 workers. The question arises as to what is the minimum peak workforce requirement that does not result in the project being delayed. This can be determined using the above procedure and progressively reducing the limit on the workforce until the time to complete the overall project is increased. Careful examination of Figure 5.8 indicates that a workforce of 20 workers is required from the start of day 39 until the end of day 41. This cannot be reduced without delaying the overall project, so 20 is the minimum workforce to complete the project in minimum time. Of course, if the available workforce is less than this (say 17 workers), the above procedure can be used to schedule activities so that the project finishes in the minimum possible time (which in this case will be more than 71 days). Then a decision will need to be made as to whether it is better to accept this delay in the completion of the project or to hire additional workers.

5.6 SUMMARY

Project planning may be defined as "the process used to implement a plan and hence to achieve a designated objective, through the efficient use of available resources. It involves the regular monitoring of progress and the scheduling of activities as appropriate to achieve the objective in the required time frame." It has existed as a science since the late 19th Century.

A number of techniques exist to assist in scheduling the activities of complex engineering projects. One of the most commonly used techniques today is the critical path method (CPM). CPM can be used to estimate the total time to complete a complex engineering project as well as the earliest start time for each activity that forms part of the project. CPM can also be used to identify which are the critical activities (i.e., those whose delay will result in a delay to the overall project). The total float for each activity is defined as the amount of time that the activity can be delayed without affecting the duration of the overall project. The total floats for all activities can be determined using the CPM technique. Free float is another attribute of each activity that can be determined using the CPM. It is defined as the amount of time that the activity can be delayed without affecting the timing of subsequent activities.

An older technique for scheduling activities that is still used today is called a "Gantt Chart." It is difficult to depict all of the precedence relationships between activities on a Gantt Chart. A Gantt Chart together with a CPM diagram for a project can be used to reduce the peak workforce requirement of a project.

PROBLEMS

5.1 A swimming pool is to be constructed in the backyard of a house as shown in Figure 5.9. The pool will be 3 m by 1.5 m in plan and range in depth from 2.4 m at one end to 1.0 m at the other. It will be constructed of reinforced concrete and covered in ceramic tiles on the top and inside. Access to the site will be via a driveway, but the carport will need to be dismantled to allow access for earthmoving equipment. Assume that you are the contractor who will construct the pool from a complete set of plans and specifications. Make a list of the activities involved and draw up an organisational network that shows the interdependencies between them.

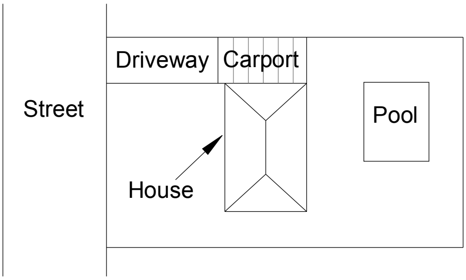


Figure 5.9 Site of a proposed swimming pool.

Table 5.6 Activities involved in constructing a steel frame building.

Activity Number	Description	Duration (days)	Preceding Activities	Number of People
1	Establish site office	3	None	3
2	Clear topsoil from site	3	1	6
3	Order steelwork	2	None	1
4	Fabricate steelwork offsite	14	3	8
5	Deliver steelwork to the site	2	1,4	4
6	Order steel reinforcement	2	None	1
7	Fabricate steel reinforcement offsite	7	6	6
8	Deliver steel reinforcement to site	1	1,7	2
9	Deliver cladding to site	1	1	2
10	Excavate for foundations and floor slab	4	2	7
11	Place reinforcement for foundations and floor slab	4	8,10	6
12	Pour concrete in foundations and floor slab	2	11	6
13	Cure concrete	7	12	0
14	Erect steelwork	8	5,13	10
15	Place cladding on steelwork	4	9,14	5
16	Complete internal fit out of the building	6	15	8
17	Clean up site	2	16	4
18	Remove site office	1	17	3

5.2 Table 5.6 contains a list of activities associated with the construction of a steel frame industrial building.

(a) Draw an organisational network for this project.
(b) Determine the earliest start time (EST) and latest finish time (LFT) for each activity.
(c) Determine the critical path and the minimum time to complete the project.
(d) If Activity 4 is delayed by 7 days, what will be the delay in the total project?

5.3 The organisational network for an engineering project using arrow notation is shown in Figure 5.10. The duration of each activity in days is indicated in the figure. Compute the following for each activity: earliest start time, latest finish time, latest start time, earliest finish time, total float, free float and interfering float. Also determine the critical path and the minimum time to complete the project.

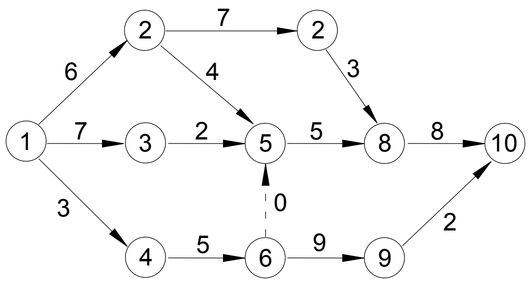


Figure 5.10 Organisational network for an engineering project.

5.4 Draw a Gantt Chart for the project described in Question 5.2 assuming that each activity commences at its earliest start time. Determine the total float, free float and interfering float for each activity.

5.5 Table 5.6 contains an estimate of the number of people required to carry out each activity.

a) Using the Gantt Chart developed in Question 5.4, estimate the peak workforce requirement for the project assuming that all activities commence at their earliest start times.
b) If the available workforce is limited to 16 people who can carry out any of the activities associated with the project, reschedule activities so that the project can be completed in the minimum possible time.

REFERENCES

Archibald, R.D. 2003, *Managing High-Technology Programs and Projects.* Third Edition (New York: John Wiley & Sons).

Burke, R. 2001, *Project Management. Planning and Control Techniques* (Chichester, UK: Wiley & Sons Ltd).

Faniran, O. 2005*, Engineering Project Management* (Pearson Education Australia).

Griffis, F.H. and Farr, J.V. 2000, *Construction Planning for Engineers* (Boston USA: McGraw-Hill).

Hyman, B. 1998, *Fundamentals of Engineering Design* (Upper Saddle River, New Jersey: Prentice –Hall, Inc.).

Meredith, D.D., Wong, K.M., Woodhead, R.W. and Wortman, R.H. 1985, *Design and Planning of Engineering Systems, Second Edition* (Englewood Cliffs, New Jersey: Prentice –Hall, Inc.).
Shtub, A., Bard, J.F. and Globerson, S. 2005, *Project Management. Processes, Methodologies and Economics* (Upper Saddle River, New Jersey: Pearson Education Inc.).