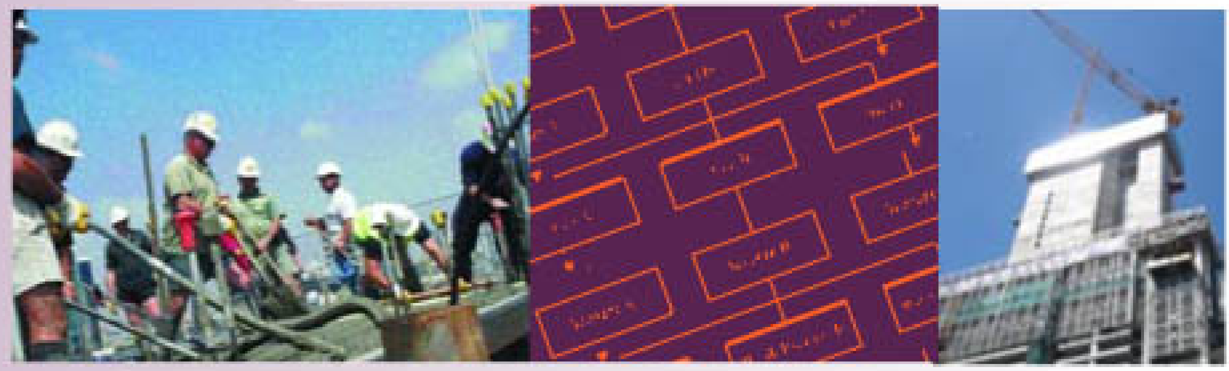
CONSTRUCTION MANAGEMENT



THOMAS E UHER

PROGRAMMING AND SCHEDULING TECHNIQUES

UNSW PRESS

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Thomas E Uher

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PREFACE

Planning is an important management function and its effective execution is a condition precedent for successful project outcomes. This book addresses operational rather than strategic aspects of planning of construction projects. It describes specific scheduling techniques and processes commonly used in the construction industry. While used mainly at the construction stage, the described techniques and processes are suitable for application across all the stages of the project life cycle.

Many books have been written on aspects of construction scheduling, but they largely focus on the critical path method and do not provide a comprehensive review of a range of scheduling techniques. This book attempts to redress this problem.

While this book serves as a reference for construction industry practitioners, it has mainly been written as a text and reference material for students studying architecture, building, construction management and civil engineering, and for quantity surveying undergraduate and postgraduate programs.

The bulk of the book describes deterministic scheduling techniques, but the last two chapters introduce the concept of probability scheduling using Monte Carlo simulation and PERT. The book examines scheduling techniques such as the bar chart, critical path method, multiple activity chart and line of balance. It includes a brief chapter on critical chain scheduling and describes its main features. Although not a scheduling technique, work study has nevertheless been included since it assists planners and project managers in developing efficient production methods. Practical exercises at the ends of chapters have detailed solutions posted on the UNSW Press website:
http://www.unswpress.com.au

T.E. Uher

ABBREVIATIONS

ACWP	Actual cost for work performed
AS	Activity slack
BAC	Budget at completion
BCWP	Budget cost for work performed
BCWS	Budget cost for work schedule
CCM	Critical chain management
CCS	Critical chain scheduling
CIM	Control interval and memory
CPI	Cost performance index
CPM	Critical path method
CV	Cost variance
DEP	Department
EAC	Estimate at completion
EFD	Earliest finish date
ES	Event slack
ESD	Earliest start date
ESTM	Estimating department
EV	Earned value
FF	Free float
FTS	Finish-to-start
FTF	Finish-to-finish
ID	Identification code
LSD	Latest start date
LFD	Latest finish date
LOB	Line of balance
LSM	Linear scheduling method
LSMh	Linear scheduling model
MAC	Multiple activity chart
MAX	Maximum
MBO	Management by objectives
MIN	Minimum
PC	Percentage complete
PERT	Program evaluation and review technique
RPM	Repetitive project modelling
RUF	Resource utilisation factor
SPI	Scheduled performance index
STS	Start-to-start
STF	Start-to-finish
SV	Scheduled variance
TF	Total float
TOS	Theory of constraints
VPM	Vertical production method
WBS	Work breakdown structure

CHAPTER 1

THE CONCEPT OF PLANNING

INTRODUCTION

The purpose of this chapter is to introduce the concept of planning, and in particular operational planning. A systematic approach to planning will be discussed first, followed by a brief review of different types of planning activities such as strategic, operational and co-ordinative. A range of planning tools and techniques will then be examined, followed by a discussion on important issues relevant to planning of construction projects. In particular, the distinction will be made between time and resource scheduling. In the next section, an overview of specific planning tasks employed in individual stages of the project life cycle will be given. Finally, examples of plans, programs and schedules used in the construction industry will be illustrated.

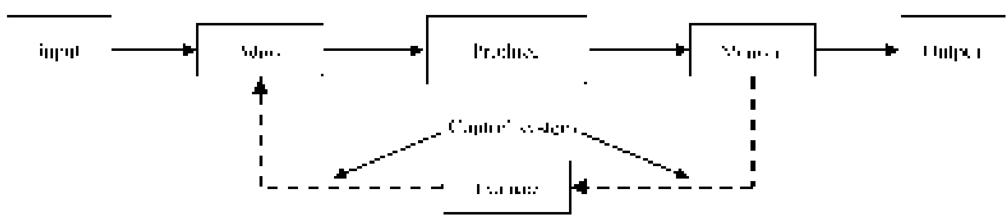
Planning is one of the four main functions of management. Together with organising, control and leading, it forms the foundation pillars of effective management (Robbins et al. 2000). In simple terms, planning is a process of forecasting future outcomes that may be uncertain or even unknown. It means assessing the future and making provision for it by gathering facts and opinions in order to formulate an appropriate course of action. Planning thus develops a strategy and defines expected outcomes (objectives) for undertaking a specific task before committing to such a task.

Once a planning strategy has been determined and objectives defined for a specific task, the manager will select and allocate necessary resources for carrying out the work. This is referred to as 'organising'. It is the second of the four most important management functions.

Because a plan is only a forecast of some specific future events whose outcomes are uncertain, it would be unreasonable to expect it to be accurate. Realistically, the manager must expect the actual progress to deviate from the plan. Accepting that some deviation will occur, the manager will look for it by monitoring the progress, evaluating deviations from the plan and replanning accordingly. This process is referred to as ‘control’. It is the third of the four important management functions.

Planning, organising and control functions are closely linked within a typical production process. This is illustrated graphically in Figure 1.1.

Figure 1.1 A typical production process



Planning is the foundation stone of control. It would be pointless to develop a plan if there was no attempt to control its implementation. Effective control of the production process involves its continuous monitoring, evaluation and adjustment. The control process needs to be dynamic to reflect changing circumstances caused by issues such as:

- fluctuations in the level of demand and sales
- availability of resources
- changes in the level of economic activity
- changing strategies of competitors.

PLANNING PROCESS

If the main focus is to generate profit and increase it annually, the organisation would regard profitability as its objective and would develop appropriate strategies for achieving it. Construction projects are no different. They are expected to be completed on schedule, within the cost budget and to the required quality standards. These are the most common objectives of projects.

Establishing objectives is the first step in a typical planning process. Other steps are (Fulmar 1983):

- forecasting
- examining resources
- establishing policies
- developing alternatives
- creating procedures and rules
- establishing budgets
- establishing timetables
- determining standards.

These planning steps will now be briefly discussed.

Setting objectives

Planning begins by setting objectives and defining strategies for achieving them. It occurs at each organisational level and leads to the development of a comprehensive hierarchy of strategies and actions relevant to the whole organisation as well as to its individual levels of activity.

Planning across the entire organisation is a complex, systematic process that requires careful co-ordination and integration of a wide range of activities. At the top are the objectives of the organisation as a whole. These are broken up from the top down into a set of objectives relevant for each level of organisational activity.

The overall organisational objectives may often be vague. Becoming the market leader, increasing profitability, providing the best customer service or promoting best practice serve as examples of organisational objectives that illustrate the degree of their generality.

As organisational objectives are passed down the line, they usually become more specific. For example, objectives of the construction department of a building contractor might be to improve the tender success rate, deliver construction projects ahead of time or improve people's skills. At a project level, objectives become quite specific. For example, in the project period they define its cost and the required quality standards. They may also define safety performance and the maximum permissible level of contractual and industrial disputes. With such specific objectives in place, the project manager is able to assess the actual level of progress and performance.

In setting objectives, particularly those at the organisational level, the company's management need to take a broader view of objectives by asking themselves what business they are in and what their customers really pay them for. If, for example, Hewlett-Packard, which is better known for producing office machines, had not defined its business as 'supplying information', its growth could have been inhibited in the fast-expanding field of information technology.

Similarly, in setting their own objectives, subordinate managers need to identify what the organisation really wants from them and from their functional units or projects. This process will ensure that objectives are correctly defined and properly integrated across the entire organisation. They will then form an integrated network or 'a means-ends chain' (Robbins et al. 2000: 260) where the objectives at a lower level (referred to as means) need to be satisfied if the objectives at the next higher level (referred to as ends) are to be met.

Setting objectives from the top down has an advantage in that subordinate managers know what they need to achieve within their sphere of responsibility. Sometimes, however, managers down the line may become frustrated when their input is not sought from above in setting the objectives. This may impact negatively on managers' motivation and lead to inefficiency.

The ideal scenario is when managers down the line are asked to contribute to setting objectives and the formulation of plans for reaching them. For example, state managers of a construction company may be required to forecast the future volume of work in their respective states and suggest strategies for increasing turnover. This information would help top management in developing the overall corporate objectives. When objectives are set jointly by subordinates and their superiors across different levels of organisation, and rewards allocated on the basis of achieving progress, management practice is referred to as 'management by objectives' (MBO). It is a popular and well-established system for setting objectives and ensuring their successful accomplishment (Robbins et al. 2000).

Forecasting

Forecasting is the estimation of future controllable and uncontrollable events and opportunities pertinent to an organisation's business activities. It involves systematic assessment of future conditions, such as economic climate, political and social issues, future demand for goods and services, changes in the population growth, and the like.

Forecasts are by their nature always wrong. It is therefore the manager's task to continually revise and update the information that the manager uses in decision-making.

Examining resources

The achievement of objectives is largely dependent on the correct allocation of resources in the form of people, materials, plant, equipment and money. Time may also be regarded as a resource.

Even well-defined plans may go astray. When, for example, a project falls behind its schedule and the project manager is unable to speed it up by simply making the committed resources work harder or by improving the work method, often the only remedy available is to inject additional resources. These, however, may not be available when needed, or may not have the required skill or capacity. Furthermore, the cost of injecting additional resources may be prohibitive, particularly in the case of heavy plant or equipment. The manager's task is to allocate enough resources to achieve the given objectives and to make contingency plans for securing additional resources for times when they might be needed.

Establishing policies

Policies are guides for thinking. They govern the execution of activities within an organisation. They are the foundation of an organisation. 'Policy is a broad pathway within which the worker moves toward an objective' (Fulmar 1983: 103). The recruitment policy and the promotion policy serve as examples of typical organisation policies.

Organisations form their own policies, but sometimes policies are imposed by external sources such as governments. The NSW Government policy on tendering (NSW Government 1996) is an example of an externally imposed policy on organisations bidding for government work.

Developing alternatives

No planning task is accomplished without the development of plausible alternatives. All possible courses of action need to be identified and evaluated, even those that may appear to be unusual or even ridiculed by some. It may well be that the most unusual alternative will provide the best solution for achieving the objectives.

Creating procedures and rules

Within the bounds of the organisation's policies, procedures and rules provide a precise recipe for the manager to follow in taking action. Procedures define a logical sequence of steps to be followed in decision-making. Rules are agreed to in advance. They define specific conditions of various procedural steps. For example, a contractor has a policy for awarding work to subcontractors on the basis of competitive tendering. The tendering procedure then defines, step by step, the contractor's approach to administering competitive tendering to subcontractors. One of the rules defined in the tendering procedure may be that tenders must be sought from at least three subcontractors per trade contract.

Establishing budgets

The purpose of budgets is to work out beforehand an expected outlay of resources necessary for the accomplishment of the objectives. Depending on the planning task, budgets may be expressed in financial terms, which is the most common form, or in some other terms, such as labour hours or the volume of materials installed.

Budgeting is both a planning and a control task. The accurate knowledge of where the resources have actually gone to is essential in measuring efficiency in the production process. It also assists in future planning.

Establishing timetables

Like cost and other resources, time is an important element in planning. Practically all planning tasks are constrained by time. There is almost always a deadline for accomplishing the work.

In the absence of any time constraints, a manager would be able to establish the completion date of a project from the planned quantity of work and the required level of resources employed to carry out the work. However, most construction projects are rigidly constrained by time. Delays in completion have serious financial implications for the parties concerned. The development of a project schedule often requires the project manager to plan from the end, that is, from the deadline set for the completion of the project. In such situations, the planning task is focused more on fitting all the required work and the necessary resources into a rigid time-frame, which often results in inefficiencies and high cost, rather than on developing a plan optimised in terms of time, cost and other resources.

Determining standards

Since a plan is an essential element of control, it must be developed so as to permit assessment of progress and performance in terms of time, cost, the use of resources and the like.

Reviewing

Before a plan for a particular task is finalised and implemented, the manager will review the plan and critically reassess the overall planning strategy, particularly sequences, methods, resources and budgets.

Implementing

No matter how good the plan is, its effectiveness will ultimately depend on the degree of commitment the organisation's personnel give it. The starting point in developing the required degree of commitment is to involve those people who are going to be affected by the plan in its development. If the plan requires the adoption of new processes or techniques, people involved in such processes may need to improve their existing skills or acquire new ones through training.

TYPES OF PLANNING ACTIVITIES

Planning occurs at all levels of an organisation, but the emphases vary from level to level. At the highest level is the 'strategic planning' that determines an overall business strategy such as mission and objectives. At lower levels, 'operational' and 'co-ordinative' planning activities take place.

Strategic planning

Strategic planning is defined by Bryson & Alston (1996: 3) as 'a disciplined effort to produce fundamental decisions and actions that shape and guide what an organisation is, what it does, and why it does it'. While the definition suggests that an organisation is an ongoing corporate entity, the concept of strategic planning is equally relevant to an organisation of a limited life span, such as a construction project organisation.

Strategic plans are long-term, covering a period of up to three years. They include the formulation of a statement of mission, objectives, and broader strategies for accomplishing the stated objectives.

Operational planning

In comparison to strategic plans, operational plans are medium to short-term with a time-scale defined in days, weeks or months. The main purpose of operational plans is to develop detailed strategies for achieving specific objectives. Construction schedules are an example of operational plans.

Co-ordinative planning

Co-ordinative planning establishes policies, procedures, rules, tactics and strategies through which strategic and operational planning are linked together. A risk management plan or a quality management plan are examples of co-ordinative planning.

PLANNING TOOLS AND TECHNIQUES

Numerous planning tools and techniques have been developed to assist managers with planning. A comprehensive description of planning tools and techniques can be found in Robbins and colleagues (2000). Some of these will now be briefly reviewed.

Environmental scanning

Environmental scanning is a systematic screening of information from which the manager is able to detect emerging trends. In some industries such as IT, advances in technology are rapid. Managers need to be constantly on the alert for new advances and trends that could maintain or improve their organisation's competitiveness. The most commonly used techniques are competitor intelligence, global scanning and scenario building.

Forecasting

Forecasting assists the manager to predict future outcomes. This topic has already been briefly discussed on page 4.

Benchmarking

'Benchmarking is the comparison of practices either between different departments within the company, or with other companies in the same industry, or finally with other industries' (McGeorge & Palmer 1997: 81). The aim of benchmarking is to search for the best practice in order to achieve superiority among competitors. It has become a popular and a widespread technique across many industries, including construction.

Budgeting

Budgets were defined on page 6 as plans for allocating resources to specific activities that would be performed by an organisation in its attempt to attain objectives. Budgets are formed for many different items or areas of activities, examples of which are revenue, expense or capital expenditure budgets.

Operational planning tools

Operational planning tools are used by managers in day-to-day problem-solving. This may involve scheduling of work using bar charts or the critical path method, allocating and levelling resources using linear programming, predicting profitability through, say, break-even analysis, assessing cost performance by way of earned value, and assessing risk in decision-making through the concept of risk management. There are other techniques such as queuing theory, marginal analysis and simulation that assist managers in decision-making.

This is the area of planning that this book addresses. The following chapters will discuss several operational planning tools used in planning and controlling construction projects.

PLANNING OF CONSTRUCTION PROJECTS

The foregoing discussion has addressed the general principles of planning that can be applied in any organisation. Since the main purpose of this book is to examine the scheduling of construction projects, the focus of discussion will now shift to important issues pertinent to the planning of construction projects.

A project can be said to be a particular and unique form of organisation with a limited lifespan. It exists for a finite period only: the achievement of its objective means that it comes to an end. An important characteristic of projects is that they are driven by objectives that are defined at the start. The project manager assumes overall responsibility for the project and leads the project team.

Between their beginning and their ending, projects pass through a series of stages commonly known as the 'project lifecycle', through which a project is conceived, designed, constructed and commissioned. Planning activities that take place in individual stages of the project lifecycle will be discussed later in this chapter.

Definition of planning terms

Although the terms 'planning', 'programming' and 'scheduling' are generally used indiscriminately, they are fundamentally different from each other. Using a top-down hierarchical approach, 'planning' sits at the top. It is the overall approach to predicting a future course of action. ‘Programming’ is placed in the middle. It is the name given to the task of identifying activities, establishing relationships, and developing logical sequences among such activities that would depict their order of execution. ‘Scheduling’ sits at the bottom. It is a process of quantifying the program. This involves, for example determining times and costs of activities, and the efficiency of allocated resources.

For the sake of simplicity and clarity, no distinction will be made between the terms ‘programming’ and ‘scheduling’ in this book. But a distinction will be maintained between ‘planning’ and ‘scheduling’.

‘Construction planning’ may refer to a range of tasks concerned with determining the manner in which a job is to be carried out: budgeting, forecasting, preparing feasibility studies, or creating construction schedules. ‘Construction scheduling’, however, is concerned only with sequencing and timing of activities in a particular production process.

Hierarchy of plans and schedules

A well-planned construction project will use a series of plans and schedules. There will be those that show the planned use of time, such as bar charts or critical path schedules. There will also be those that show planned use of other important resources such as labour, materials, plant and money. These will be prepared in the form of schedules, charts, graphs or histograms, with close attention paid to their co-ordination and integration.

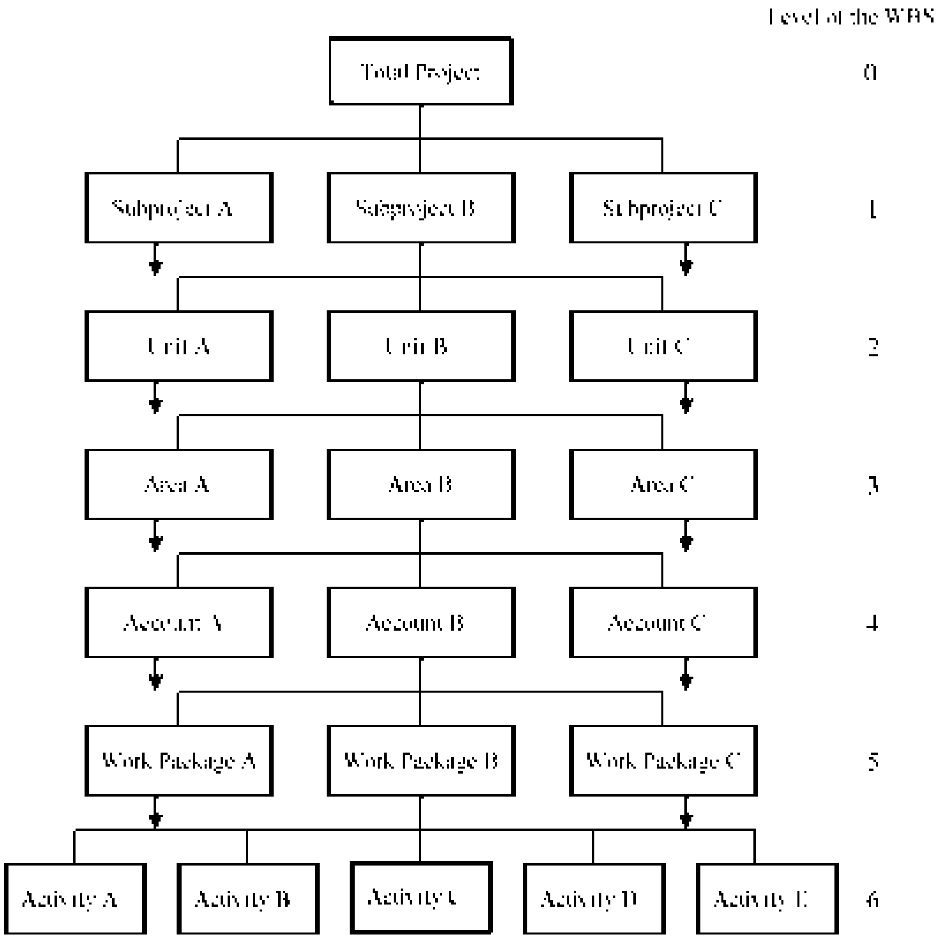
While in theory it is possible to prepare a schedule for a large project that would show activities across all its lifecycle stages in great detail (for example charting each day), in practical terms such a schedule would be too large, too complex and probably unworkable. There is ample anecdotal evidence of schedules that cover the entire wall space of site offices. Such schedules are better suited for interior decoration of offices than for managing construction projects.

Clearly, it is necessary right from the beginning to agree on a hierarchical system of schedules for a given project. This is achieved using a ‘work breakdown structure’ or WBS.

The WBS assists in breaking down the total scope of the project into subsystems, elements and activities related to its design and construction. Typically, the project is divided hierarchically into five or six levels to show the required degree of detail and to ensure that every important aspect of the project has been identified. A typical example of a WBS is given in Figure 1.2 where

‘Subproject A’, for example, may involve the development of a brief, ‘Subproject B’ refers to the process of design and documentation, and ‘Subproject C’ represents construction of the project. Lower levels of WBS define project tasks in more detail.

Figure 1.2 WBS of a project (from Hamilton 1997: 86)



Once the WBS has been defined, scheduling of the work begins for each level. The format of schedules developed at each level of the WBS is likely to vary, as will the amount of detail shown. Those prepared to higher levels of the WBS will show a graphic overview of the total project period with only major work sequences, while the amount of detail will increase for lower-level schedules.

The program hierarchy becomes the basis for planning of work activities, monitoring and evaluating their progress, and exercising control. At the top is a long-term schedule for the entire project. Its time-scale will commonly be in weeks or months and will show the overall strategy for the job. Specifically, it will show the start and completion of each project stage, major activities and their interdependencies, the key resources needed and the provision for delay contingency. It also shows the key target dates that must be met across the entire project lifecycle. Depending on the size of the project and its overall period, it may well be that more than one long-term schedule will be prepared. For example, for the project in Figure 1.2 the total of four long-term schedules may be prepared, one for level 0 and three for level 1 of the WBS.

A 'medium-term' schedule is prepared next. It commonly shows a period of 8–12 weeks of work within the overall long-term schedule. It is more detailed than a long-term schedule and commonly shows work tasks on a weekly scale. For the project in Figure 1.2, three medium-term schedules would be prepared for level 2 of the WBS.

A 'short-term' schedule shows the greatest level of detail, such as resources. The main activities are broken down into sub-activities in order to determine the extent of resource requirements. A short-term schedule commonly shows between one- and four-week production periods and its scale is in days. Because the main resources have already been committed, the task is then to allocate the work to the committed resources. Short-term schedules are thus said to be resource-driven.

A short-term schedule may further be broken down into a series of 'daily schedules' for specific tasks. A daily schedule would simply list activities to be performed in one day together with their durations expressed in hours. Alternatively, a simple bar chart can be used for this purpose.

An overall long-term schedule is a reference point for schedules on the next lower level of WBS, which in turn becomes a reference point for schedules on levels further down.

The concept of scheduling

Scheduling involves answering the questions, such as 'When can the work be carried out?' 'How long will it take?' and 'What level of resources will be needed?' Scheduling is concerned with sequencing and timing. Since time is money, it is also concerned with cost.

Scheduling is performed using appropriate operational planning tools such as a bar chart or the critical path method. Scheduling is a modelling task that assists in developing a desired solution for a problem and tests its validity. Through modelling, the physical size of a problem (say the development of an overall construction schedule for a large project) is scaled down to a smaller number of representative activities that are then scheduled by an appropriate scheduling tool. The solution is checked and validated for accuracy. The derived schedule is used to plan, organise and control construction of the project.

To check time progress, individual parts of the job are tracked to determine if they are completed within the specified time limits. Such information is then analysed to determine where the problems are.

The most common form of a model in scheduling is a graphic chart or network generated either by hand or by computer. The form and shape of a chart varies from technique to technique. For example, a sheet of paper lined with columns and rows represents a bar chart format, while charts generated by the critical path method are rather more complex and are commonly referred to as networks (see for example Figures 3.7 or 3.14 in Chapter 3).

Types of schedules

This book makes reference to three types of schedules:

- a time schedule
- a resource schedule
- a target schedule.

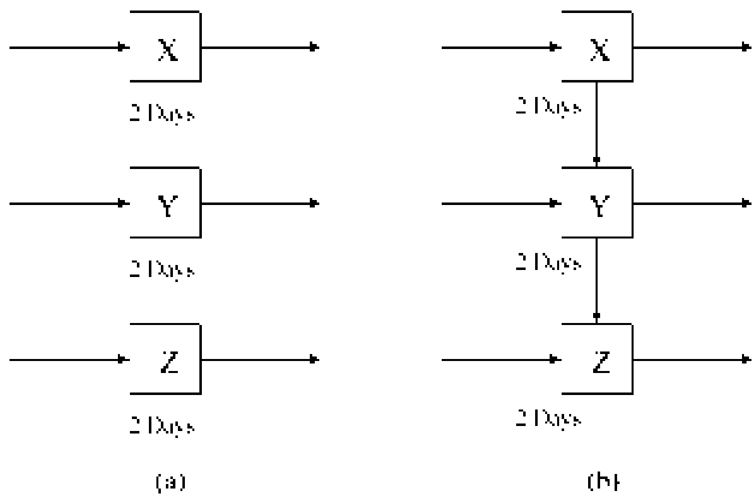
Time schedule

Sometimes a schedule may be prepared to show a logical sequence of activities with only notional information about duration of activities. The main aim would be to see the logic of the production process and its approximate duration. Schedules produced for this purpose are referred to as 'time schedules'.

A time schedule is prepared on the assumption that its activities will be given all the required resources when needed. In other words, time scheduling assumes that resources are unlimited and available when needed. This is an unrealistic assumption, however, since resources may simply be unavailable when needed, or available in limited quantity, size and type or technical specification. Furthermore, the assumption of unlimited resources will lead to inefficient allocation of resources and the likelihood of higher cost. This is illustrated in the following example.

Let's focus on just three concurrent activities X, Y and Z in a schedule in Figure 1.3(a). Assume that the three activities X, Y and Z take two days each to complete. Let's assume further that each of the three activities requires access to a crane for two days. Under the assumption of unlimited resources, a project manager could order three cranes, one for each activity. The three activities X, Y and Z would then be completed in two days.

Figure 1.3 Example of time and resource schedules



Time schedules are useful in developing an overall strategy within a broadly defined time-frame. But since they assume that resources are readily available when needed, they may not create a realistic plan of the actual production process. More realistic planning can be achieved using resource schedules.

Resource schedule

When resources are limited in availability, technical specification, cost or some other means, those resources that are actually available then drive the scheduling task. For example, a very large high-rise project may require a crew of 2000 workers to be employed at the peak of activities. With such a large number of people working on the site, part of the project manager's task will be to ensure that the site provides the required volume of site amenities, the necessary safety equipment for the workers, and that the workers can be moved efficiently through the structure to their work stations. It may well be that the site is too confined to provide the necessary volume of amenities for so many workers. The site may also be too confined to accommodate a sufficient number of personnel hoists that would ensure speedy distribution of workers to their stations. The project manager may respond by limiting the number of workers engaged on the site (say 1200 maximum) to match available resources. The project manager will then schedule the work around the maximum number of 1200 workers. This approach ensures that resources are used efficiently, but the project will take longer to complete. A schedule based on the available or committed resources (in this case based on the maximum of 1200 workers) is referred to as a 'resource schedule'.

In resource schedules the work to be accomplished is assigned to available or committed resources. When the volume of resources is insufficient to carry out the work that has been scheduled, the project manager would need to either inject more resources or reschedule the work to free over-committed resources. Injecting additional resources is likely to incur extra cost while keeping to the same schedule. Rescheduling the work around committed resources will most likely extend the project period and possibly even its cost. In organising resources in the planning stage, the project manager has the opportunity to seek an optimum relationship between the cost and time of the project. But once the project is under way with committed resources, it is not possible for the project manager to keep the cost and time at optimum when the committed resources are insufficient to carry out the scheduled volume of work. The project manager then has either to inject more resources or to reschedule the work. Neither scenario is desirable since this is likely to increase the project cost and extend its duration.

Let's go back to the problem in Figure 1.3 and assume that only one crane is available for the scheduled work involving activities X, Y and Z. Clearly, these activities cannot be performed concurrently as scheduled. The project manager would need to allocate the only available crane to one activity at a time in some order of priority. Let's assume that the order is X, Y and Z. The completion of all three activities, X, Y and Z, will now take six days as illustrated in Figure 1.3(b). In both (a) and (b), the total volume of work will be the same: six crane days. But the completion times and costs will be different. The difference in completion times is clearly apparent, but why would the costs be different? Since time is money, the former case would incur lower overhead costs due to a shorter schedule, but the cost of assembling and dismantling the cranes would be higher than in the latter case.

In summary, the concept of time scheduling requires the project manager to vary the volume of resources to meet work demands. This means bringing in additional resources such as plant/equipment and people to satisfy short-term peaks in resource requirements, and removing them when they are no longer required. Apart from the extra cost associated with bringing resources in and taking them away, there is an additional administrative cost associated with planning, organising and controlling such activities.

An important observation here is that time schedules are likely to provide an overly optimistic assessment of the project period. For example, a contractor who has won a tender on the basis of a time schedule runs a serious risk of either delaying the contract due to having insufficient resources at certain times, or spending money on additional resources that must be injected to keep the project on schedule, or both.

Clearly, control of time and cost are more likely to be achieved using resource-based scheduling. The process of managing resources, particularly in terms of allocation and levelling, will be discussed in detail in Chapter 4.

Target schedule

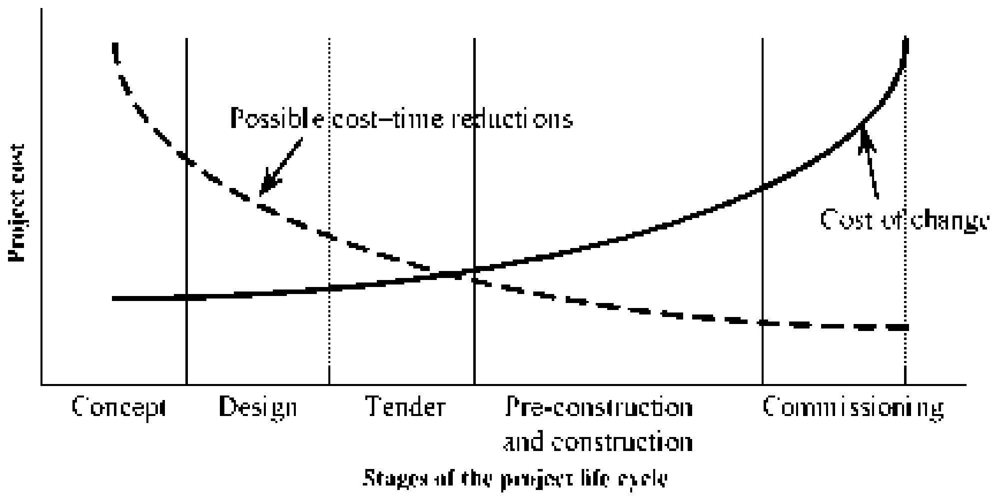
Adding specific targets, such as starting or finishing dates, to activities in a resource schedule results in the creation of a 'target schedule'. The term 'target date' implies that a specific activity or task must be accomplished by that date. Target dates are commonly imposed by a contract. A schedule that is resource-based and contains target dates is a realistic scheduling tool.

PLANNING TASKS AT DIFFERENT STAGES OF THE PROJECT LIFECYCLE

A project success is dependent on the effective management of each stage of the project lifecycle and the project as a whole.

The conceptual stage defines the project's scope and includes the client's needs, the main objectives, and the preferred development strategy. Upon these a project brief is framed from which the design consultant designs and documents the project in the design stage. The design documentation is then used in the tendering stage to assist in selecting a general contractor. In the pre-construction stage, a successful contractor develops a strategy for building the project and then constructs it in accordance with the contract documentation in the construction stage. At the end of the construction stage, the client takes possession of the completed project. This stage is commonly referred to as commissioning. The individual stages of the project lifecycle are illustrated in Figure 1.4.

Figure 1.4 Cost of change and possible cost–time reduction across the project lifecycle



Of particular importance are the first two stages, which are concerned with defining the project concept and developing its design. This is because the capacity to control project objectives effectively (especially in terms of cost and time) diminishes as the project progresses through its lifecycle. For example, if the client alters the scope of the project at the conceptual stage, the impact on the overall project cost–time is likely to be fairly small since no design or construction have yet begun. But if the changes to the scope occur in the later stages when the work either on the design or construction is under way, the cost–time impact will be considerably greater, particularly in the construction stage.

Conversely, effective co-ordination and management of the conceptual and design stages provide an opportunity for better control of cost and time later in the construction stage. The importance of the conceptual and design stages is shown in Figure 1.4.

The importance of effective lifecycle management is obvious. Since planning is one of the essential elements of effective management, it is worth examining specific planning tasks that take place in individual stages of the project lifecycle.

Planning at the conceptual stage

The conceptual stage is characterised by the definition of the project's scope, the development of the preferred strategy, budgeting, and the formulation of a brief.

A project manager will be engaged in two distinct planning tasks: (i) strategic planning, and (ii) scheduling.

The function of strategic planning was discussed on page 7. Let's now examine the function of scheduling at the conceptual stage. Once the overall project strategy has been determined, the project manager starts work on developing an overall project schedule that shows important tasks or activities across all the stages of the lifecycle. The schedule will be a time schedule that will not show a great deal of detail but will show a logical sequence of important activities to be accomplished at each stage. It will also show relationships among activities within and across individual lifecycle stages from which the project manager will attempt to foresee potential co-ordination and integration problems. The degree of detail shown will be governed by the scale of the schedule, which is likely be in months or perhaps even weeks. Of particular importance is the identification of dates for major decisions.

Apart from the overall project schedule, the project manager also develops a detailed schedule for managing the conceptual stage. It will be a medium-term schedule with a time-scale in weeks. It will show a sequence of activities to be undertaken at the conceptual stage, together with the dates for the key decisions and targets. The most important target date will be that for the completion of a brief. The execution of the work at the conceptual stage requires commitment of human resources by specialist consultants. These need to be carefully assessed and built into the schedule.

Planning at the design stage

The aim of the design stage is to design the project and prepare the necessary design and tender documentation. Design is a creative task that is often difficult to fit into a rigid time-frame. It is a time-consuming process that adds substantially to the total development period. It is also a process that is often subjected to a wide range of risks. Nevertheless, every effort is required to (i) set aside a sufficient time for design and documentation, (ii) allocate the necessary resources to ensure that the work can proceed as planned, and (iii) monitor and control the process to ensure that the work is completed on time.

Planning tasks in the design stage comprise the development of:

- a design management plan
- a medium-term schedule of design activities
- a short-term schedule of weekly design tasks
- a schedule of drawings.

A design management plan is basically a strategic plan formulated for the design stage. It states the main objectives, describes strategies for achieving them, and gives budgets. For more information on strategic planning, refer to page 7.

Apart from determining the overall strategy, the project manager, together with a project team, prepares a design schedule (a medium-term schedule) showing a sequence of design and documentation activities. This schedule will need to be developed around available resources such as designers, draftspeople and computer-aided graphics equipment, and must take into account specific target dates such as that for submitting design documentation to local councils for approval and the date for tendering. Since the design work may involve a number of separate design organisations, a design schedule is vitally important, not just for planning of design activities but also for their co-ordination and integration.

A weekly design schedule will be prepared to show in detail activities and resources needed to accomplish the design work. This schedule will be used to control the everyday design production process.

Another important schedule that will be prepared in the design stage is a schedule of drawings. Since the design process brings together many different design organisations that may produce hundreds of drawings and details, a schedule of drawings will assist in monitoring the production of individual drawings. It will ensure that drawings are produced when required and distributed to the right parties.

Planning in the tendering stage

In the tendering stage, bidding general contractors prepare tender proposals based on tender documentation and other relevant information from which the client selects the winning tenderer.

Tendering is a form of competition for work among bidding contractors. Each bidding contractor estimates the cost of construction based on a preferred construction strategy defined in a tender schedule. In developing an appropriate construction strategy, the contractor would need to focus on issues such as:

- type and nature of project to be built
- site location
- site conditions
- contract conditions
- alternative construction strategies
- an appropriate form of WBS.

A tender schedule is produced in the form of an overall construction program. It is resource-based and is sufficiently detailed to enable the client to establish how the contractor will meet the project objectives.

Planning in the pre-construction and construction stages

After the contract has been awarded to the general contractor, the contractor begins work on developing an overall construction schedule. At first, the contractor reviews a tender schedule and highlights those tasks that may need to be modified as more up-to-date information becomes available, particularly with regard to the design. The contractor also reviews the previously defined WBS and affirms its final structure.

The WBS determines the extent of the contractor's scheduling in the pre-construction stage. Large projects constructed over a number of years will require the development of a hierarchy of schedules from the top down, starting with an overall construction schedule that will be supplemented with schedules for each level of the WBS. Smaller projects may require the development of only one overall construction schedule.

In developing a construction schedule, the contractor needs to consider a range of issues:

- off-site activities, for example prefabrication
- incomplete or missing segments of the design and documentation
- production of shop drawings
- lead times and processes for approvals by authorities, consultants and the client
- lead times for orders of materials and equipment, and their deliveries to the site
- off-site work of specialist contractors, particularly in the area of building services, such as air-conditioning, lifts, hydraulics and electrical
- risks associated with on-site and off-site activities that are generally outside the contractor's control

- lead times for delivery and installation of temporary equipment such as cranes, formwork systems and the like.

Since most construction activities are performed by specialist subcontractors, it is essential for the contractor to seek their input into scheduling. This is particularly important for co-ordinating and integrating the work of subcontractors and in defining the required level of resources. Similarly, the contractor would need to seek input into scheduling from suppliers of materials and plant/equipment, particularly those whose delivery times are likely to require long lead times. For example, in order to ensure timely delivery of airconditioning plant manufactured overseas, the contractor would want to know how many weeks in advance the contractor would need to place an order with the manufacturer.

In the construction stage, the contractor uses the schedules developed in the pre-construction planning to control the production process. These schedules need to be reviewed in line with the progress achieved, and updated at regular intervals.

The contractor manages date-to-date construction activities using short-term schedules. These are prepared each week and show in detail the work to be accomplished by committed resources.

The contractor also prepares a range of schedules for control of materials, labour, subcontractors, and plant/equipment. These will be discussed in more detail in Chapter 4.

Planning in the commissioning stage

The commissioning stage is reached when the project under construction is said to be 'practically complete'. The client takes legal possession of the project although it may not be fully completed. From the legal perspective, the project has reached a defects liability period during which the contractor is required to complete the work under the contract, commission all the services, and repair any defects. It is also during this stage that the client signs up tenants and commences fitout. Clearly, a schedule is needed at the commissioning stage to plan, organise and control such a wide range of activities. It is commonly the responsibility of the project manager to prepare such a schedule. Since it covers a period between two and six months, the schedule will be medium-range, with the time-scale in days.

EXAMPLES OF CONSTRUCTION PLANS AND SCHEDULES

There are many different types of plans and schedules used in construction planning and control. They vary from simple tables and charts to complex networks. The decision on what type of plan or schedule to use is generally governed by the size of a project, the WBS level of planning, which determines the level of detail and the time-scale, and the nature of the activities to be planned.

Plans and schedules must be presented in a manner that facilitates transfer of information from one party to another in the most effective manner. Too often they may be mathematically and technically correct but fail to communicate the planning information effectively. Furthermore, plans and schedules must be prepared in a manner suitable for monitoring and controlling of the production process.

The most common examples of plans and schedules used in the construction industry will now be briefly reviewed.

Lists

A list represents the simplest form of a schedule. It is nothing more than a written account of a series of activities presented in some logical order that need to be accomplished by a specific resource in a fairly short time such as one day. The following example shows the simplicity of such a list.

A list of activities to be performed by the plastering crew on 25 June 2002:

- sand back joints in plasterboard ceilings and walls in launch and dining rooms
- set joints (second coat) in plasterboard ceilings and walls in lunch and dining rooms
- fix plasterboard sheets to ceilings in bedrooms 1 & 2
- fix plasterboard sheets to walls in bedrooms 1 & 2
- tape and set joints in plasterboard ceilings and walls in bedrooms 1 & 2.

Tables

Tables are similar to lists but are presented in a more compact and systematic manner. For example, the following table shows specific activities that a site crane will perform on hourly basis over one day.

TIME	ACTIVITY	LOCATION
7–8am	Unloading trucks	Site loading zone
8–9am	Lifting formwork	From level 2 to 6
9–10am	Lifting formwork	From level 2 to 6
10–11am	Pouring concrete	Level 5 columns
11–12noon	Pouring concrete	Level 5 columns
12–1pm	Lunch	
1–2pm	Lifting reinforcement	From ground to level 6
2–3pm	Lifting bricks	From ground to level 1
3–4pm	Lifting electrical material	From ground to level 2
4–5pm	Lifting a/c ducts	From ground to level 2

Coloured or marked-up drawings

Contract drawings of large projects, particularly plans and sections, are often used to show daily or weekly expected progress by marking up the work to be performed using different colours or textures. Such plans are highly visual and are useful in planning activities such as bulk excavation, installation of services, horizontal formwork and the like.

Diagrams

Flowcharts, bar charts, line of balance charts and multiple activity charts are common examples of diagrams.

A 'flow chart' is a simple diagram showing a flow of information or work. It is particularly useful for developing a logical sequence of activities and for illustrating the flow of work in the production process. A flow chart is shown in Figure 11.6.

A 'bar chart' is the most commonly used scheduling tool. It is relatively easy to prepare and read, but its clarity diminishes with an increasing number of activities. An example of a bar chart is given in Figure 2.2.

A 'multiple activity chart' is used effectively for allocating the work to committed resources on daily basis; see Figure 9.5.

A 'line of balance' is a chart used for scheduling highly repetitive work, which is performed by different resources; see Figure 10.7.

Graphs

Graphs are useful to highlight the relationship between two or more variables. They are used in many applications including cash flow forecasting, assessing distribution of resources, production planning, and analysing production trends; see Figure 6.3.

TABLE 1.1

ADVANTAGES AND DISADVANTAGES OF DIFFERENT PRESENTATION FORMS OF PLANS AND SCHEDULES

PRESENTATION FORMS	ADVANTAGES	DISADVANTAGES
List	Simple	Doesn't reflect complex situations
	Easy to understand	
Table	Simple	Doesn't reflect complex situations
	Easy to understand	
	Better structured	
Coloured or marked-up drawing	Simple and visual Easy to understand	Not capable of time and resource scheduling
Diagrams		
Flow chart	Simple and visual Easy to understand	Not capable of time and resource quantification
Bar chart	Shows sequencing of activities Generally easy to understand Time-scaled Visual	Relationships between activities shown by links Not capable of quantification
Line of balance	Shows a delivery program Simple and powerful Visual when coloured	Not supported by computer software Difficult to update
Multiple activity chart	Allocates work to committed resources	Not supported by computer software Its development is time-consuming
	Useful to assess productivity	
Graph	Simple	Doesn't reflect complex situations
	Easy to understand	
Networks		
CPM and PERT	Work sequence shown Easy to update and alter Resources considered	Complicated Not visual

Networks

Networks are diagrammatic models showing a logical sequence and relationships among activities. They provided a basis for the critical path and PERT (program evaluation and review technique) scheduling. These scheduling techniques will be discussed in detail in Chapters 3 and 13 respectively. Examples of networks are given in Figures 3.7 and 3.15.

The advantages and disadvantages of different presentation forms of plans and schedules are summarised in Table 1.1.

SUMMARY

This chapter described the planning process in broad terms and identified important issues relevant to planning and controlling construction projects. In particular, it examined the hierarchy of schedules defined by the WBS, types of schedules, planning tasks in different stages of the project lifecycle, and examples of plans and schedules commonly used in the construction industry. In the next chapter, the scheduling technique known as a bar chart will be discussed in detail.

CHAPTER 2

BAR CHARTS

INTRODUCTION

The purpose of this chapter is to examine bar chart scheduling technique. A bar chart structure will be defined first, followed by a description of the logical steps taken in developing a bar chart. This will be followed by a process of determining the duration of an activity. The development and application of method statements, which serve the purpose of recording planning information for future use, will be examined next, followed by a brief discussion of the limitations of traditional, unlinked bar charts. The importance of activity links in bar charts will be emphasised. Finally, the use of bar charts will be demonstrated by a simple example.

The 'bar chart' is the first scheduling technique that will be examined in this book. It is most popular and is widely used in the construction industry. The work of Henry L. Gantt and Frederick W. Taylor in the early 1900s, which was associated with graphic representation of work on a time-scale, led to the development of the Gantt or bar chart. The term 'bar chart' is more commonly used and will be adopted in this book.

Scheduling is a decision-making task. It is also a modelling task performed on the model provided by the format of the bar chart. In scheduling, the planner reduces the physical size of the project to a relatively small number of activities that can fit on a sheet of paper. Upon finding the best solution, the planner relates it to the actual project. In any modelling exercise, the accuracy of the solution depends on the development of a model that is representative of the actual project.

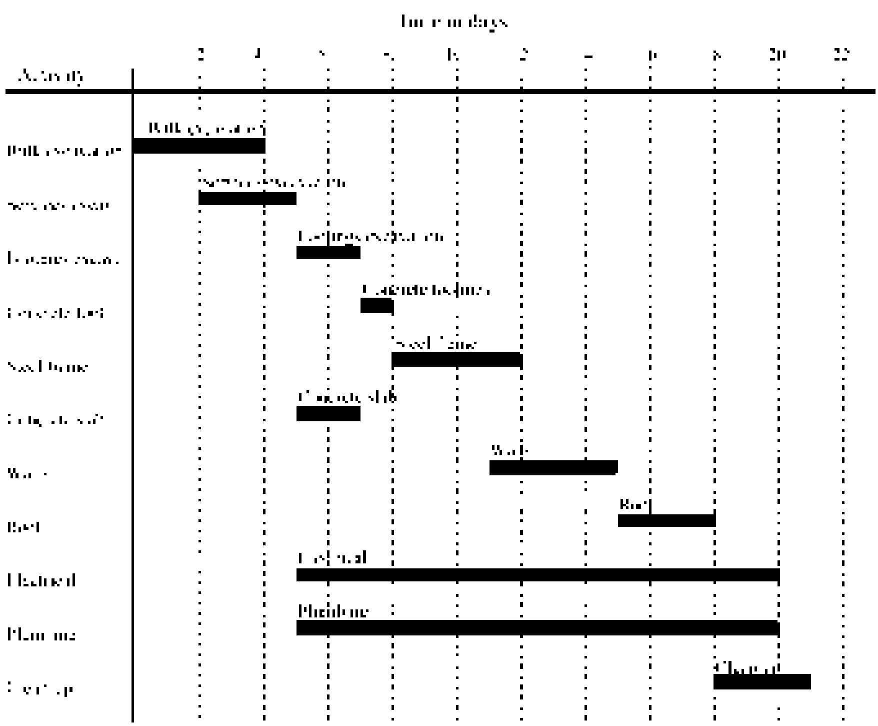
WHAT IS A BAR CHART?

A bar chart is a simple, visual scheduling tool that is easy to use. It displays planning information graphically in a compact format to a time-scale. It is a diagram divided into columns and rows. Columns represent a given time-scale, which could be expressed as months, weeks, days or even hours. Activities are scheduled as bars within horizontal rows.

The first column lists activities that are to be scheduled in a more or less logical order of production. The production process is then represented by horizontal bars which are drawn for each activity within the time-frame of the bar chart. The length of an activity bar gives activity duration. Figure 2.1 is an example of a simple bar chart.

The start and end points of an activity bar are significant in determining the position of that activity within a logical production sequence. In other words, the start point of an activity bar is closely related to the end point of a preceding activity bar. Similarly, the end point of an activity bar shows the relationship between that activity and the following activities. For example, the start of the activity 'Footings excavation' is linked to the finish of the preceding activity, 'Services excavation', and the finish of the activity 'Footings excavation' is linked to the start of the next activity, 'Concrete footings'.

Figure 2.1 A typical bar chart



However, it is unclear whether the start of the activity 'Concrete footings' is only related to the finish of the preceding activity, 'Footings excavation', or to 'Concrete slab' as well. It is also difficult to determine if the activity 'Concrete footings' is in any way related to the activities 'Electrical' and 'Plumbing'.

The graph shown in Figure 2.1 represents a traditional format of bar chart. It should be clear from the foregoing discussion that this format makes it difficult for the user to interpret the relationships between activities. If one of the activities is delayed, would the user be able to interpret the impact of this delay on other activities? For example, would the user be able to correctly deduce the impact of a one-day delay in the completion of the activity 'Concrete slab' on the activities 'Steel frame', 'Electrical' and 'Plumbing'? For this simple project, the experienced user would most likely deduce the correct answer. When projects become more complex, interpretation of relationships among activities is much more difficult. This problem can easily be overcome by constructing a linked bar chart.

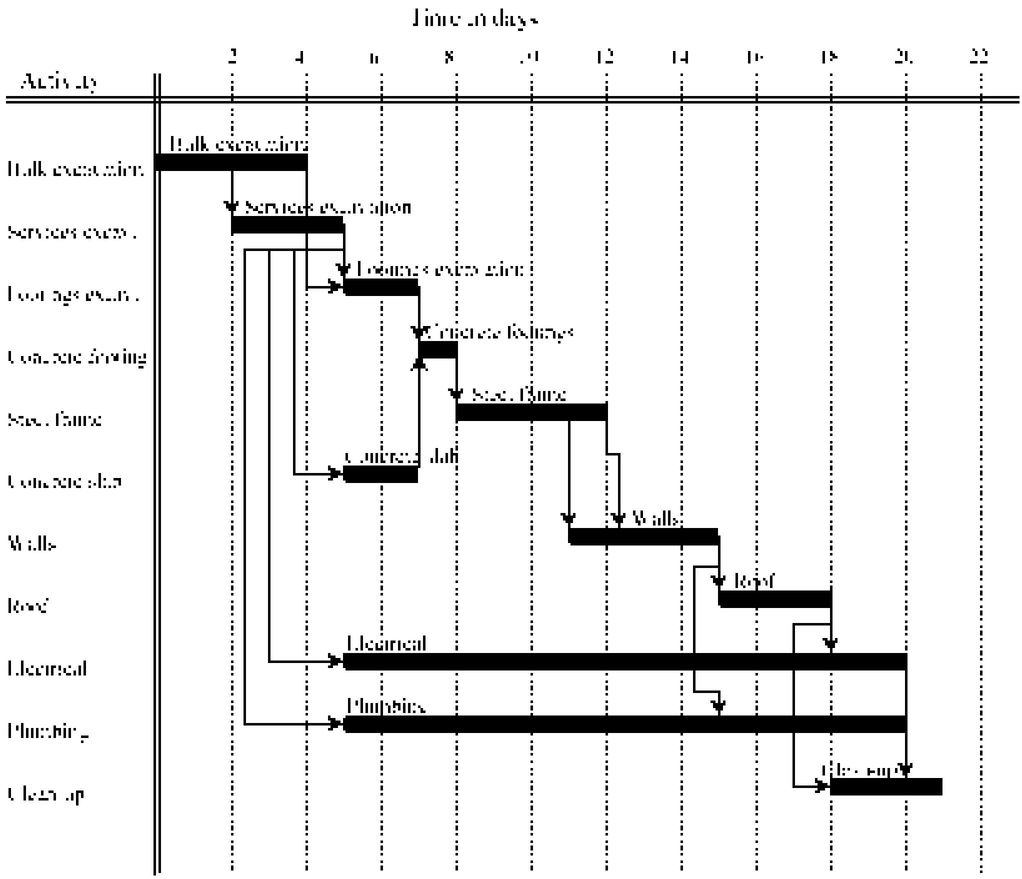
LINKED BAR CHART

When the end of a preceding activity is connected to the start of a following activity by a link line, the traditional bar chart format is converted into a linked format; see Figure 2.2.
A linked bar chart provides a clear picture of relationships among scheduled activities. It even defines relationships between those activities that are scheduled concurrently. For example, the completion of 'Walls' affects the completion of 'Plumbing'; similarly, the completion of 'Roof' affects the completion of 'Electrical'. Without these links, the relationship between the activities 'Wall' and 'Plumbing', and 'Roof' and 'Electrical' would be extremely difficult to define.

Linking of activities has overcome the main shortcoming of bar charts. Positive features of a bar chart scheduling technique include:

- speed and ease of development
- ease of understanding
- the ability to schedule complex relationships among activities
- the ability to communicate information
- the ability to monitor and control the production process.

Figure 2.2 A linked bar chart



Despite numerous benefits, linked bar charts are rarely used as a primary planning tool, particularly on larger projects. This is because they lack a computational base, which prevents calculation of a critical path (for the definition of a critical path, see Chapter 3). This also prevents periodic recalculation of the schedule, which is necessary for regular updating.

PROCESS OF DEVELOPING A BAR CHART

A typical planning process is defined in Chapter 1. It provides a framework on which a process of developing a bar chart or any other technique used in scheduling is based. Logical steps in developing a bar chart include:

1. identifying the work to be done and setting an objective
2. determining the extent of planning detail for a particular level of WBS
3. breaking the work down into activities
4. developing alternative planning strategies:
   - preparing a logic diagram (that is, a logical sequence of activities) for each alternative
   - determining duration of activities (see this section for more details) based on the volume of work and the required resources (that is, people, plant/equipment, materials)
   - recording planning information in method statements (see pages 33–34 for details)
   - preparing preliminary bar charts, one for each alternative
   - considering the use of resources; for example, one crew of workers cannot be scheduled to work on two separate activities at the same time
   - checking the volume of resources at each time interval to prevent their unnecessary accumulation
5. selecting the preferred planning strategy
6. reviewing the preferred planning strategy illustrated on a bar chart schedule. Does it all make sense? Will the user be able to understand it? Does the bar chart schedule include enough information to be workable? Has anything been left out? Is there a better alternative? Does the bar chart schedule meet the planning objectives?
7. committing to the bar chart schedule
8. monitoring the progress regularly.

ACTIVITY DURATION

An activity is a task that needs to be accomplished. It describes a particular type of work, for example bulk excavation or plumbing. But 'work' may not always involve human activity, for example the curing of concrete occurs by natural means. Nevertheless, it must be included in a schedule since it adds time to the project.

One of the most difficult tasks in planning is establishing the duration of activities. To do that, the planner needs to know:

- the quantity of the work
- the resources needed for its execution
- productivity rates of the required resources
- the specific contractual requirements imposed on the project
- the presence of risk.

Determining time duration of activities from labour productivity rates

The quantity of work is commonly measured and compiled by a quantity surveyor in a document called a 'bill of quantities'. In some countries, such as the USA and Japan, clients don't commission consulting quantity surveyors to prepare a bill of quantities as a bidding document; rather, bidding contractors are required to prepare their own quantities.

When a bill of quantities for a particular project is available to the contractor, the contractor's planner can easily determine the volume of work for each activity in the project. For example, the bill of quantities specifies the quantity of 'trench excavation' as 60 m^3. Let's assume that the trench is 15 metres long, 2 metres wide and 2 metres deep, and the soil is clay.

If this excavation activity is to be performed by labourers, the planner needs to know a productivity rate or units of work for labour excavating the trench. The planner may deduce this productivity rate from experience or extract it from readily available published databases. The task of calculating duration of this activity is fairly simple once the planner has determined the total volume of labour hours and the size of the labour crew.

Total labour hours = quantity of work × productivity rate
Activity duration = total labour hours/number of persons

Assume that 1.5 labour hours is required to excavate 1 m^3 of soil. Therefore,

Total labour hours = 60 m^3 × 1.5 labour hours = 90 labour hours or 12 labour days (at 8 hrs per day).

With, say, three persons assigned to this activity, duration will be:

Activity duration = 12/3 = 4 days

The planner may vary the activity duration by either increasing or decreasing the labour crew size, provided this is possible or practicable. For example, with two and four people assigned to the above activity, its duration would be six and three days respectively. The planner may then optimise alternative activity durations in terms of cost and time to determine the optimum outcome. Cost/time optimisation will be examined in Chapter 6.

Determining time duration of activities from daily output rates of resources

Duration of activities can also be calculated from the volume of work and the daily output rates of resources. In most countries, output rates per day for plant/equipment and labour may be obtained from published cost data catalogues. The calculation process to determine activity duration in days is:

Activity duration in days = quantity of work/resource output rate per day

For the previous example, assume that a backhoe will be used to excavate the trench. The output rate of the selected backhoe is say 80 m^3 per day. To excavate the required 60 m^3 will be calculated as follows:
Activity duration = 60/80 = 0.75 day

Although it takes less than one day to excavate the trench, the planner will probably round the duration to the nearest day, in this case one day. More complex tasks performed by plant or equipment may require the allocation of additional labour to assist with and supervise such tasks.

Determining duration of activities from the target dates

Sometimes a bidding contractor is required to prepare a construction schedule that meets a tight completion date. The contractor's planner would need to schedule the project by working from its completion date to the start date by fitting all the work within the given time-frame. This often results in some activities having unrealistically short durations. In such cases, the planner is required to allocate whatever resources are needed to meet the required activity duration.

Single-value estimates of activity duration

Before leaving this topic, it is useful to note that productivity and output rates of resources from which activity durations are calculated are commonly expressed as single-value estimates. They are extracted from databases in the form of mean or average rates. For example, an average output rate for laying bricks extracted from a database may be 300 per bricklayer per day. This rate has been compiled from virtually thousands of past bricklaying output rates stored in the database. An average estimate of the output rate is in fact a mean of a distribution of individual output rates. The range of the output rate distribution is defined by its standard deviation.

When the standard deviation is high, the range is correspondingly wide. For example, with the standard deviation of 50 bricks per day, the range of the output rate distribution would be approximately between 150 and 450 bricks per bricklayer per day.

By definition, the mean or average is 50 per cent. It means that the output rate of 300 bricks per bricklayer per day has around 50 per cent probability of being achieved. Since the range of the distribution is wide, the actual output rate that will be achieved could in fact be anywhere within the defined range. Scheduling a project on the basis of average time estimates is obviously risky.

Scheduling that relies on using average productivity and output rates of resources is referred to as single-value (deterministic) scheduling. An alternative approach known as probability (stochastic) scheduling expresses estimates of productivity and output rates in the form of probability distributions. Using an appropriate probability analysis method such as the Monte Carlo simulation, the combined effect of individual probability distributions on the schedule can be assessed statistically. The technique of the Monte Carlo simulation will be discussed in Chapter 12.

RISK CONTINGENCY

Schedules built up from 'average' estimates of activity durations do not reflect the presence of risk. Risk that may cause delays in execution of the work is commonly assessed separately by the planner. Most frequent risks responsible for delays include inclement weather, latent site conditions, variations orders, unavailability of resources, re-work, accidents and the like. From the contractor's perspective, delays caused by the client are not risk events if the contractor is able to claim time extension under the contract, for example delays caused by variations orders or latent site conditions. For such risk events, the contractor will add no time contingency to the schedule. However, the other risks for which the contractor is responsible would need to be carefully assessed and added to the schedule in the form of a time contingency. The contractor may deal with a time contingency in one of the following ways:

- add time contingencies to 'risky activities' only, or
- add a time contingency to the whole project as a lump-sum allowance (to the end date of the schedule), or
- break up the lump-sum time contingency into a number of smaller contingencies that are then added to the schedule at regular intervals, for example each month.

The issue of contingency will be discussed in Chapters 8 and 12.

METHOD STATEMENT

In determining the duration of activities, the planner makes a series of decisions about required resources, productivity and output rates of resources, and assessment of risk. If unrecorded, these important decisions would be largely unknown to those who are responsible for the schedule's implementation. Instead of using the previously formulated decisions, they would need to replicate it entirely.

A detailed account of decisions made by the planner in the preparation of a schedule can effectively be compiled in the form of a method statement. When compiled systematically for each activity, method statements store highly detailed information of all key scheduling decisions for future retrieval. The project manager is then able to review information in the method statements and use it in developing the final operational schedule that meets all the contract requirements.

The format and the development of method statements will now be briefly demonstrated on the following simple example.

Let's assume that a contractor's planner is developing a tender schedule for construction of a single-storey storage facility. The work involves:

- excavating the site
- excavating footings
- forming footings
- reinforcing footings
- concreting footings
- stripping footings' formwork
- forming the ground floor slab (edge formwork only)
- reinforcing the ground floor slab
- concreting the ground floor slab
- forming walls (internal formwork)
- forming walls (external formwork)
- reinforcing walls
- concreting walls
- stripping walls
- erecting the steel roof
- installing roofing
- electrical work
- cleaning up.

Durations of activities are calculated from the quantities of work, and productivity and output rates of required resources. A method statement in Table 2.1 gives information on quantities, units of quantities, output rates of specific resources, number of resources, duration and the actual output rates. A largely sequential bar chart schedule for this project is given in Figure 2.3.

Figure 2.3 A sequential bar chart

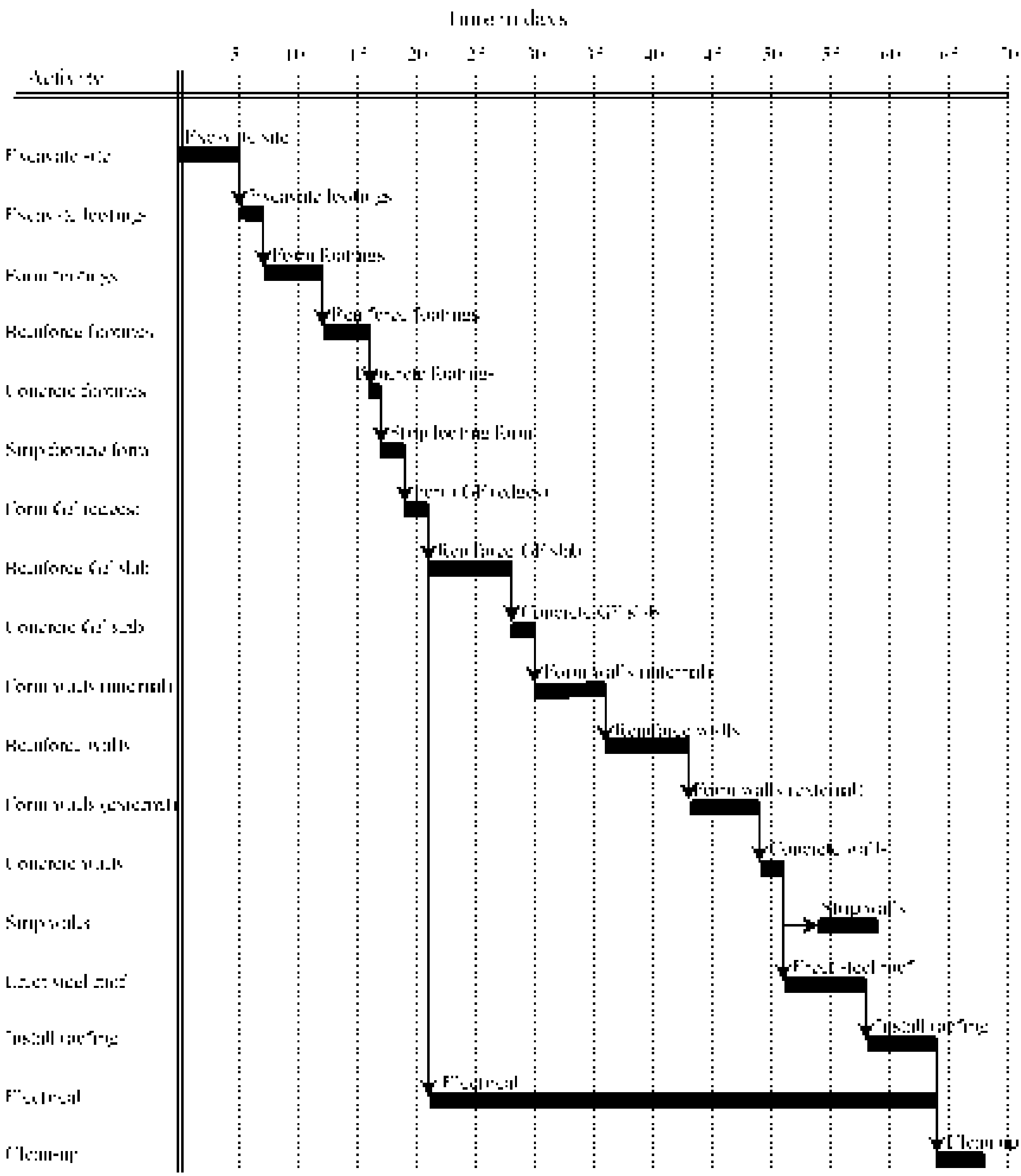


TABLE 2.1

A METHOD STATEMENT

	QUANTITY	UNIT	RESOURCE OUTPUT PER DAY	NUMBER OF RESOURCES	DURATION IN DAYS	ACTUAL TOTAL OUTPUT
Excavate site	2000	m^3			5	
1 m^3 track excavator			450	1		2225
Labour to assist				1		
Excavate footings	100	m^3			2	
$^1/_3$ m^3 backhoe			80	1		160
Labour to assist				1		
Form footings	320	m^2			5	
Formworkers			70	4		350
Reinforce footings	6	tonne			4	
Steelfixers			1.5	6		6
Concrete footings	60	m^3			1	
Concrete pump			180	1		180
Concreters			100	6		100
Strip footing formwork	320	m^2			2	
Formworkers			160	6		320
Form ground floor (edges)	160	m			2	
Formworkers 160 m			100	8		200
Reinforce ground floor slab	22	tonne			7	
Steelfixers			3.5	6		24.5
Concrete ground floor slab	240	m^3			2	
Concrete pump			180	1		360
Concreters			140	8		280
Form walls (internal)	480	m^2			6	
Formworkers			90	10		540
Form walls (external)	490	m^2			6	
Formworkers			90	10		540

Reinforce walls	10	tonne			7	
Steelfixers			1.5	6		10.5
Concrete walls	110	m^3			2	
Concrete pump			180	1		360
Concreters			60	6		120
Strip walls	980	m^2			5	
Formworkers			200	6		1000
Erect steel roof	50	tonne			7	
Mobile crane			40	1		280
Riggers			8	6		56
Install roofing	160	m^2			6	
Mobile crane			100	1		600
Riggers			30	6		180
Electrical	item				43	
Subcontracted				2		
Clean-up	item				4	
Labourers				6		

SUMMARY

This chapter has reviewed the fundamentals of bar chart scheduling. In particular, it focused on defining a process of developing a bar chart and explaining the difference between the traditional and the linked formats of bar charts. The chapter also examined the process of determining activity duration. In the final section, the importance of method statements in recording planning information was discussed. The next chapter will examine the fundamentals of critical path scheduling.

CHAPTER 3

THE CRITICAL PATH METHOD

INTRODUCTION

The purpose of this chapter is to describe the concept of critical path scheduling, which is the most frequently used time-scheduling technique in the construction industry. The critical path method (CPM) will be defined first, followed by a brief history of its development. Both the original format of the critical path method, known as the 'arrow method', and a later version, the 'precedence method', will be described in detail, including calculation of forward and backward paths, identifying the critical path, and the computation of 'float'. An alternative computational method known as the 'link lag method' will also be examined.

Although a bar chart is effective in communicating planning information, it lacks a computational base for more detailed analysis of a schedule. The lack of a computational algorism prevents the planner from locating a critical path (that is, the longest path through a schedule), calculating float, analysing the use of resources, and accelerating a schedule at the least possible cost.

The CPM overcomes these shortcomings by providing a computational algorism for a highly detailed level of schedule analysis. The CPM has the ability to calculate the start and finish dates of each activity in a schedule. These dates help to identify a specific chain of activities that cannot be delayed without delaying the end date of the schedule. The path connecting these activities from the start to the end of the schedule is known as a 'critical path' and the activities are 'critical activities' in the sense that if any one of them is delayed, the entire schedule would be delayed. Non-critical activities, on the other hand, may be delayed, if needed, by the amount of time known as ‘float’ (see pages 49–53 for definition). The CPM also provides a framework for a highly detailed analysis of committed resources and for achieving the most effective schedule compression by keeping the cost and time at optimum. These issues will be discussed in detail in Chapters 4 and 6 respectively.

A CPM schedule is developed in the form of a graphic model known as a ‘network’. A network is a maze of activities linked together in a logical sequence to create a visual map of relationships and dependencies. A convention has been established for representing activities in networks. In the arrow network, activities are shown as arrows, each accompanied by a pair of circles (see Figure 3.5), while in the precedence network, activities are expressed as a set of connected boxes (see Figure 3.10).

A BRIEF HISTORY OF THE CRITICAL PATH METHOD

The CPM was first used in Great Britain in the mid-1950s on the construction of a central electricity-generating complex. Its full potential was later realised by Walker of Du Pont and Kelley of Remington Rand, in the USA. Their critical path method was based on a graphic network commonly referred to as the ‘arrow method’. It was driven by a computational process requiring no more than additions and subtractions. The benefits of critical path scheduling were quickly realised by a wide range of organisations including construction firms, many of whom have successfully implemented it in their planning. The advent of the CPM computer software in the 1970s has made the CPM a universal scheduling technique.

In 1961, Professor Fondahl of Stanford University presented a different version of the CPM, known as the ‘precedence method’. Fondahl’s method offers a number of improvements over the arrow method, particularly with regard to schedule construction and its analysis. This method has in recent years become the preferred critical path method.

The critical path method is widely used throughout the construction industry. Apart from contractors, who are the main proponents of the method, other project participants such as clients, designers, consultants and subcontractors rely on the CPM in scheduling. In addition to planning activities, the CPM method assists in organising resources and controlling progress.

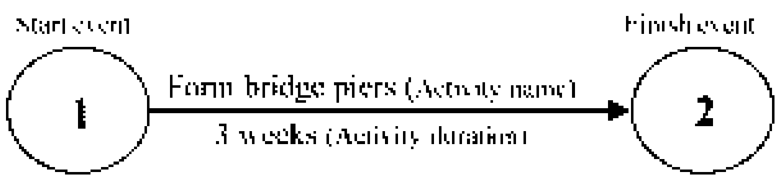
ARROW METHOD

The arrow method of critical path scheduling has largely been superseded by the precedence method, but some organisations continue to rely on it, largely because of the knowledge and the experience it embodies. Another possible reason for retaining it lies in its similarity to the bar chart in representing activities as bars or lines.

Network construction

The arrow method of critical path scheduling is 'event oriented' because it emphasises individual events rather than activities. Events are shown as nodes or circles and signify start and finish points of activities. An activity is shown as an arrow that connects a pair of start and finish events of that activity. The length of an arrow has generally no significance since arrow networks are not drawn to a time-scale. Events have no time duration but activities do. Figure 3.1 shows how an activity is represented by its two events and an arrow.

Figure 3.1 Graphic representation of activity in an arrow schedule



The activity 'Form bridge piers' in Figure 3.1 is interpreted in the following terms:

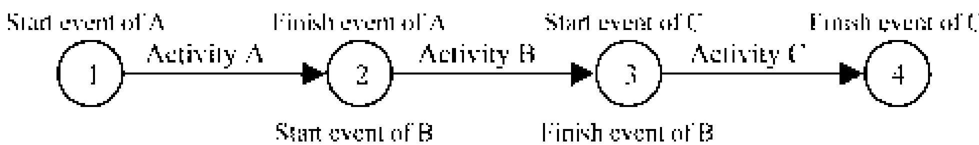
- Event 1 is the start of the activity 'Form bridge piers'.
- Event 2 is the finish of the activity 'Form bridge piers' and the start of another event.
- An arrow connecting events 1 and 2 is the activity 'Form bridge piers'.

Finish events of preceding activities are linked to start events of succeeding activities to form relationships depicting the logic of a production sequence. The convention requires arrows to be drawn from left to right in the arc between horizontal and vertical to ensure that for any pair of preceding and succeeding activities, the preceding activity is to the left of the succeeding activity. Drawing arrows from right to left is not allowed.

In developing the concept of the critical path method, it is assumed that the preceding activity must be fully completed before its succeeding activity can begin. This is referred to as a 'finish to start' relationship. This assumption will be removed in Chapter 5 when a number of overlapping models for critical path scheduling will be introduced.

When activity A in Figure 3.2 is followed by activity B, only one event is needed to show the end of activity A and the start of activity B. The finish event of activity A and the start event of activity B merge into one (the circled 2). Similarly, other finish events of preceding activities and start events of succeeding activities will merge.

Figure 3.2 Example of a chain of activities in an arrow schedule



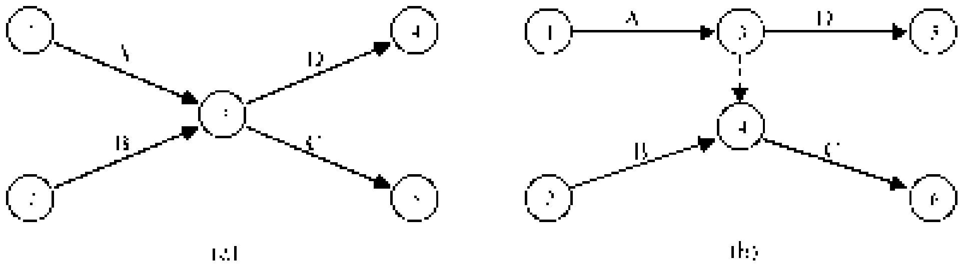
When an arrow schedule is completed, its events are numbered from left to right, ensuring that the number of the start event is smaller than the number of the finish event. A pair of start and finish event numbers then represents the activities to be performed in a schedule. For example, activity B in Figure 3.2 is identified as activity 2–3. Activities need to be identified by event numbers to facilitate computer processing.

Dummy activities in an arrow network schedule

The most problematic aspect of the arrow method is the complexity associated with the construction of an arrow network. Because a finish event of the preceding activity and a start event of the succeeding one merge into a single event, unwanted dependencies may erroneously be created when two or more activities converge to the same event point. This is illustrated on a simple example in Figure 3.3(a). Four activities, A, B, C and D, form the following relationships:

- Activities A and B are independent.
- Activities C and D cannot start until activities A and B have been completed.
- Activities C and D are also independent.

Figure 3.3 The use of a dummy activity to maintain the logic of an arrow network



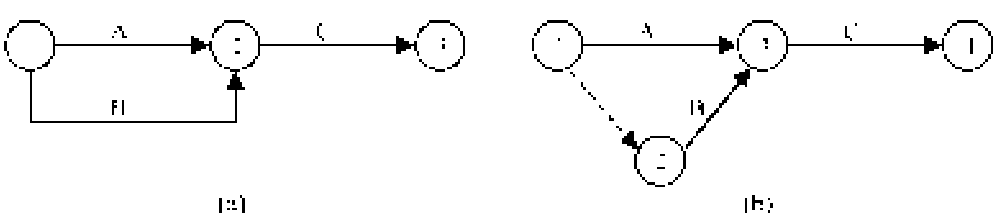
Let's now assume that the start of activity D depends only on the completion of activity A (in this case D is independent of B). Clearly, a schedule in Figure 3.3(a) does not correctly show the altered relationship between activities A, B and D. Specifically, it incorrectly links activity B and D together. This is the common problem in constructing arrow networks. So how should the above schedule be drawn to separate activities B and D from each other? The solution lies in inserting a 'dummy activity' into an arrow network.

A dummy activity has zero duration. Its presence is needed to maintain the logic of an arrow network. It is shown in the form of a broken line connecting specific preceding and succeeding events.

Let's go back to Figure 3.3 and insert a dummy activity to separate activities B and D. When a dummy activity is inserted, as in Figure 3.3(b), a new event, 4, is created. It is the inclusion of this new event that makes it possible to separate activities B and D from each other. The problem has been solved. Activity D is now independent of activity B. The other dependencies have not been affected.

Dummy activities serve another purpose in arrow networks: they are needed to identify activities by their correct event numbers. For example, two parallel activities, A and B, in Figure 3.4(a) share the same events and event numbers. CPM computer software would be unable to distinguish between those two activities.

Figure 3.4 Example of the use of a dummy activity for the purpose of identifying activities A and B



When a dummy activity is inserted as shown in Figure 3.4(b), a new event is created (shown by the broken arrow). The logic has not been altered but activities A and B are now identified by their own unique set of event numbers.

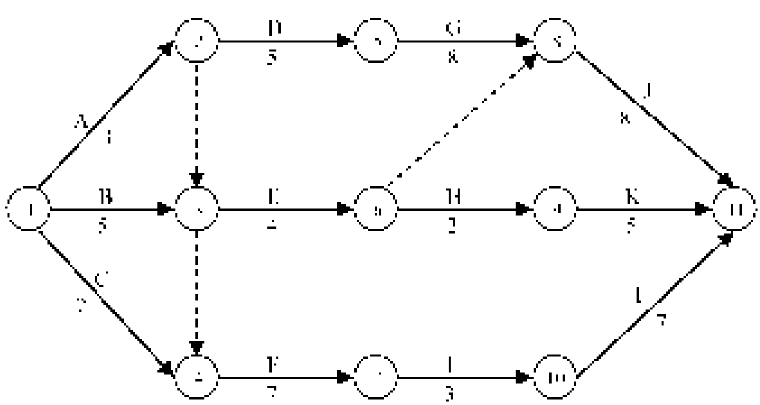
The construction of logically and technically correct arrow networks is dependent on the planner's knowledge of the use of dummy activities. Let's demonstrate the use of dummy activities in a more complex schedule shown in Figure 3.5, which has been constructed from information given in Table 3.1.

TABLE 3.1

TYPICAL INFORMATION REQUIRED FOR CONSTRUCTION OF AN ARROW NETWORK

ACTIVITY	TIME DURATION IN DAYS	DEPENDS ON COMPLETION OF
A	3	Starting activity
B	5	Starting activity
C	2	Starting activity
D	5	A
E	4	A and B
F	7	A, B and C
G	8	D
H	2	E
I	3	F
J	8	G and E
K	5	H
L	7	I

Figure 3.5 Example of an arrow network



Three dummy activities were inserted into the schedule to maintain logic. Let's check whether activities E and F have been correctly scheduled. Table 3.1 states that activity E depends on the completion of activities A and B, and that activity F depends on the completion of activities A, B and C. It is clear from Figure 3.5 that the dummy activities 2–3 and 3–4 have been correctly inserted.

The number of dummy activities required to maintain the logic of an arrow schedule also depends on the manner in which a schedule is drawn. For example, if activity B in Figure 3.5 is drawn below activity C, two additional dummy activities would need to be inserted. The reader is encouraged to verify that this is true.

With more than one starting activity in an arrow schedule, it is common practice to originate such starting activities from the same event. Similarly, when a network has a number of end activities, such activities are linked into one common finishing event. This is illustrated in Figure 3.5.

The critical path

The critical path has already been defined as the longest path through a schedule (from the start event to the finish event). A typical schedule will have many paths, of which at least one will be critical. A schedule may have more than one critical path and in the most extreme case all of its paths may in fact be critical.

The knowledge of the location of critical activities is vital for the effective planning and control of a project. It assists the planner in allocating sufficient resources to critical activities to ensure their completion on time.

A critical path can be calculated using a simple mathematical procedure, which involves calculation of four event times for each activity. These are:

- earliest event start date (ESD)
- earliest event finish date (EFD)
- latest event start date (LSD)
- latest event finish date (LFD).

When these event times are calculated, activities that have the same earliest and latest event start dates (or earliest and latest event finish dates) are critical. Other activities in a schedule will have different earliest and latest event start dates (or earliest and latest event finish dates) and are non-critical.

The calculation process involves two distinct steps: a forward pass and a backward pass through a network. A 'forward pass' calculates earliest event start and finish dates by working through an arrow schedule from its start to its finish. Because the earliest event start date of the first activity in a schedule is known (let's refer to this activity as activity I), its earliest event finish date is calculated using the following general formula:

$EFD_I = ESD_I + Duration_I$

When a critical path schedule is calculated manually, the start event date of the first activity in a schedule is assumed for simplicity's sake to be zero, but CPM computer software defines the start event date of the project as week 1, day 1 and hour 1.

For a schedule with only two activities, I and J, the EFD event of the preceding activity, I, becomes the ESD event of the succeeding activity, J. The EFD event of the succeeding activity, J, is then calculated by adding the duration of activity J to its ESD event. This process is repeated for other succeeding activities until the EFD event of the last activity in the schedule is calculated. This last EFD event gives the total duration of the schedule. The last EFD event in Figure 3.5 is event 11.

Let's look at the situation where two or more preceding activities, I_1, I_2 … I_n, meet in the same EFD event, which becomes the ESD event of the following activity, J. Which of the three preceding activities, I_1, I_2 … I_n, will determine the ESD event of activity J? Clearly, it will be activity I that has the greatest or maximum EFD event. This is expressed in the following general formula as follows:

$ESD_J = MAX\ EFD_{I_1, I_2 \ldots I_n}$

For example, activities A, B and C in Figure 3.5 meet in the same event, 4, which is the ESD event of the following activity, F. Since activity B is longer in duration than activities A and C, the EFD event of activity B will become the ESD event of the following activity, F.

The 'backward path' through a schedule calculates latest event start and finish dates by working from the end of the schedule back to its start. The backward pass determines the LFD event of activity I first, from which its LSD event is calculated as follows:

$LSD_I = LFD_I - Duration_I$

The very last EFD event in a schedule determines its overall duration. Since this event is critical (under the assumption of a 'finish to start' relationship), it must also be an LFD event (refer to event 11 in Figure 3.5). The backward pass process starts from this last event.

For example, LSD event 8 of activity J in Figure 3.5 will be calculated by deducting the duration of activity J from LFD event 11. Similarly, LSD events 9 and 10 will be calculated by deducting the duration of activities K and L respectively from LFD event 11. LSD event 9 of activity K becomes the LFD event of the preceding activity, H, and so on. The computation process moves progressively from the end to the start of the schedule until the LSD of event 1 is calculated.

Let's look at the situation where two or more following activities, $J_1, J_2 \dots J_n$, originate from the same finish event of the preceding activity, I. In determining the LFD event of activity I, the planner will consider the LSD events of the three following activities, $J_1, J_2 \dots J_n$, and will select the minimum of the three LSD event values as expressed in the following general formula:

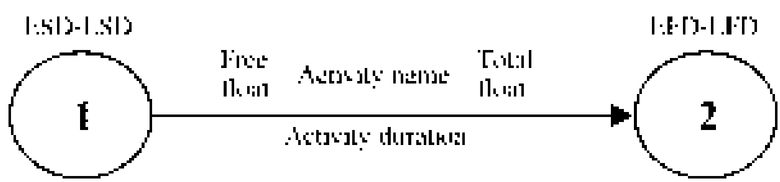
$$LFD_I = MIN\ LSD_{J_1, J_2 \dots J_n}$$

For example, activities H and J in Figure 3.5 originate from finish event 6 of activity E. Please note that activity E is linked to activity J through the dummy activity 6–8. The smaller of the LSD events of activities H and J will become the LFD event of activity E.

When the backward path has been completed, each activity in a schedule will be defined by its four event times. 'Critical activities' are then those that have identical ESD and LSD events (or EFD and LFD events). A path connecting the critical activities is the 'critical path'.

Before demonstrating how forward and backward paths are calculated, let's first define the convention for labelling arrow networks. This is illustrated in Figure 3.6.

Figure 3.6 The convention for labelling arrow networks



A schedule in Figure 3.5 will be used to demonstrate the calculation of forward and backward paths. Let's start with a forward path:

ESD event 1 of activity A = 0
EFD event 2 of activity A = 0 + 3 = 3 = ESD event 2 of activity D

Activity E cannot start until both activities A and B have been completed. It means that

ESD event 3 of activity E = EFD event 2 of activity A = 3 or
ESD event 3 of activity E = EFD event 3 of activity B = 0 + 5 = 5

Therefore, the earliest start of event 3 of activity E is 5.

Activity F cannot start until all the preceding activities, A, B and C, have been completed. It means that

ESD event 4 of activity F = EFD event 2 of activity A = 3 or
ESD event 4 of activity F = EFD event 3 of activity B = 5 or
ESD event 4 of activity F = EFD event 4 of activity C = 0 + 2 = 2

Therefore, the earliest start of event 4 of activity F is 5. Thereafter,

ESD event 2 of activity D = 3 and EFD event 5 of activity D = 8
ESD event 3 of activity E = 5 and EFD event 6 of activity E = 9
ESD event 4 of activity F = 5 and EFD event 7 of activity F = 12

Similarly,

ESD event 5 of activity G = 8 and EFD event 8 of activity G = 16
ESD event 6 of activity H = 9 and EFD event 9 of activity H = 11
ESD event 7 of activity I = 12 and EFD event 10 of activity I = 15

Activity J cannot start until the preceding activities, E and G, have both been completed. Since EFD event 8 of activity G is greater than that of activity E, then

ESD event 8 of activity J = 16 and EFD event 11 of activity J = 24

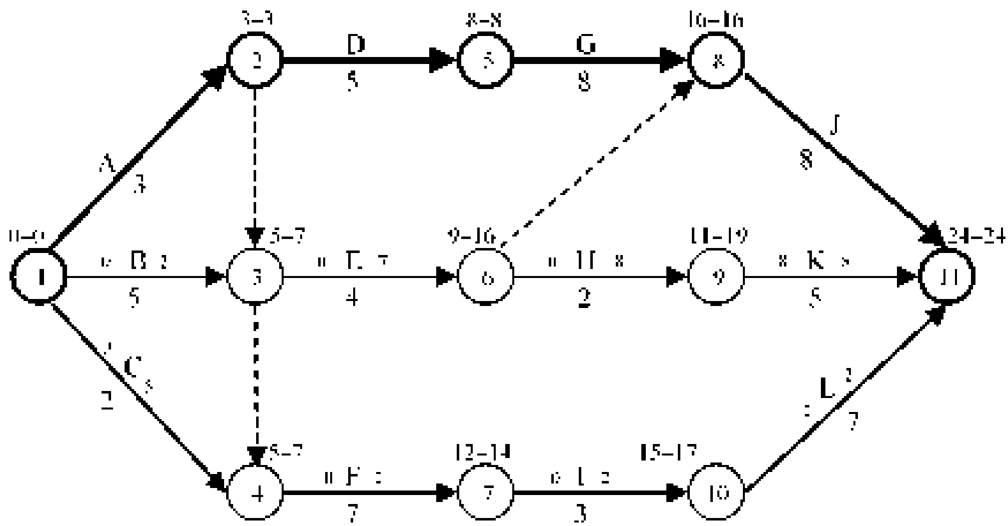
For activities K and L,

ESD event 9 of activity K = 11 and EFD event 11 of activity K = 16
ESD event 10 of activity L = 15 and EFD event 11 of activity L = 22

The very last event in the schedule, 11, has three different EFD values, one for each of activities J, K and L. Clearly, its correct value is 24, which is the maximum value of the EFD related to activity J.

This is the end of the forward pass computation. The calculated values of ESD and EFD events are shown in Figure 3.7.

Figure 3.7 The calculated arrow network schedule



Let's perform a backward path through the schedule. The EFD event 11 of activity J determines the overall duration of the schedule. It means that activity J is critical and so is event 11. Therefore, the value of EFD event 11 is in fact the value of LFD event 11. The value of LFD event 11 is 24. Therefore,

LSD event 8 of activity J = 24 – 8 = 16 and LFD event 8 of activity G = 16
LSD event 9 of activity L = 24 – 5 = 19 and LFD event 9 of activity H = 19
LSD event 10 of activity L = 24 – 7 = 17 and LFD event 10 of activity I = 17

Consequently,

LSD event 5 of activity G = 16 – 8 = 8 and LFD event 5 of activity D = 8
LSD event 7 of activity I = 17 – 3 = 14 and LFD event 7 of activity F = 14
LSD event 6 of activity H = 19 – 2 = 17

Since activity E must be completed before the following activities, H and J, could start, LFD event 6 of activity E will be the smaller of the two LSD events of activities H and J. Therefore,

LFD event 6 of activity E = 16

Thereafter,

LSD event 2 of activity D = 8 – 5 = 3
LSD event 3 of activity E = 16 – 4 = 12
LSD event 4 of activity F = 14 – 7 = 7 = LFD event 4 of activity C

Activity A must be completed before the following activities, D, E and F, could start. LFD event 2 of activity A will be the smallest of the three LSD events of activities D, E and F. Therefore,

LFD event 2 of activity A = 3

Activity B must be completed before the following activities, E and F, could start. LFD event 3 of activity B will then be the smaller of the two LSD events of activities E and F. Therefore,

LFD event 3 of activity B = 7

Then,

LFD event 2 of activity A = 3
LFD event 3 of activity B = 7, and
LFD event 4 of activity C = 7

Finally,

LSD event 1 of activity A = 3 – 3 = 0
LSD event 1 of activity B = 7 – 5 = 2
LSD event 1 of activity C = 7 – 2 = 5

The very first event in the schedule, 1, has three different LSD values, one for each of activities A, B and C. Clearly, its correct value is 0, which is the minimum value of the LSD related to activity A.

This is the end of the backward pass computation. The calculated values of LSD and LFD events are shown in Figure 3.7. Activities A, D, G and J have identical pairs of ESD and LSD event values (as well as EFD and LFD event values). It means that they are critical and fall on a critical path. In Figure 3.7 the critical path is indicated by a thick line.

Free and total float

In most CPM schedules, only a small number of activities are critical. The remaining non-critical activities are characterised by the availability of float, which is the time by which a non-critical activity may be delayed without extending the final completion date of the schedule. When a non-critical activity has float, it may commence between the dates given by ESD and LSD event values of that activity.

Four different float values can be calculated for non-critical activities. They are:

- free float
- total float
- interfering float
- independent float.

Only free and total float will be discussed in this book. Information on interfering and independent float can be found in Harris (1978).

'Free float' is defined as the amount of time by which a particular non-critical activity, I, in a schedule may be delayed without delaying the ESD event of the succeeding activity, J. When activity I is followed by two or more succeeding activities, J_1, J_2 …J_n, a free float value will be calculated for each link that activity I has with the following activities, J_1, J_2 …J_n. The smallest of the individual free float values will become a free float of activity I.

$$\text{Free float}_I = \text{MIN}\,(\text{ESD}_{J_1, J_2 \ldots J_n} - \text{EFD}_I)$$

The reader should note that the values of EFD events in an arrow schedule should not be mechanically read off the schedule but should be derived for each particular event as a sum of ESD plus activity duration. The reason for this is that when two or more preceding activities converge to the same finish event, which becomes the start event of a succeeding activity, the ESD of that succeeding activity is governed by the maximum EFD value of one of the preceding activities. Only this value will be recorded as the ESD event of the succeeding activity. This is illustrated by an example in Figure 3.7. Activities J, K and L converge to the same finish event, 11, which in this case is the finish event of the entire schedule. This end event assumes the value of 24, which in fact is the EFD event of activity J. What are the EFD events of activities K and L? They need to be calculated by adding their respective ESD events and activity duration together. Thus,

The EFD event of activity K = 11 + 5 = 16
The EFD event of activity L = 15 + 7 = 22

Similarly, LSD event times should also be calculated individually by deducting activity duration from LFD event times to avoid reading off incorrect values.

'Total float' is the amount of time by which a particular non-critical activity, I, in the schedule may be delayed without delaying the LSD event of the succeeding activity, J. When an activity is scheduled to start at its LSD event, that activity is critical. If an LSD event of that activity is delayed, the completion date of the schedule will be delayed.

When the preceding activity, I, is followed by two or more succeeding activities, J_1, J_2 … J_n, a total float value will be calculated for each link that activity I has with the succeeding activities, J_1, J_2 … J_n. The smallest of the individual total float values will be a total float of activity I.

$$\text{Total float}_I = \text{MIN}\ (\text{LSD}_{J_1, J_2 \ldots J_n} - \text{EFD}_I)$$

To fully understand the definition of free and total float, let's examine a schedule prepared as an arrow network in Figure 3.8. In particular, let's focus on activities G and K. The meaning of free and total float is not clear from the arrow schedule. However, when the relationship between activities G and K is presented in the form of a bar chart, the meaning of free and total float becomes immediately apparent.

The free and total float of activities B, C, E, F, H, I, K and L in Figure 3.7 will now be calculated. Let's start with activity B.

FF_B = either
ESD event 3 of activity E – EFD event 3 of activity B = 5 – 5 = 0 or
ESD event 4 of activity F – EFD event 3 of activity B = 5 – 2 = 3

Therefore,

$FF_B = 0$

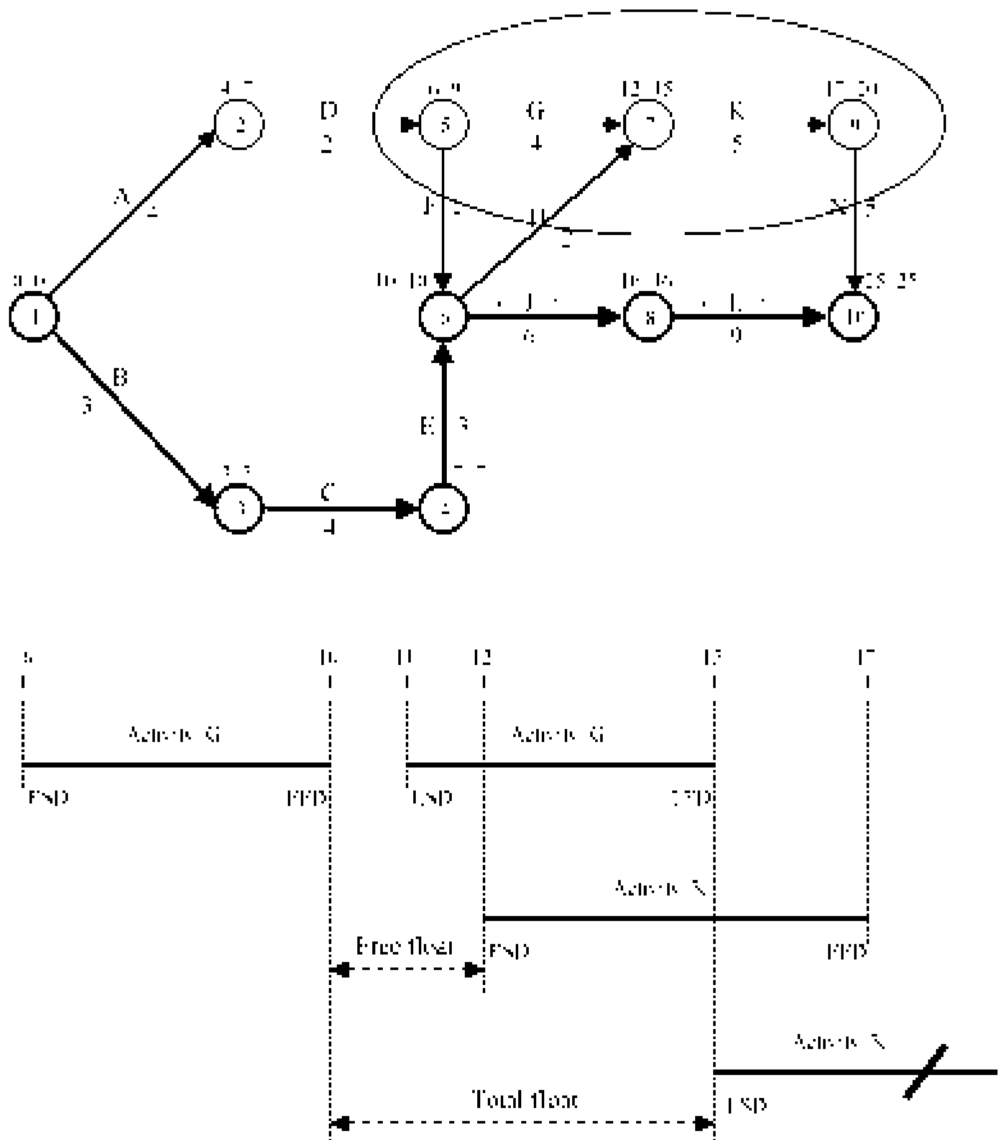
What will be the value of total float of activity B?

TF_B = either
LSD event 3 of activity E – EFD event 3 of activity B = 12 – 5 = 7 or
LSD event 4 of activity F – EFD event 3 of activity B = 7 – 5 = 2

Therefore,

$TF_B = 2$

Figure 3.8 Definition of free and total float



Let's calculate the free and total float of activity C.

FF_C = ESD event 4 of activity F – EFD event 4 of activity C = 5 – 2 = 3
TF_C = LSD event 4 of activity F – EFD event 4 of activity C = 7 – 2 = 5

The float of the other activities can be calculated in a similar manner. The fully calculated schedule including free and total float values is given in Figure 3.7.

Significance of float

Float may be viewed as extra time available in a schedule. If a CPM schedule has no float, it would have no capacity to accommodate delays. Apart from reducing the risk of time overruns, float also gives the planner an opportunity to manage allocated resources better.

From the scheduling point of view, float may be viewed as a time contingency. It gives the planner flexibility to schedule the start of a particular activity or activities within the ESD and LSD event times.

Equally important is the contribution of float to effective management of committed resources. If all activities in a CPM schedule are required to start at their ESD event times, committed resources in such a schedule would be inefficiently utilised. Float enables some non-critical activities to be delayed within the float limits to improve the efficiency of committed resources. For example, two concurrent activities, one critical and the other non-critical, compete for the same resource, say a mobile crane. Clearly, these two activities cannot be performed concurrently with only one crane available. To resolve the problem, the planner may consider one of the following alternative solutions:

1. Assign the crane to the critical activity first and delay the start of the non-critical activity until the crane becomes available, provided the extent of the delay can be accommodated within the float limits.
2. Same as in 1, but the amount of float is insufficient to offset the delay. In this case the project completion date will be delayed.
3. Hire another crane at an extra cost to perform both activities concurrently. This alternative is conditional on availability of the second crane.
4. Reschedule the project.

The first alternative, which uses the available float, appears to offer the best solution, though the loss of float may increase the risk of future delays. The other solutions are likely to incur either extra cost or extra time or both. This and other issues concerning resource management will be discussed in more detail in the next chapter.

Since the presence of float in a CPM schedule is important for containing delays and achieving better efficiency of committed resources, who actually owns it? From the legal perspective, a party that is contractually bound to execute the work under the contract generally owns the float. For example, the contractor who has a contract to build a building project owns the float during the construction period. If the client issues a variation order that causes a loss of float but doesn't delay the completion of the project, the contractor has no ground to claim for extra time since the project has not been delayed. If, however, the amount of float is insufficient to offset the delay caused by the variation order, the contractor would have a legitimate claim for a time extension. If the contractor has prepared a resource-based schedule (see pages 13–16), the loss of float is likely to cause reallocation of committed resources and the contractor may be able to claim for cost.

PRECEDENCE METHOD

The precedence method has largely replaced the arrow method as the preferred CPM scheduling technique. Although it uses the same computational approach as the arrow method, it is fundamentally different in terms of network modelling. It is activity-oriented. There are no events in the precedence method.

Network construction

The precedence method focuses on activities. A square or a box graphically represents activities, though other shapes such as a circle or a hexagon have also been used. The Australian Standard AS2443-1981: Glossary of items for network planning in the building and construction industry (AS 1981) prescribes a box for representing activities in a precedence schedule.

The following protocol has been adopted in this book for labelling activity boxes in a precedence schedule:

Excavate site	Activity name
05	Activity ID number
10	Activity duration

The construction of a precedence network is fairly simple. Since the precedence method is activity-oriented, relationships among activities are formed by simply linking activities together, and these links are referred to as dependency lines. The process of constructing a precedence network is the same as for the arrow method. The flow of work is shown in a schedule to progress from left to right. Dependency lines may be drawn up and down, but never from right to left. For ease of interpreting a schedule, it is suggested that arrowheads are attached to dependency lines to show the direction of the workflow.

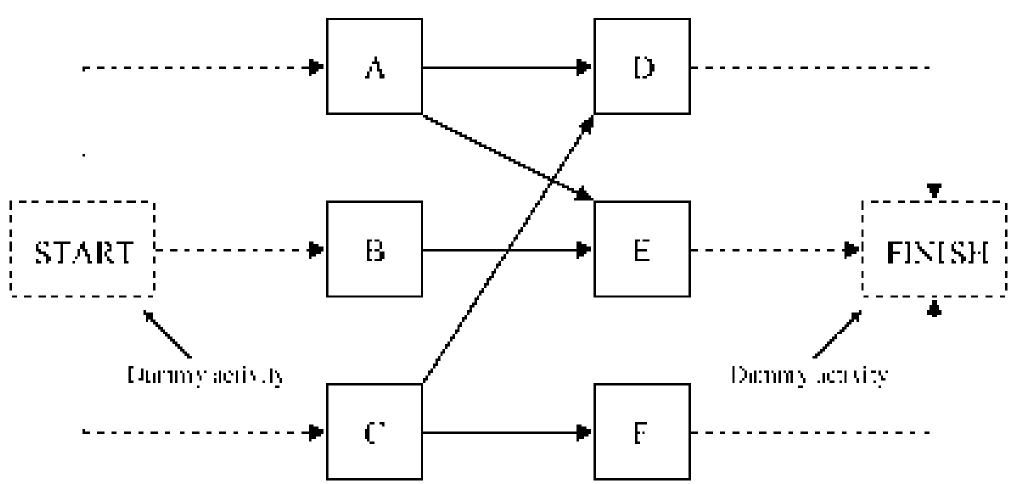
The assumption made earlier that the preceding activity must be fully completed before the succeeding activity could begin still holds. This assumption will be removed in Chapter 5 when different overlapping models will be introduced.

The manner in which activities in a precedence schedule are linked together is illustrated in Figure 3.9. The schedule shows the following relationships:

- **Activity C cannot start until activity A has been completed.**
- **Activity D cannot start until activities A and B have been completed.**
- **Activity A is independent of activity B.**
- **Activity C is independent of activities B and D.**

Dummy activities are not required in a precedence network to maintain logic, but they may be used to show the start and finish points of a schedule. This is illustrated in Figure 3.9. The dummy activities ‘Start’ and ‘Finish’ have zero duration and consequently add no time to the schedule.

Figure 3.9 Linking of activities in a precedence schedule



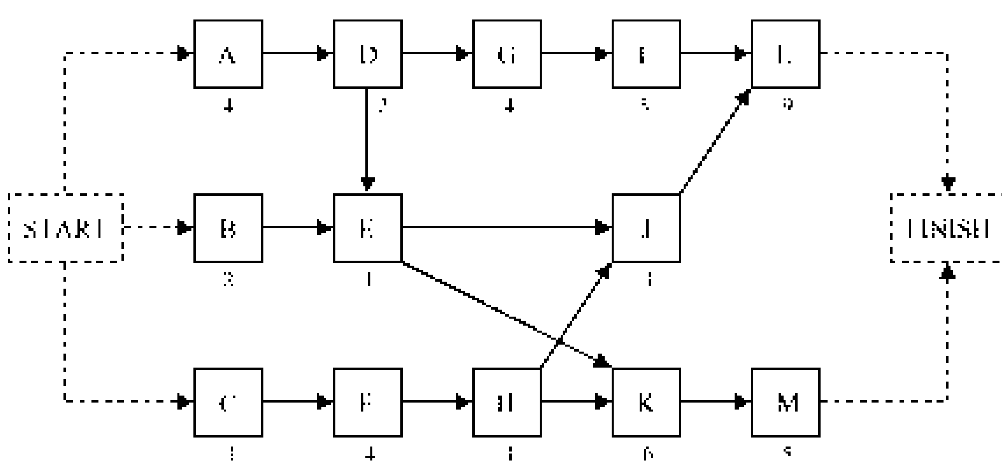
Let’s construct a precedence schedule based on information in Table 3.2. No matter how complex relationships among the activities are, the defined relationships are easily constructed by simply linking the activities together. The final shape of a schedule may vary depending on the planner's personal preference. One possible configuration of a schedule is shown in Figure 3.10.

TABLE 3.2

TYPICAL INFORMATION REQUIRED FOR CONSTRUCTION OF A PRECEDENCE NETWORK

ACTIVITY	TIME DURATION IN DAYS	DEPENDS ON COMPLETION OF:
A	4	Starting activity
B	2	Starting activity
C	3	Starting activity
D	2	A
E	1	B and D
F	4	C
G	4	D
H	3	F
I	5	G
J	3	E and H
K	6	E and H
L	9	I and J
M	5	K

Figure 3.10 Example of a precedence network



The dummy activity 'Start' defines the start point of the schedule, which has three start activities A, B and C. Similarly, the dummy activity 'Finish' defines the end point of the schedule for two end activities, L and M.

The critical path

The precedence method computational process is identical to that of the arrow method. First, a forward pass through a schedule (from start to finish) calculates the ESDs and EFDs of activities. A backward pass through a schedule (from finish to start) then calculates the LSDs and LFDs of activities.

The convention for recording scheduling information in a precedence network is given below. It will be used throughout this book.

FF   ESD–EFD
LSD–LFD   TF

Excavate site
05

10

Let's proceed with a forward pass using a schedule in Figure 3.10. The ESD of start activities A, B and C is zero and so is the ESD of the dummy activity 'Start'. When the ESD of activity I is known, its EFD is simply calculated as follows:

$EFD_I = ESD_I + Duration_I$

Therefore,

$EFD_{START} = 0 + 0 = 0$
$EFD_A = 0 + 4 = 4$
$EFD_B = 0 + 2 = 2$
$EFD_C = 0 + 3 = 3$

Given the assumption that the preceding activity must be fully completed before the succeeding activity could begin, the EFD of activity A becomes the ESD of activity D. Similarly, the EFD of activity C becomes the ESD of activity F. Therefore,

$EFD_D = 4 + 2 = 6$
$EFD_F = 3 + 4 = 7$

Activity E cannot start until its two preceding activities, B and D, have been completed. For the link D and E, the ESD of activity E is 6 (because EFDD = 6) and for the link B and E, the ESD of activity E is 2 (because EFDB = 2). Therefore, the ESD of activity E is 6. In general, when two or more preceding activities, I_1, I_2 … I_n, join the same succeeding activity, J, the ESD of activity J will be the greatest or maximum value of EFDs of the preceding activities I_1, I_2 … I_n.

$$ESD_J = MAX\ EFD_{I_1, I_2 \dots I_n}$$

Then,

$$EFD_E = 6 + 1 = 7$$

Calculations of ESDs and EFDs are shown in Figure 3.11. The remaining forward pass calculations are as follows:

$ESD_G = EFD_D = 6$, therefore $EFD_G = 6 + 4 = 10$
$ESD_H = EFD_F = 7$, therefore $EFD_H = 7 + 3 = 10$
$ESD_I = EFD_G = 10$, therefore $EFD_I = 10 + 5 = 15$
$ESD_J = EFD_H = 10$, therefore $EFD_J = 10 + 3 = 13$
$ESD_K = EFD_H = 10$, therefore $EFD_K = 10 + 6 = 16$
$ESD_L = EFD_I = 15$, therefore $EFD_L = 15 + 9 = 24$
$ESD_M = EFD_K = 16$, therefore $EFD_M = 16 + 5 = 21$

The ESD of the dummy activity 'Finish' is therefore 24 (governed by the EFD of activity L) and its EFD is also 24 since its duration is zero. This is the end of the forward pass computation.

The backward pass computation begins from the end activity in a schedule and proceeds to the start activity. It calculates LSDs and LFDs. It determines LFD values first, from which it calculates ESD values as follows:

$$LSD_I = LFD_I - Duration_I$$

The EFD of the dummy activity 'Finish' determines the overall schedule duration, which is 24. Since it is the critical activity (under the assumption of a 'finish to start' relationship), its LFD must also be 24. Therefore, its LSD is 24 minus zero, which is 24. The LSD of the dummy activity 'Finish' becomes the LFD of the preceding activities L and M. Therefore,

$LSD_L = 24 - 9 = 15$
$LSD_M = 24 - 5 = 19$

Similarly,

$LFD_I = LSD_L = 15$, therefore $LSD_I = 15 - 5 = 10$
$LFD_J = LSD_L = 15$, therefore $LSD_J = 15 - 3 = 12$
$LFD_K = LSD_M = 19$, therefore $LSD_K = 19 - 6 = 13$
$LFD_G = LSD_I = 10$, therefore $LSD_G = 10 - 4 = 6$

When two or more succeeding activities, J_1, J_2 … J_n, originate from the same preceding activity, I, the LFD of activity I will be the minimum LSD time of the following J_1, J_2 … J_n activities.

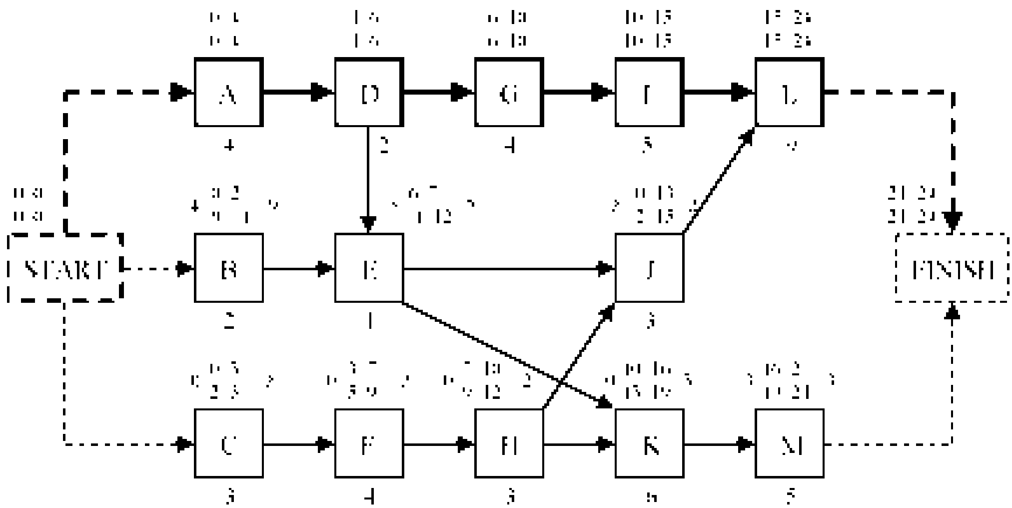
$$LFD_I = \text{MIN } LSD_{J_1, J_2 \ldots J_n}$$

For example, the succeeding activities, J and K, have a preceding link with activity E. Since the LSD of activity J is smaller than that of activity K, the LFD of activity H will be equal to the ESD of activity J. The remaining calculations are then as follows:

$LFD_H = LSD_J = 12$, therefore $LSD_H = 12 - 3 = 9$
$LFD_E = LSD_J = 12$, therefore $LSD_E = 12 - 1 = 11$
$LFD_D = LSD_G = 6$, therefore $LSD_D = 6 - 2 = 4$
$LFD_F = LSD_H = 9$, therefore $LSD_F = 9 - 4 = 5$
$LFD_A = LSD_D = 4$, therefore $LSD_A = 4 - 4 = 0$
$LFD_B = LSD_E = 11$, therefore $LSD_B = 11 - 2 = 9$
$LFD_C = LSD_F = 5$, therefore $LSD_C = 5 - 3 = 2$
$LFD_{START} = LSD_A = 0$, therefore $LSD_{START} = 0 - 0 = 0$

The precedence network in Figure 3.11 includes both the forward and backward paths calculations. It also highlights critical activities, which are identified by having the same ESD and LSD times (as well as EFD and LFD times). The critical activities A, D, G, I and L then form a critical path, which is the longest pass through the network.

Figure 3.11 The calculated precedence schedule



Free and total float

The definitions of free and total float are the same as for the arrow method. 'Free float' is defined as the amount of time by which a particular non-critical activity, I, in a schedule may be delayed without delaying the ESD of the succeeding activity, J. When activity I is followed by two or more succeeding activities, $J_1, J_2 \ldots J_n$, a free float value is calculated for each link that activity I has with the following activities, $J_1, J_2 \ldots J_n$. The smallest of the individual free float values becomes a free float of activity I.

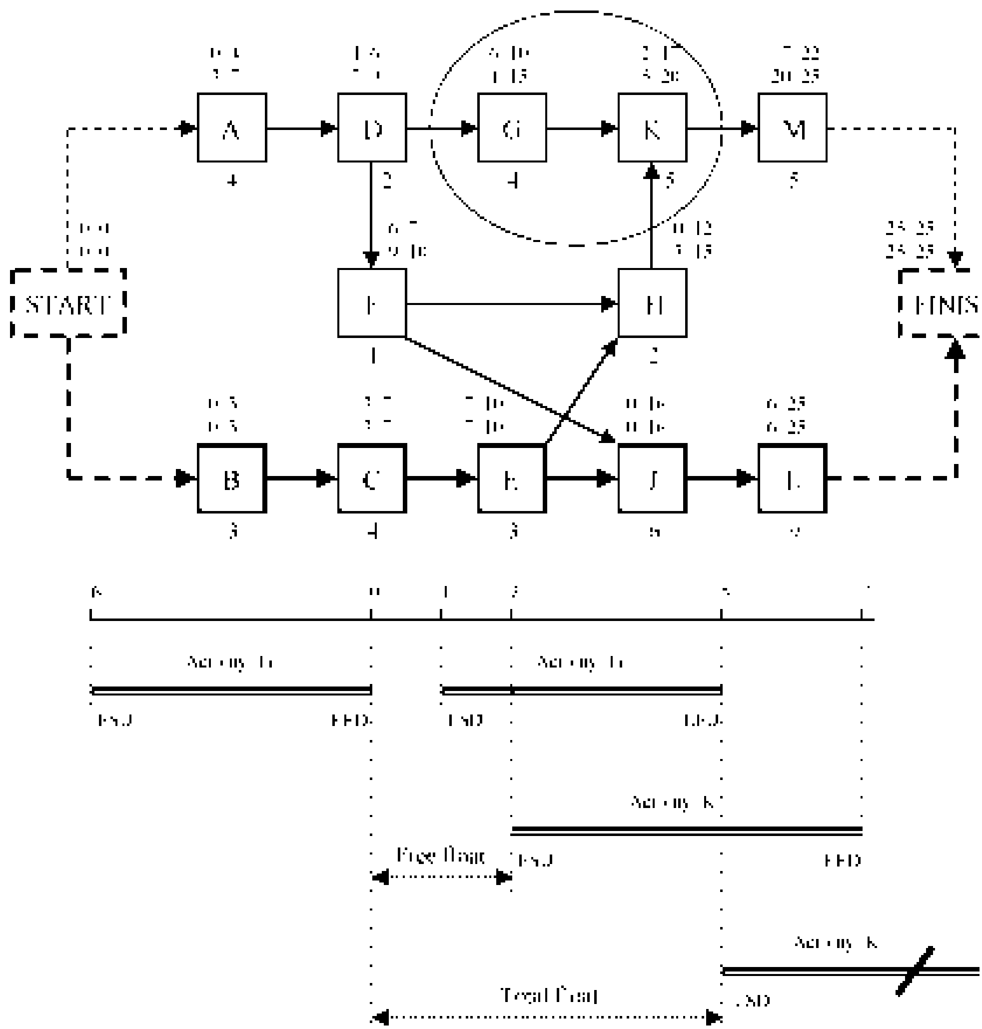
$$\text{Free Float}_I = \text{MIN}\ (\text{ESD}_{J_1, J_2 \ldots J_n} - \text{EFD}_I)$$

'Total float' is the amount of time by which a particular non-critical activity, I, in the schedule may be delayed without delaying the LSD of the succeeding activity, J. When the preceding activity, I, is followed by two or more succeeding activities, $J_1, J_2 \ldots J_n$, a total float value is calculated for each link that activity I has with the succeeding activities $J_1, J_2 \ldots J_n$. The smallest of the individual total float values is then a total float of activity I.

$$\text{Total Float}_I = \text{MIN}\ (\text{LSD}_{J_1, J_2 \ldots J_n} - \text{EFD}_I)$$

The graphic definition of float in a precedence network is given in Figure 3.12 using activities G and K. When the relationship between these two activities is illustrated in a bar chart format, the meaning of free and total float becomes immediately apparent.

Figure 3.12 The graphic definition of float in a precedence network



It should become apparent from the definition of free and total float that for any given non-critical activity, free float cannot be greater than total float:

$\text{Free Float}_I \leq \text{Total Float}_I$

Free and total float of the non-critical activities B, C, E, F, H, J, K and M in Figure 3.11 will now be calculated. Let's start with activity B.

$FF_B = ESD_E - EFD_B = 6 - 2 = 4$
$TF_B = LSD_E - EFD_B = 11 - 2 = 9$

Free and total float of the other non-critical activities are as follows:
$FF_C = ESD_F - EFD_C = 3 - 3 = 0$
$TF_C = LSD_F - EFD_C = 5 - 3 = 2$

$FF_E = ESD_J - EFD_E = 10 - 7 = 3$ or
$FF_E = ESD_K - EFD_E = 10 - 7 = 3$, therefore, $FF_E = 3$
$TF_E = LSD_J - EFD_E = 12 - 7 = 5$ or
$TF_E = LSD_K - EFD_E = 13 - 7 = 6$, therefore, $TF_E = 5$

$FF_F = ESD_H - EFD_F = 7 - 7 = 0$
$TF_F = LSD_H - EFD_F = 9 - 7 = 2$

$FF_H = ESD_J - EFD_H = 10 - 10 = 0$ or
$FF_H = ESD_K - EFD_H = 10 - 10 = 0$, therefore, $FF_H = 0$
$TF_H = LSD_J - EFD_H = 12 - 10 = 2$ or
$TF_H = LSD_K - EFD_H = 13 - 10 = 3$, therefore, $TF_H = 2$

$FF_J = ESD_L - EFD_J = 15 - 13 = 2$
$TF_J = LSD_L - EFD_J = 15 - 13 = 2$

$FF_K = ESD_M - EFD_K = 16 - 16 = 0$
$TF_K = LSD_M - EFD_K = 19 - 16 = 3$

$FF_M = ESD_{FINISH} - EFD_M = 24 - 21 = 3$
$TF_M = LSD_{FINISH} - EFD_M = 24 - 21 = 3$

A fully calculated precedence schedule is given in Figure 3.11. It shows a critical path formed by activities A, D, G, I and L. It also shows the values of free and total float of the non-critical activities. It is interesting to note that some non-critical activities such as J and M have free and total float identical, while the other non-critical activities don't. The reason is that the non-critical activities J and M have a succeeding link with the critical activities L and Finish respectively. Because critical activities have identical values of ESD and LSD, free and total float of preceding non-critical activities must therefore be identical.

The significance of free and total float was discussed in detail on pages 53–54 with regard to the arrow method. That section is equally relevant to the precedence method.

CONCEPT OF LINK LAG

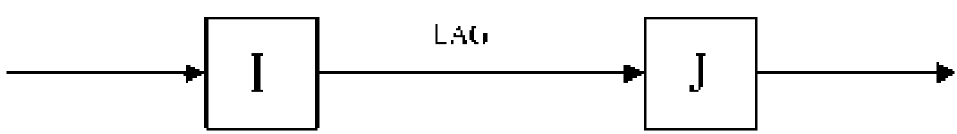
The mathematical procedure employed in critical path scheduling consists of forward and backward passes through the network. Networks with a small number of activities, such as the one in Figure 3.11, can easily be computed manually, but the complexity of computations increases with an increase in the size of the network. Computers are essential for scheduling large networks. When the first CPM software for use on personal computers was developed in the 1980s, these computers did not have the necessary computation power to handle the volume of information generated through the forward and backward passes. It required simplification of the computational process, particularly of the backward pass, and resulted in some degree of inaccuracy of computer-generated CPM scheduling.

The concept of 'link lags' offers a more efficient method of calculating a precedence network. It eliminates the backward pass calculations entirely. Apart from computing the forward pass, the remaining calculations are governed by simple formulas.

What is a link lag?

In a precedence network, a dependency line connecting a pair of preceding and succeeding activities is also referred to as a 'link lag' or simply a 'lag'. In reference to Figure 3.13, a link lag between activities I and J implies that the start of activity J lags after the finish of the preceding activity, I.

Figure 3.13 A link lag in the precedence network



If activity J starts immediately after the completion of activity I, the lag value is zero. If, however, activity J starts some time after activity I has been completed, then the lag value will be positive. It is therefore possible to express lag using the following formula:
$LAG_{IJ} = ESD_J - EFD_I$

A closer examination of the above formula shows that LAG_{IJ} is expressed in the same manner as the free float of activity I. Therefore the free float of activity I is LAG_{IJ}. For more than one succeeding J activity, the general free float formula is:

$$\text{Free Float}_I = \text{MIN}\ (\text{LAG}_{\ I\ J_1\ J_2\ \ldots\ J_n})$$

Total float can also be expressed using the concept of lag (Harris 1978). It can be derived from the expression of total float given on pages 60–61 and from other expressions of total float that can be derived from Figure 3.12. Three formulae of total float have been derived. They are as follows:

$TF_I = LSD_J - EFD_I$ (1) or
$TF_I = LFD_I - EFD_I$ (2) or
$TF_I = LSD_I - ESD_I$ (3)

If the total float formula (1) expressed for activity I holds, it must also hold for activity J or any other activity. Hence,

$TF_J = LSD_J - ESD_J$ (4) and by rearranging the formula,
$LSD_J = TF_J + ESD_J$ (5)

Substituting the above expression (5) of LSD_J to the formula (1) results in:

$TF_I = TF_J + ESD_J - EFD_I$ by rearranging the formula,
$TF_I = (ESD_J - EFD_I) + TF_J$

The expression in brackets ($ESD_J - EFD_I$) is in fact LAG_{IJ}. Therefore,

$$TF_I = LAG_{IJ} + TF_J$$

With more succeeding activities $J_1\ J_2 \ldots J_n$, the general formula for total float is:

$$\text{Total Float}_I = \text{MIN}\ (\text{LAG}_{\ I\ J_1\ J_2\ \ldots\ J_n} + TF_J\ )$$

It is worth noting that in order to calculate total float of the preceding activity, I, the planner needs to know the value of total float of the succeeding activity, J. Since critical activities have zero total float, calculation of total float of preceding non-critical activities will start from succeeding critical activities, one of which will be the terminal activity that gives the total schedule duration.

Link lag process

The computation process of a precedence schedule using a link lag approach involves a number of sequential steps:

Step 1: Perform a forward pass and calculate ESDs and EFDs of all activities in a schedule.

Step 2: Calculate link lags.

Step 3: Identify a critical path. The critical path is a path of zero lags.

Step 4: Calculate free and total float.

Step 5: Calculate the LSDs and LFDs of all activities in a schedule. Instead of performing a backward path, the values of LSDs and LFDs are calculated from the total float formula 2:

$TF_I = LFD_I - EFDI_I$ (2)

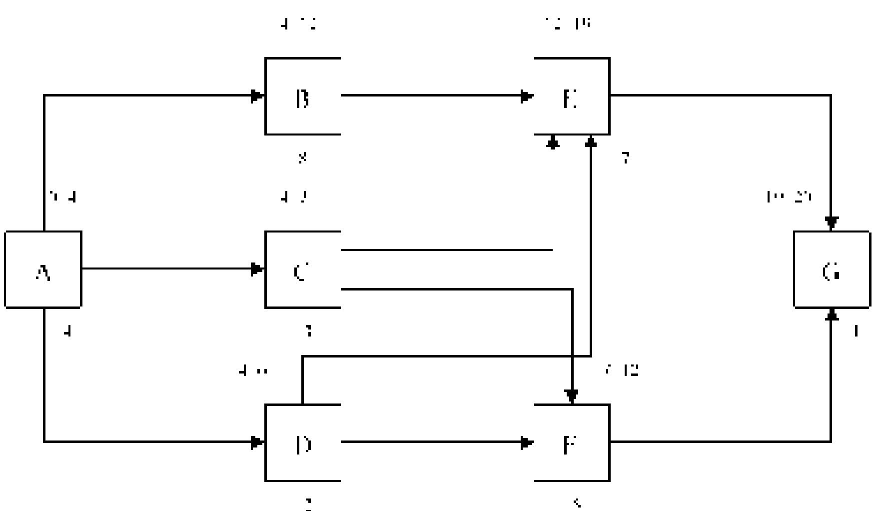
From this expression, the value of the LFD is calculated as:

$LFD_I = TF_I + EFD_I$

The activity's LSD is then calculated by deducting its duration from the value of the LFD.

Let's now calculated a simple precedence schedule using the concept of lag. A schedule in given in Figure 3.14.

Figure 3.14 Example of a precedence schedule

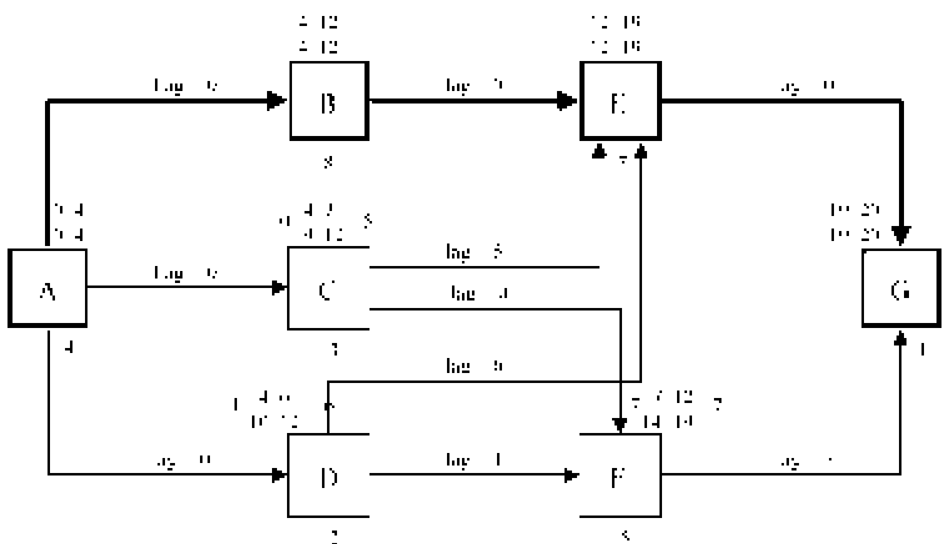


Step 1 involves a forward pass. Values of ESDs and EFDs of the activities in the schedule have already been calculated. In Step 2 lags are calculated. A list of all lags in the schedule is given below together with individual calculations:

$Lag_{AB} = ESD_B - EFD_A = 4 - 4 = 0$
$Lag_{AC} = ESD_C - EFD_A = 4 - 4 = 0$
$Lag_{AD} = ESD_D - EFD_A = 4 - 4 = 0$
$Lag_{BE} = ESD_E - EFD_B = 12 - 12 = 0$
$Lag_{CE} = ESD_E - EFD_C = 12 - 7 = 5$
$Lag_{CF} = ESD_F - EFD_C = 7 - 7 = 0$
$Lag_{DE} = ESD_E - EFD_D = 12 - 6 = 6$
$Lag_{DF} = ESD_F - EFD_D = 7 - 6 = 1$
$Lag_{EG} = ESD_G - EFD_E = 19 - 19 = 0$
$Lag_{FG} = ESD_G - EFD_F = 19 - 12 = 7$

The above lag values have been added to a schedule in Figure 3.15. It should be noted that the values of lags are also values of free float. Step 3 requires identification of a critical path. Since it is defined as a path of zero lags, it is then a simple task to locate a critical path. There is only one path of zero lags in a schedule in Figure 3.15. It connects the critical activities A–B–E–G. In step 4, free and total float are calculated. Since critical activities have no float, the calculation process will only involve non-critical activities. Free float have already been calculated as lags and it is therefore a simple task of assigning them to each non-critical activity.

Figure 3.15 Example of a precedence network including lags and the critical path



Total float, however, needs to be calculated from the formula derived previously. The computation process started from the end critical activity, G, which has two preceding links, one with the non-critical activity E and the other with the critical activity F.

The latter link is discarded since it involves critical activities. Consequently,

$TF_F = LAG_{FG} + TF_G = 7 + 0 = 7$

Similarly,

$TF_C = LAG_{CE} + TF_E = 5 + 0 = 5$ or
$TF_C = LAG_{CF} + TF_F = 0 + 7 = 7$, therefore, $TF_C = 5$

$TF_D = LAG_{DE} + TF_E = 6 + 0 = 6$ or
$TF_D = LAG_{DF} + TF_F = 16 + 7 = 8$, therefore, $TF_D = 6$

The values of free and total float are given in Figure 3.15.

In the last step, values of LSD and LFD of all the activities in the schedule are calculated from a simple total float formula:

$TF_I = LFD_I - EFD_I$

Then

$LFD_I = TF_I + EFD_I$

Let's now calculate the LSD and LFD values of the non-critical activities. The LSD and LFD values of the critical activities are already known since they are the same as the ESD and EFD values respectively.

$LFD_C = TF_C + EFD_C = 5 + 7 = 12$, $LSD_C = LFD_C - duration_C = 12 - 3 = 9$
$LFD_D = TF_D + EFD_D = 6 + 6 = 12$, $LSD_D = LFD_D - duration_D = 12 - 2 = 10$
$LFD_F = TF_F + EFD_F = 7 + 12 = 19$, $LSD_F = LFD_F - duration_F = 19 - 5 = 14$

The entire computation process has now been completed and all the necessary information has been derived. The fully calculated schedule is given in Figure 3.15.

SUMMARY

This chapter has presented the basic concept of critical path scheduling. In the first part the arrow method was described in terms of network construction, forward and backward path calculation, identification of a critical path, and calculation of float. The precedence method of critical path scheduling was then examined and its computation process described. In the final part of this chapter the concept of link lag as an alternative method of critical path scheduling was defined and its computational simplicity demonstrated by an example.

The concept of critical path scheduling will be further expanded in other chapters of this book. The following three chapters will discuss applications of the CPM method in resource scheduling, overlapping of activities, and in monitoring and controlling of projects respectively. Computer-based CPM scheduling will be examined in Chapter 7. The extension of the critical path method to critical chain scheduling will briefly be discussed in Chapter 8. Probability scheduling using the Monte Carlo simulation and PERT techniques will be explored in Chapters 12 and 13 respectively.

EXERCISES

Solutions to the exercises can be found on the following UNSW Press website: http://www.unswpress.com.au

EXERCISE 3.1

Plot both arrow and precedence schedules for the following list of activities:

Activity	Depends on completion of these activities
C	A
D	A
E	A
F	D
G	C and D
H	E
J	B
K	B and E
L	B, D and E
M	F and G
N	H, K and L
O	G and J
P	M, N and O

EXERCISE 3.2

Plot both arrow and precedence schedules for the following list of activities:

Activity	Depends on completion of these activities
C	A
D	A
E	B
F	B
G	C
H	B and D
J	B and D
K	J
L	J
M	E
N	F
O	E, G, H, K and L
P	M and N
Q	M and O

EXERCISE 3.3

Plot both arrow and precedence schedules for the following list of activities:

Activity	Depends on completion of these activities
B and C	A
G and K	F
H	E and G
D and J	B,C and H
L	J and K
N	D, J and K
M	L

EXERCISE 3.4

Plot both arrow and precedence schedules for the following list of activities:

Activity	Depends on completion of these activities	Duration
A	START	2
B	START	3
C	START	4
D	A and B	4
E	B	10
F	B	12
G	C	6
H	A	5
J	D, E and H	12
K	F and G	4
L	G	7
M	L	7
N	J	4
O	N	3
P	J and L	5
Q	J, K and M	6
R	N and P	3
S	O	8
T	Q	10
U	Q and R	5

a) **Calculate the schedule using the forward and the backward path method. Determine the ESD, EFD. LSD, LFD values for all the schedule activities.**
b) **Determine the position of a critical path.**
c) **Calculate free and total float of all non-critical activities.**
d) **Fully recalculate the schedule using the link lag approach.**

EXERCISE 3.5

Plot both arrow and precedence schedules for the following list of activities:

Activity	Depends on completion of these activities	Duration
A	START	5
B	START	3
C	A	3
D	A	2

E	B	2
F	B	4
G	C	7
H	B and D	2
J	B and D	4
K	J	6
L	J	5
M	E	7
N	F	6
O	E, G, H, K and L	5
P	M and N	11
Q	M and O	3

a) **Calculate the schedule using the forward and the backward path method. Determine the ESD, EFD. LSD, LFD values for all the schedule activities.**

b) **Determine the position of a critical path.**

c) **Calculate free and total float of all non-critical activities.**

d) **Fully recalculate the schedule using the link lag approach.**

EXERCISE 3.6

Apart from having a link with the succeeding activity B, activity A has no further succeeding links. Scheduling information for activity A is given below.

Duration	4 days		
ESD	4	FF	5
EFD	8	TF	7

Activity B has a link with the preceding activity A and may have links with other unspecified preceding activities. Duration of activity B is two days. Determine from a bar chart relationship between activities A and B the following scheduling information for activities A and B:

For activity A:

LSD	…
LFD	…

For activity B:

ESD	…	LSD	…
EFD	…	LFD	…

CHAPTER 4

RESOURCE MANAGEMENT

INTRODUCTION

The purpose of this chapter is to introduce the concept of resource management, which is vital in medium and short-range planning. Specifically, this chapter looks at how resources are distributed throughout a project. It also examines the process of resource levelling, and the management of labour, material and plant/equipment resources.

The concept of critical path scheduling was described in the previous chapter. The discussion has thus far been restricted to the construction of networks in the form of time schedules. Time schedules were defined in Chapter 1 as plans that are concerned with developing the overall production strategy within a given time-frame. They tend to be overly optimistic because they largely ignore resources. Time scheduling in fact assumes that resources are unlimited and can be allocated to activities in a schedule whenever needed. Despite ignoring resources, they are nevertheless useful in long-range planning when all that a planner is interested to know is the overall production strategy and the total time-frame for a project.

Time schedules are, however, inappropriate in medium to short-range scheduling where efficiency in the use of resources is of the utmost importance. There are two reasons for this. First, the availability of required resources is almost always limited in some way, for example in quantity of resources or in the required level of skill and technical specification. The use of resources may also be limited by their cost. To illustrate this, let's assume that according to a time schedule the contractor is required to repair the sand-stone façade of a historical building within four months. To meet the scheduled completion time, the contractor expects to employ eight highly skilled stonemasons. But only six suitably qualified persons are available locally for work. The contractor's options are: to bring additional stonemasons from interstate or overseas at an extra cost; to do the work with six stonemasons only and risk delaying the contract with the consequence of incurring liquidated damages; or to try to renegotiate the contract with the client. The assumption of 'unlimited resources' in the time schedule has clearly placed the contractor in a difficult position.

The second reason is that time scheduling ignores the efficiency of committed resources. Let's assume that a time schedule for construction of a high-rise building requires a number of activities such as formwork, reinforcement, airconditioning ductwork, concreting, brickwork, precast concrete façade, scaffolding, etc., all to be performed concurrently within specific periods. Let's assume further that the contractor has committed to the project a specific type of tower crane based on the contractor's past experience of a machine that can handle the total volume of work to be performed. The crane has already been erected on the site. While the crane may have the capacity to handle the total volume of work, the contractor learns rather too late that it is unable to handle the daily volume of work within specific periods when a number of activities are scheduled in parallel. If the contractor is unable to increase the capacity of the crane or supplement it with additional hoisting equipment, delays in the execution of the work are likely. To minimise such a possibility, the contractor would attempt to reschedule the work around the committed crane by using the available float (spare time) in non-critical activities. This will require delaying the start of some of non-critical activities in an attempt to reduce the resource demand peak. However, the amount of float may not always be sufficient to permit effective rescheduling of the work around committed resources.

Resource scheduling overcomes shortcomings of time scheduling by assuming that resources are always limited in some way. Its function is to allocate work efficiently to what resources have already been committed. By considering resources, a schedule becomes more realistic and more representative of the actual production process.

The critical path method is suitable for resource scheduling. The actual process of resource scheduling involves first constructing a time schedule then converting it to a resource schedule through a process of resource levelling. Other scheduling techniques such as a 'multiple activity chart' and a 'line of balance' are effective in resource scheduling and are discussed in detail in Chapters 9 and 10.

RESOURCES

'A resource is something that lies ready for use or that can be drawn upon for assistance' (Walker 1990:55). Examples of resources are:

- time
- labour
- plant or equipment
- materials
- money.

Time is the main resource in time scheduling, while resource scheduling is concerned with the most efficient use of labour, plant/equipment and materials. Managing labour, plant/equipment and materials will be examined later in this chapter. Money is obviously an important resource in construction, but its management lies outside the scope of this book and the reader is referred to Raftery (1991) and Betts & Gunner (1993).

DISTRIBUTION OF RESOURCES

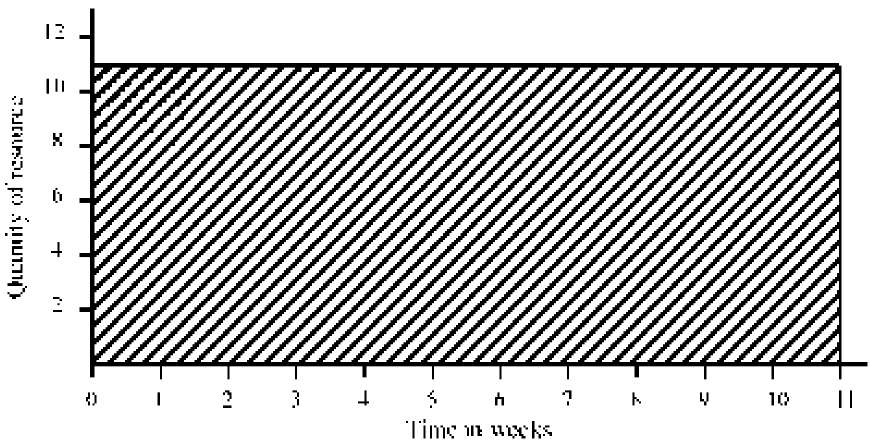
The financial success of a project is largely dependent on the ability of a project manager to employ resources efficiently. If resources are employed inefficiently, for example a large tower crane gets only 60 per cent use or a group of carpenters is idle for two days because there is no work for them, a project incurs extra costs. The more inefficient the project is in its use of resources, the more extra costs it will incur. It is a challenge for a project manager to ensure that resources are used to their maximum efficiency, thus keeping the cost down. This requires:

- an orderly and even flow of work
- continuous work without interruptions (idle time costs money)
- an adequate volume of allocated resources
- the employment of appropriately skilled labour resources, technologically adequate plant/equipment resources and material resources of the highest quality
- the employment of a correct mix of labour to plant/equipment.

Even or uniform distribution of resources

Such efficiency in the use of resources implies that resources should be distributed evenly as illustrated in Figure 4.1. But it is unrealistic to expect to achieve such an even distribution over the entire period of the project.

Figure 4.1 Example of the uniform distribution of a resource

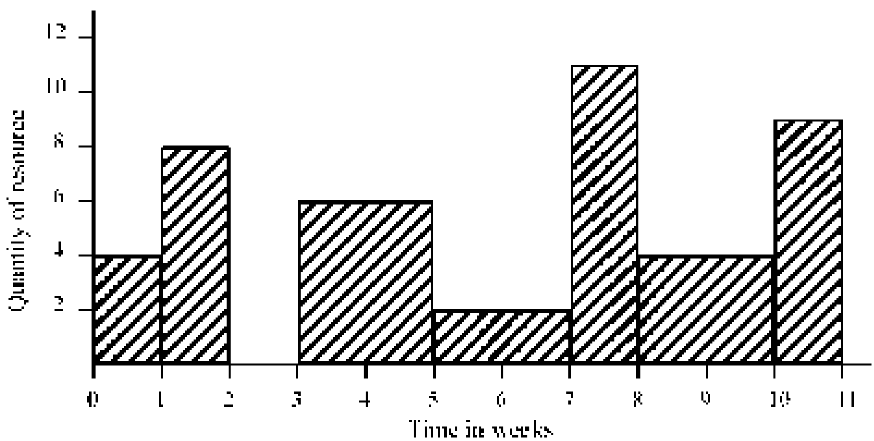


Uneven distribution of resources on construction projects is largely related to the fluctuating volume and intensity of work over the project period. In the initial construction period, involving mainly ground works, only a small number of resources, both human and physical, are engaged. Thereafter, more and more subcontractors and other resources join the project until at the peak of construction activity, which usually occurs about two-thirds into the project period, all the resources are engaged. In the final phase, individual subcontractors and other resources gradually withdraw from the project when they are no longer needed. The volume and intensity of work then gradually diminishes until the project is fully accomplished at the end of the contract period.

Uneven distribution of resources

The labour resource tends to be unevenly distributed over the period of a project. This is graphically illustrated in Figure 4.2. Let's assume that Figure 4.2 illustrates distribution of the labour resource of a civil engineering contractor engaged in construction of some drainage work. Assume further that the contractor's workers are multiskilled and capable of performing all the activities associated with this project. The scheduled resource demand in Figure 4.2 will clearly result in a highly inefficient use of the labour resource. It is unlikely that the contractor would attempt to build the project by varying the number of workers from day to day to meet such an uneven resource demand.

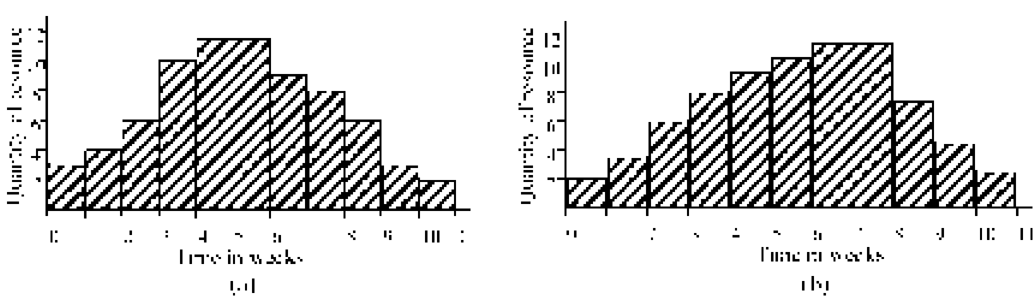
Figure 4.2 Example of the uneven distribution of a resource



Normal, skewed and complex distributions of resources

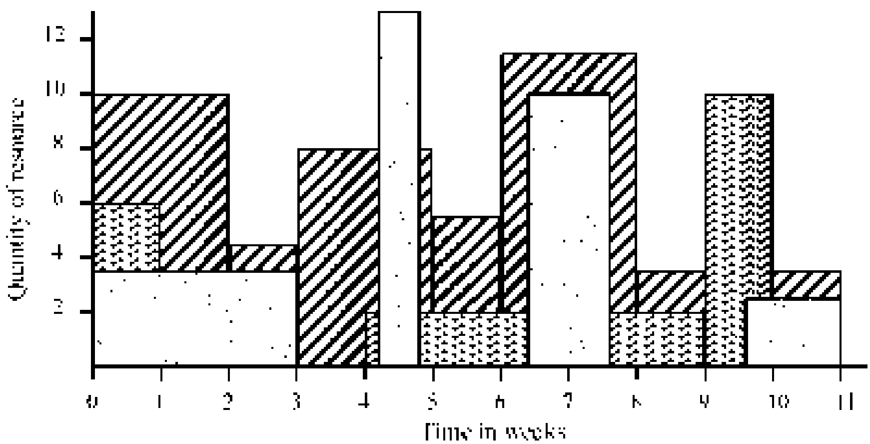
Between the extremes of even and uneven resource distributions, many other distributions of which normal, skewed and complex are worth noting. The normal and in particular the right-skewed distribution are examples of ideal distributions of resources on construction projects. This is because they take into account a low level of activity in the beginning and the tapering off of the work at the end of the project. These distributions are shown graphically in Figure 4.3 (a) and (b) respectively.

Figure 4.3 Example of the normal and the right-skewed distributed resources



Managing one unevenly distributed resource may not be so difficult, but managing an array of unevenly distributed resource such as those given in Figure 4.4, which is characteristic of most construction projects, is a challenging task. In suitable CPM software, however, project managers have a powerful tool for managing even very complex distributions of resources. A brief overview of how computer software can manage resources will be given in Chapter 7.

Figure 4.4 A complex distribution of resources



RESOURCE LEVELLING

The previous section has described different patterns of resource distribution and highlighted those that are desirable for achieving resource efficiency. Since the distribution of resources in construction projects is largely uneven, the task of the planner is to ensure their best possible use.

A time schedule requires that activities begin at their earliest start dates. Because non-critical activities have float, they could start at a later date. It is this characteristic of non-critical activities that provides an opportunity for a more efficient management of committed resources. This is achieved by 'resource levelling', which is a process of rescheduling the work within the limits of float by adjusting resource peaks and troughs.

Harris (1978) identified two approaches to resource levelling: linear programming and heuristics. Although mathematically superior, linear programming is computationally intensive, particularly in relation to construction schedules. Heuristic processes offer low computation intensity but may not provide an optimum solution. It was because of computational intensity that linear programming came to be passed over in favour of heuristic processes. Harris (1978: 255) defines heuristics as 'a set of rules of thumb designed to progressively lead the user [by trial and error] to a feasible solutions'.

The development of heuristic processes has followed two distinct paths: unlimited resource levelling and limited resource levelling. Unlimited resource levelling attempts to minimise the resource input and therefore its cost while maintaining the project duration generated by the CPM schedule. Limited resource levelling attempts to minimise the project duration while keeping the resource levels constant.

In the practical sense, since the finish date of construction projects is commonly fixed by a contract, unlimited resource levelling is a more appropriate method to use. The most commonly used unlimited method is the sum of squares of the daily resource demands. Most CPM software performs resource levelling using this method. An alternative approach, referred to as the 'minimum moment method', was proposed by Harris (1978). It is based on the sum of squares method with the addition of an 'improvement factor' that selects the activity to be reallocated along its float.

Manual resource levelling of only one resource is extremely time-consuming. Considering that construction projects comprise many resources, manual levelling is just not feasible. Computers can perform this task quickly and efficiently. However, to get a better insight into the process of resource levelling, a method of trial and error will now be briefly described.

Resource levelling by the method of trial and error

The method of trial and error is an example of the limited resource-levelling approach where the level of resources is fixed while the schedule duration may be varied. It represents the most basic heuristic algorithm, which consists of the following steps:

1. Prepare a time schedule for the project and calculate it.
2. Convert the time schedule to a scaled bar chart and allocate required resources to each activity.
3. Calculate total daily resource sums for each day of the schedule.
4. Plot a histogram of the resource demand (one for each resource).
5. Determine resource availability on a day-to-day basis. Compare demand and availability, and determine if the demand histogram is acceptable.
6. Evaluate possible alternatives for levelling using the resource utilisation factor (RUF).

$$\text{RUF} = \frac{\text{Useable resource} \times \text{Days used}}{\text{Useable resource} \times \text{Days available}} \times 100\%$$

7 **Implement levelling by rescheduling selected activities within the limits of their float.**

The levelling method of trial and error attempts to move non-critical activities along their float away from peak periods of resource demand while keeping the resource input levels constant. The aim is to achieve best possible use of committed resources without unduly extending the project period. In shifting non-critical activities along their float, care is needed to ensure that the logical links between the activities are maintained.

Example of resource levelling using the method of trial and error

Resource levelling will be performed on a simple precedence schedule in Figure 4.5 for one resource only. Assume that the resource in question is labour. Let's further assume that the workers are multiskilled and therefore able to perform any activity in the schedule. The maximum number of available workers for this job is seven. The contractor's task is to ensure that this project could be accomplished with seven workers only.

Figure 4.5 A precedence network for the resource-levelling example

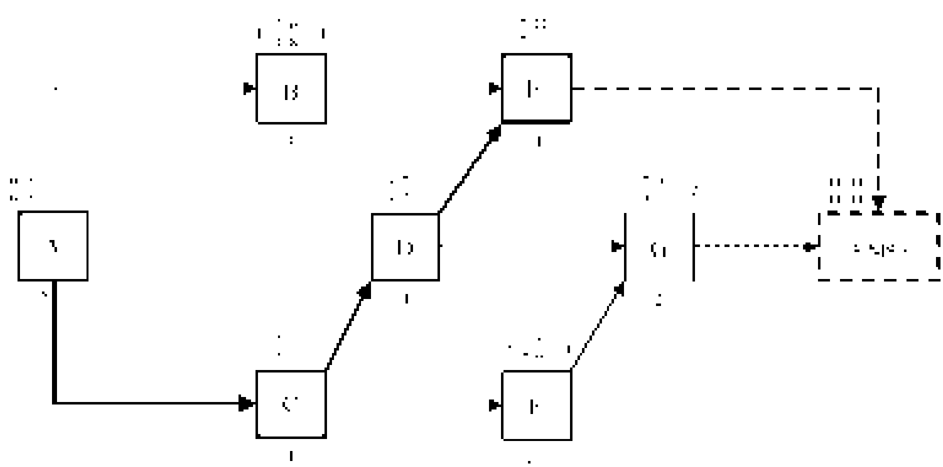


Table 4.1

Data for the resource-levelling example

Activity days	Duration in rate per day	Resource days	Resource
A	2	3	6
B	4	5	20
C	1	6	6
D	4	2	8
E	4	4	16
F	2	2	4
G	2	2	4
Total			64

Resource levelling using the method of trial and error is best performed on a scaled bar chart. Let's begin resource levelling step by step.

Step 1. Prepare a time schedule for the project and fully calculate it

The fully calculated precedence schedule is given in Figure 4.5.

Step 2. Convert the time schedule to a scaled bar chart and allocate resources to each activity

A time schedule in Figure 4.5 was converted to a linked bar chart (see Figure 4.6). The bar chart is organised so that the critical activities are separated from the non-critical ones. Each activity displays its daily labour resource rate.

Step 3. Calculate total daily resource sums

At the base of the bar chart, the total daily resource sums are calculated. The total daily resource sums $\sum 0$ reflect the distribution of the labour resource for the original time schedule, which ranges from two to 11 workers.

Step 4. Plot a histogram of the labour resource demand

The labour resource demand histogram is given in Figure 4.7(a). It shows the demand peak of 11 workers on day 3. With only seven workers available for this job, the demand levels on days 3, 4 and 5 cannot be met.

Figure 4.6 A bar chart of the resource-levelling example

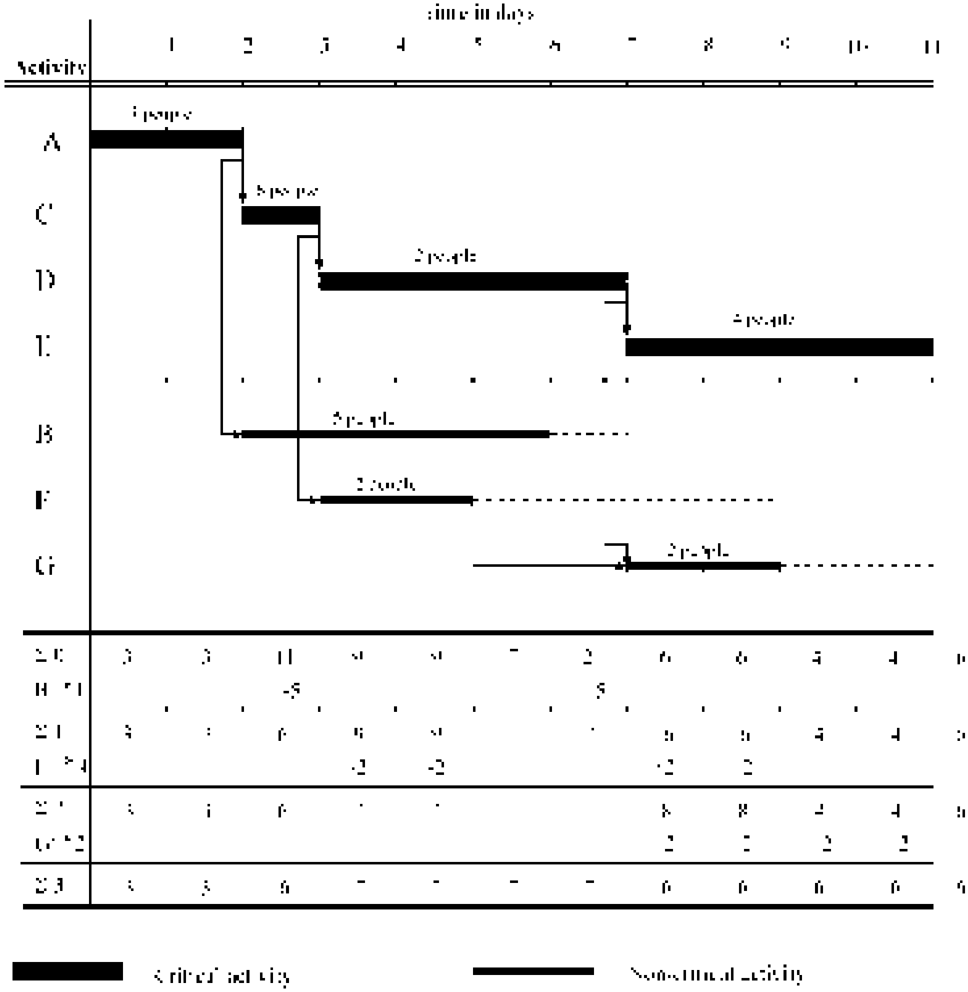
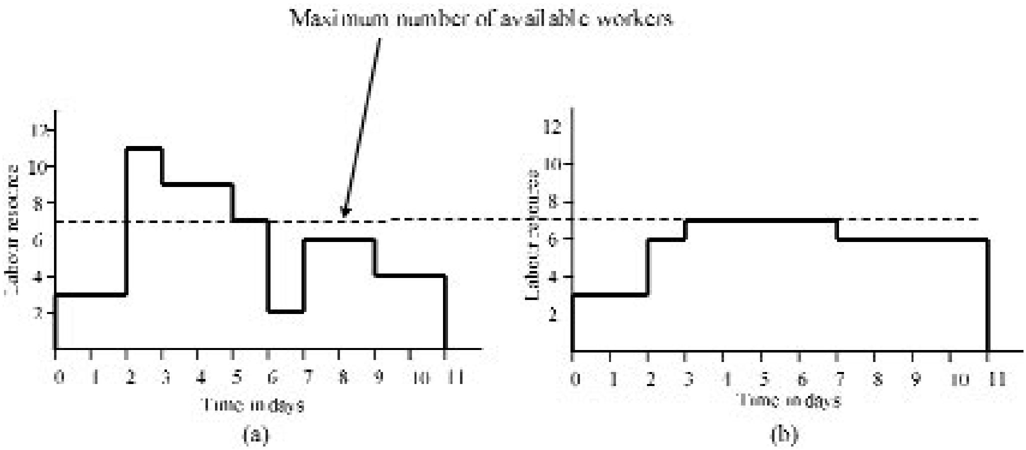


Figure 4.7 A histogram of the labour demand before and after levelling



Step 5. Level the labour resource

The peak of the resource demand on day 3 was caused by two concurrent activities, B and C. Activity B has one day of total float. If moved by one day to the right, the peak of 11 persons on day 3 will be reduced to six and the resource daily sum on day 7 would increase from two to seven. It is therefore logical to commence levelling by moving activity B by one day. This is noted on the bar chart as 'B → 1'. The new total daily labour sums $\sum 1$ are then calculated (see Figure 4.6). It should be noted that activity B has now become critical since its float has been used up.

Although the peak of 11 workers on day 3 has been reduced, the available labour resource is still insufficient to deal with the work scheduled for days 4 and 5. On these two days, nine people are required per day to work on three concurrent activities, B, D and F. Of these, only activity F is non-critical, with four days of total float. Moving activity F by two days to the right would reduce the resource sums on days 4 and 5 by two days to seven, but at the same time would increase the resource sums on days 6 and 7 by two days to nine. It means that activity F would need to be moved by a further two days; this is possible since it has four days of total float. However, shifting activity F beyond two days requires shifting of activity G in order to maintain the logical order of work. When moved by four days, activity F will increase the daily labour demand on days 8 and 9 from six to eight. However, when activity G is moved by two days, the labour demand on days 8 and 9 will drop back to six. After activity F has been moved by four days, the total daily labour sum $\sum 2$ was calculated within the range from three to eight workers. Activity F is now critical.

After activity G has been shifted by two days, the calculated total daily labour sums $\sum 3$ show the range of workers as between three and seven. The available crew of workers is now able to meet the daily labour demand. It should be noted that activity G has also become critical

Step 6. Evaluate the levelling process

The levelling process described above provides a solution for the given problem, that is, the project can be accomplished by employing the maximum of seven workers. The labour demand histogram after levelling given in Figure 4.7(b) shows that the labour resource is now better utilised. This is verified by the calculation of the RUF, which has improved from 52.9% to 83.1%.

$$\text{RUF (before levelling)} = \frac{\text{Useable resource} \times \text{Days used}}{\text{Useable resource} \times \text{Days available}} \times 100\% = 52.9\%$$

$$\text{RUF (after levelling)} = \frac{\text{Useable resource} \times \text{Days used}}{\text{Useable resource} \times \text{Days available}} \times 100\% = 83.1\%$$

(Note that in calculating the denominator in the above equations it was assumed that the peak of the resource demand would be required for the duration of the project.)

The impact of resource levelling on a schedule

The process of resource levelling reallocates the work in the original time schedule to achieve the most efficient use of committed resources. The final outcome of resource levelling is a resource-based schedule in which all the activities are critical in terms of committed resources. Furthermore, there are also those activities that are critical in terms of time (those on the critical path). The transformation of a time schedule to a resource schedule, which was demonstrated on the above example, raises a number of interesting issues:

1 Resource levelling reduces the amount of float

In the above example, the total float of the non-critical activities was fully used up, turning the non-critical activities B, F and G into critical ones. With more critical activities and less float, the ability of the resource schedule to absorb future delays is severely reduced. When scheduling a project, the planner will need to consider carefully the trade-off between a more efficient use of resources on one hand and the loss of float on the other.

2 Resource levelling shifts the work more towards the end of the project

Examination of the labour demand histograms before and after levelling clearly shows that resource levelling shifts more work to the end of the project. The accumulation of more work at this stage places more emphasis on coordination of activities, for which more supervisors may be needed. Another implication is that the contractor's cash flow will be altered.

3 Resource levelling locks activities into specific start and finish dates

In resource levelling, non-critical activities are shifted along their float to specific start and finish dates. The failure to start those activities as scheduled will cause the level of resource demand to be out of balance with the level of committed resources. It may therefore be said that after a schedule has been resource-levelled, all of its activities are critical in terms of committed resources, even if they have float. They must start and finish as specified. It follows that a resource-levelled schedule may be difficult to maintain where the risk of potential time overruns is high. A prudent approach to resource scheduling is to ensure that precautionary time and resource buffers are built into the schedule to mitigate the impact of future unforeseen delays.

Resource levelling of critical activities

Some schedules may contain a large proportion of critical activities, or critical activities may be dominant in their specific parts. Levelling such schedules is obviously difficult in the absence of float. However, if the planner has some flexibility in varying the distribution of a resource day by day, two potential approaches to resource levelling could be adopted: to vary the distribution of a resource from day to day and/or splitting and varying the distribution of a resource. Let's examine these two approaches in turn.

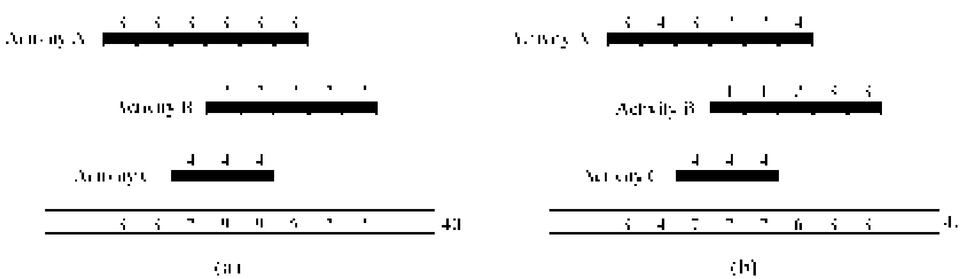
The first approach is based on the assumption that the resource may not always be distributed evenly from day to day. For example, the activity 'painting' is performed by a crew of three workers over six days. The planner would initially allocate the labour resource evenly by committing three workers to each day of the painting activity. However, the planner may be able to vary the number of workers from day to day while keeping the total labour demand constant. For example, the planner may commit four painters per day for the first three days and two per day for the remaining three days.

This may or may not be possible. The production rate of some activities such as excavation, steel fixing, painting, electrical and the like may possibly be increased proportionally to the increase in the volume of the resource. However, the same may not hold true for other activities that may be constrained in their performance by limited space, strict safety issues or specific design requirements such as those related to curing of materials.

Let's illustrate the method of varying the distribution of a resource on a simple example in Figure 4.8(a). Activities A, B and C are critical. Assume that the distribution of the resource in activities A and B can be varied. Let's further assume that only seven resource units are available to perform these three critical activities.

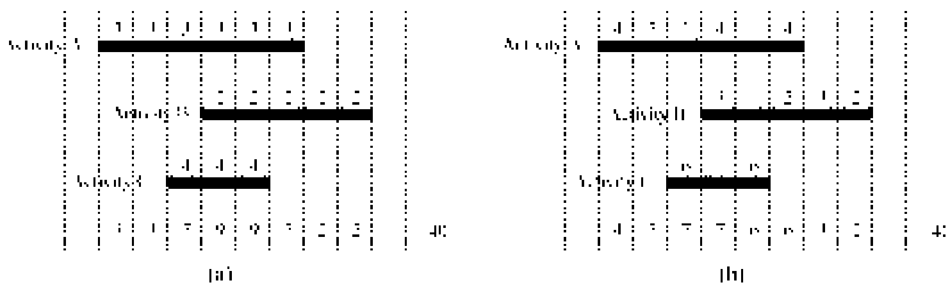
Since the activities are critical, no shifting along float is possible. But the distribution of the resource in activities A and B can be altered to bring the peak demand to seven units. This is illustrated in Figure 4.8(b).

Figure 4.8 Lowering the resource demand by varying the distribution of the resource



The second approach uses the ability of some activities to have specific periods designated as non-working. This has the effect of splitting an activity (it should be noted that not all activities are capable of being split). If the distribution of a resource can be varied within the split parts of the activity, the resource demand may be controlled. This approached is illustrated in Figure 4.9(a) and (b). After the resource has been split and varied in intensity, the scheduled work can be performed with seven resource units.

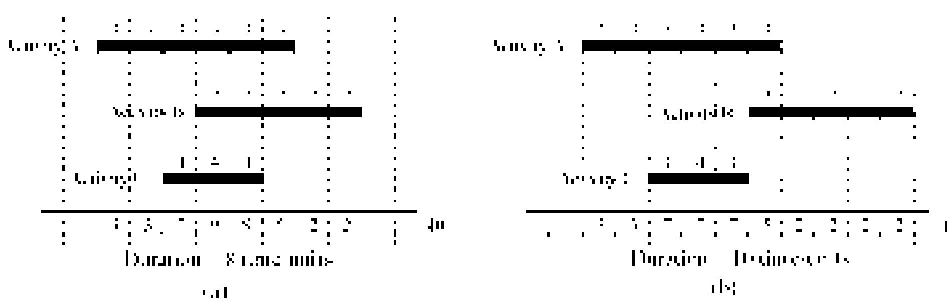
Figure 4.9 Lowering the resource demand by splitting and varying the distribution of the resource



Resource levelling by varying or by splitting the distribution of the resource is not restricted to critical activities but may be applied in the same manner to non-critical activities.

If the distribution of a resource cannot be varied or split and the activities have no float, extending the project period may be the only solution. Lowering the resource demand to seven units can achieved by delaying activity B, and hence the whole project, by two days (see Figure 4.10(a) and (b)).

Figure 4.10 Lowering the resource demand by extending the project duration



RESOURCE LEVELLING PERFORMED BY COMPUTERS

The method of trial and error (heuristics) has been used to explain the mechanics of resource levelling on a simple example involving a single resource. Levelling of a multitude of resources is a highly complex problem that is best performed by computers.

Most CPM software relies on the concept of unlimited resource levelling, which ensures that the duration of the project is not extended. Resource-levelling algorithms built into such software are commonly based on the statistical concept known as 'the sum of the squares of the daily resource demands'. Some software is highly refined and most reliable in its ability to level resources effectively, while some is relatively crude and less accurate. The levelling algorism of popular Primavera P3 software will be briefly examined in Chapter 7.

MANAGING THE LABOUR RESOURCE

The construction industry is a large employer of labour. Some construction workers are employed directly by contractors, while most are employees of subcontractors. Irrespective of who employs construction workers, when they are engaged in construction activities the contractor is responsible for the management of the entire workforce. There are a number of reasons for this. The first and probably the most important reason is efficiency: the contractor needs to integrate the work of directly employed workers and subcontractors within the overall project planning strategy. This requires coordination of the activities of preceding and succeeding subcontractors to ensure continuity of work, as even as possible distribution of labour resources, and adequate provision of plant and equipment on which the labour resource depends. The process of resource levelling described earlier can help in achieving efficient distribution of the labour resource throughout the project.

The second issue is related to the contractor's responsibility to comply with relevant statutes dealing with safety and the provision of safety equipment to the workers, and the provision of site amenities. With more workers on the site, the demand for safety equipment and amenities increases proportionally and so does the cost. If the contractor is able to decrease the labour resource from 150 workers to 100 without an undue increase in the time schedule, savings in the areas of safety and amenities are clearly apparent.

Having a very large number of workers engaged on a construction site can also create a problem in the efficient handling of personnel. Let's assume that a large high-rise commercial project will require at the peak of construction activities the services of around 2000 workers, if it is to be completed within the expected period. How will the contractor be able to effectively distribute such a large number of people through the job?

This is a very complex problem that requires, apart from determining the number of personnel hoists, consideration of a number of important issues. These may range from traffic congestion around the site created by the arrival and the departure of so many workers in the morning and the afternoon, congestion on the site itself created by the large workforce and the potential problems of managing so many people, to the loss of productivity caused by the time wasted while waiting for hoists. One possible solution would be to stagger the hours of work to reduce congestion. But in most urban areas, local development authorities may not permit such an extension outside the usual 7 am to 6 pm range. It may well be that due to restrictions imposed on the project by some of the factors mentioned above, the most effective and practical solution is to set an upper limit for the number of workers that can effectively be employed and moved on the site. The planning and scheduling of the project would then be guided by this upper labour resource limit. It would result in better efficiency of the labour resource, but at the expense of a longer construction period.

Managing the labour resource using histograms and trend graphs

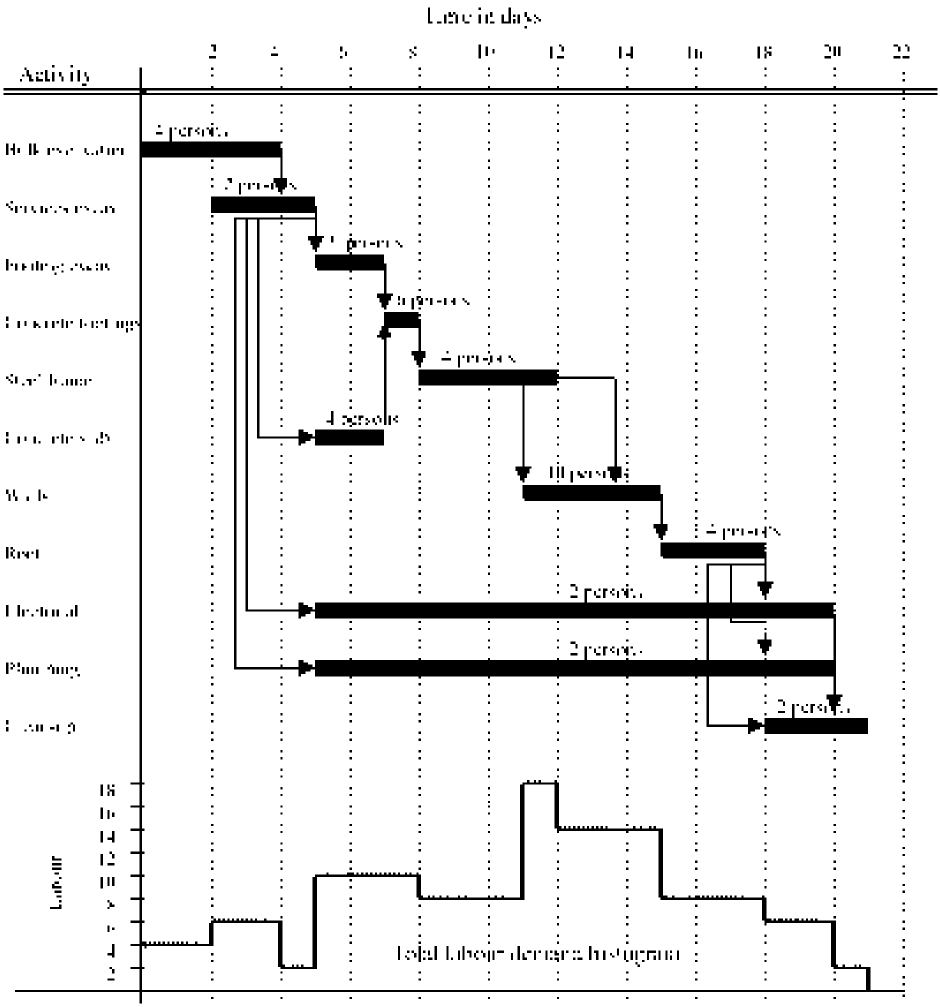
The foregoing discussion has examined problems associated with high peaks of labour demand. In summary, high peaks of demand impact on:

- the quantum of site amenities and safety equipment
- the carrying capacity of personnel hoists, lifts and other equipment needed to transport workers on the site
- overcrowding of the workplace
- supervisory needs.

Effective management of the labour resource requires, first, the determination of demand levels over the project period (it is good practice to forecast the labour demand day by day or week by week over the project period), second, the levelling of the resource to achieve its best use, and third, the control of its use.

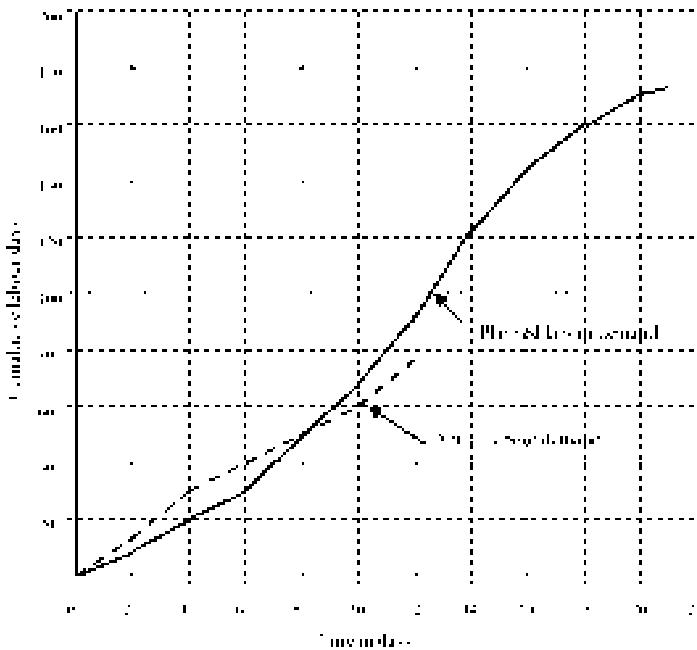
A linked bar chart serves the purpose of effectively communicating the planning information after it has been generated using the CPM method. One added advantage of a bar chart is that apart from displaying a production schedule, it is also capable of superimposing resource histograms for that particular schedule. This is illustrated in Figure 4.11. The shape of the labour demand histogram assists the planner in resource levelling, in making adequate provisions for amenities and site safety, and in developing an efficient system of labour movement on the job.

Figure 4.11 The linked bar chart with the total labour demand histogram



Trend graphs are an effective tool for monitoring and controlling resources. They are simple, highly visual, and easy to create using a spreadsheet. A cumulative total labour demand and cumulative demand trend graphs for different types of labour resources are most common examples of trend graphs. Figure 4.12 illustrates the use of a trend graph in monitoring the cumulative total labour demand. As the name suggests, a trend graph displays the actual demand level of the resource against the planned level. Trends in the level of demand, either positive or negative, can easily be detected and appropriate action taken.

Figure 4.12 Example of a trend graph showing the cumulative planned and actual labour demand



MANAGING MATERIALS

The type and quality of materials needed for a project are specified in the design documentation. Irrespective of how the contractor will actually build the structure, the quantity of materials required will be more or less constant. For example, the contractor can build a concrete chimney using either a traditional static formwork method, a slipform method, or a climbing form method. The quantity of reinforcement and concrete will be approximately the same irrespective of the formwork method employed.

Developing a materials schedule for a project is a fairly simple task provided the required materials have been clearly specified, their quantities are known, and supplies are readily available. In Australian urban areas most construction materials are available on short notice, but longer lead-times for their supply in country regions must be allowed for. Lead-times of up to 20 weeks may be required for the delivery of materials purchased overseas.

Two different types of material schedules are commonly prepared:

- a purchasing schedule
- a weekly delivery schedule.

These schedules are prepared in a table format.

A purchasing schedule lists all the required materials, their quantities, the date by which a purchase order must be placed with the supplier, the name of the supplier(s) and the first delivery date. A sample of a purchasing schedule is given in Table 4.1. The important issue here is to ensure that purchase orders have been issued to the suppliers with sufficient lead-times. This is particularly important for imported materials.

TABLE 4.2

EXAMPLE OF A PURCHASING SCHEDULE OF MATERIALS

MATERIAL	UNIT	TOTAL QUANTITY	LAST DATE TO PLACE PURCHASE ORDER	NAME OF SUPPLIER	THE DATE OF FIRST DELIVERY	ORDER PLACED
15MPa Concrete	m^3	500	6.1.02	Pioneer Concrete	12.2.02	yes
Reinforcement	Tonne	45	15.3.02	Active Steel	4.2.02	yes
Face bricks	No.	100 000	30.3.02	Austral	2.5.02	yes
Common bricks	No.	120 000	30.3.02	Austral	30.4.02	yes
Cement	Tonne	10	15.4.02	BBC Hardware	29.4.02	yes
Sand	m^3	30	15.4.02	BBC Hardware	29.4.02	yes
Timber (varying sizes)	m	900	30.3.02	BBC Hardware	20.5.02	yes
Plasterboard sheets	m^2	800	10.4.02	CSR	27.5.02	yes
Floor tiles	m^2	150	29.1.02	Italy	10.6.02	yes
Windows (varying sizes)	No.	120	1.3.02	Stegbar	23.4.02	yes

A weekly delivery schedule shows what required materials are to be delivered, when, in what quantities, and from what suppliers. Such a schedule will be prepared at least a week in advance. It is assumed that the necessary purchase orders have already been placed with the suppliers. Table 4.3 lists the required materials for delivery in the week commencing 27 May 2002.

Table 4.3

A delivery schedule of materials, week commencing 27 May 2002

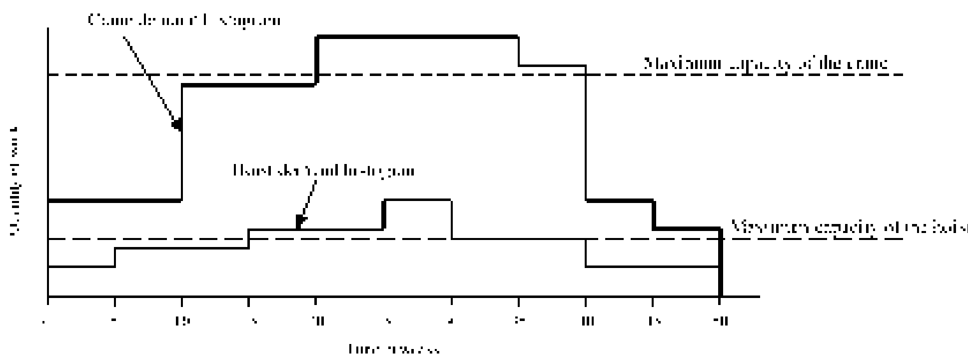
MATERIAL	UNIT	QUANTITY	NAME OF SUPPLIER	THE DATE OF DELIVERY	DELIVERY CONFIRMED
15MPa Concrete	m^3	80	Pioneer Concrete	Frid 31.5.02	yes
Reinforcement	Tonne	7	Active Steel	Mon. 27.5.02	yes
Face bricks	No.	10 000	Austral	Thur. 30.5.02	yes
Common bricks	No.	12 000	Austral	Tue. 28.5.02	yes
Cement	Tonne	2	BBC Hardware	Mon. 27.5.02	yes
Sand	m^3	5	BBC Hardware	Mon. 27.5.02	yes
Timber (varying sizes)	m	100	BBC Hardware	Wed. 29.5.02	yes
Plasterboard sheets	m^2	100	CSR	Thur. 30.5.02	yes
Floor tiles	m^2	35	Italy	Frid. 31.5.02	yes
Windows (varying sizes)	No.	20	Stegbar	Mon. 27.5.02	yes

MANAGING PLANT AND EQUIPMENT

The selection of plant and equipment, particularly the materials-handling plant for use on construction sites, is one of the most important tasks of planners. Like the labour resource, committed plant and equipment are expected to be fully utilised. Some plant, such as compressors, jackhammers, concrete vibrators and the like, is portable. It can easily be moved from activity to activity or returned to the supplier when not needed. This flexibility in mobility helps to ensure the efficient use of plant. Some other plant, such as tower cranes or hoists, may be fixed in place for a specified period, which may even extend over the entire project period. Since such plant is usually cost-intensive, its effective management is essential.

Let's focus on the management of fixed cranes and hoists. The first task that the contractor would need to address is the preparation of the demand histograms for cranes and hoists. These are developed by first identifying those activities that will need to be handled by cranes and hoists. Next, alternative types of suitable cranes and hoists will be selected and their technical specifications and capacities established. Estimates of handling times for each activity for each type of crane and hoist will be made within the schedule of work. Those individual time estimates will then be summed for each day or each week of the schedule. Such information can then be plotted in the form of a demand histogram. Figure 4.13 illustrates a typical demand histogram for cranes and hoists.

Figure 4.13 Example of a demand histogram for cranes and hoists



The next task is to determine the maximum capacity of each type of crane and hoist. In the example in Figure 4.13, the maximum capacities of a particular crane and a particular hoist are shown as horizontal broken lines. Clearly, neither the crane nor the hoist are able to fully service the scheduled work. With regard to the demand histogram of the crane, the planner may explore a number of possible solutions:

- selecting a tower crane with a greater capacity that would meet the maximum level of demand
- using the existing tower crane for the entire project period but boosting its lifting capacity to the maximum demand level between weeks 20 and 35 by committing an additional crane
- using a mobile crane of the required capacity in the first ten weeks, then replacing it with a tower crane that would meet the maximum demand level between weeks 10 and 40 and then replacing the tower crane with a mobile crane of the required capacity to complete the job between weeks 40 and 50.

If the only crane available to the contractor is the one for which the maximum capacity is shown in Figure 4.13, the contractor would need to reschedule the work within the crane's capacity.

The following example demonstrates a simple approach for determining a lifting demand histogram for a project from which the most appropriate cranes and hoists would be selected. The project in question is a high-rise office building of 40 levels with typical floors between levels 1 and 38. The work has been packaged and let to ten trade contractors. The work of these trade contractors has been scheduled sequentially from floor to floor with a cycle time of each work package per floor being one week. It means that only when the first trade contractor reaches level 10 will the tenth trade contractor be able to start work on level 1. From that point onwards, all ten trade contractors would work simultaneously until the work of individual trade contractors come to an end.

The first task is to identify activities that would need to be handled by cranes or hoists and estimate their handling demand times for different types and capacities of hoisting plant. In this case, the choice of handling plant has been restricted to one specific type of crane and one specific type of hoist (their technical specifications and lifting capacities are known but are not specified here). Since the work has been packaged, handling demand times will be calculated for each package.

This information is given in Table 4.2 in the 'Crane demand time' and the 'Hoist demand time' columns in 'Hours per week'. As the trade contractors work sequentially from floor to floor, the crane and hoist demand times increase from week to week until all ten trade contractors are engaged from week 10 onwards. Thereafter, the lifting demand level will be constant. The progressive build-up of demand for the crane and the hoist is expressed in Table 4.2 in the columns headed 'Cumulative hours/week'.

The cumulative demand histograms of the crane and the hoist are plotted in Figure 4.14. In this example, the maximum capacity of the hoisting plant (for both the crane and the hoist) is set conservatively at 40 hours per week. The cumulative crane demand histogram shows that three cranes would be required to meet the lifting demand of the project. Similarly, the cumulative hoist demand histogram suggests that four hoists would be needed. If the maximum capacity of the crane and the hoist is set at 50 hours per week, two cranes and three hoists would be needed.

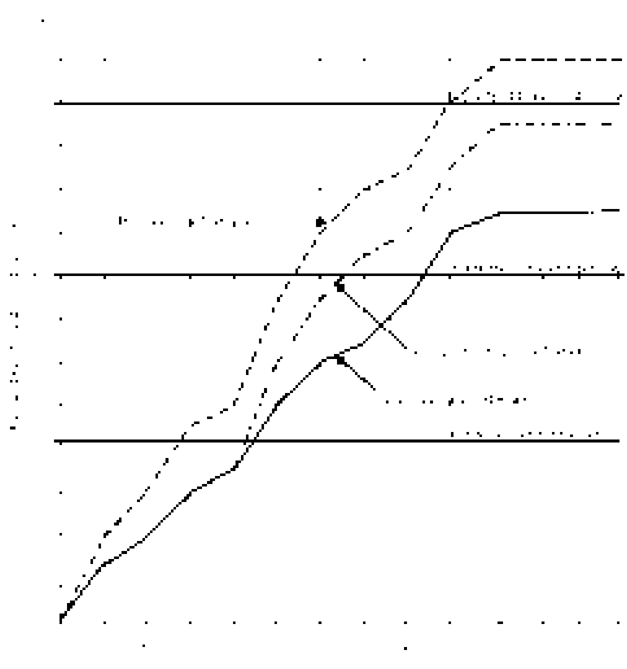
Most commonly, the planner will select a combination of cranes and hoists. Let's assume that the construction site in question can accommodate one crane only. It means that additional hoists would need to be installed to supplement the crane in order to meet the lifting demand. Let's assume further that the crane is required to service the first three trade contractors and hoists are able to service the other trades.

The cumulative crane demand histogram shows that one crane is able to service up to the first four trade contractors; thereafter, additional hoists would be needed. The number of additional

TABLE 4.4
THE LIFTING DEMAND INFORMATION

	CRANE DEMAND TIME		HOIST DEMAND TIME		CRANE+HOIST DEMAND TIME
TRADES	HOURS PER WEEK	CUMULATIVE HOURS/WEEK	HOURS PER WEEK	CUMULATIVE HOURS/WEEK	CUMULATIVE HOURS/WEEK
1	15	15	20	20	
2	5	20	10	30	
3	10	30	15	45	
4	5	35	5	50	
5	15	50	25	75	60
6	10	60	15	90	75
7	5	65	10	100	85
8	10	75	5	105	90
9	15	90	15	120	105
10	5	95	10	130	115

Figure 4.14 Example of the crane and hoist lifting demand histograms



hoists is determined in Table 4.2. The crane must be available for 35 hours per week to service the first four trade contractors (see the ‘Cumulative hours/week’ column under ‘Crane demand time’ in Table 4.2). The fifth trade requires 25 hours per week of hoist time. Therefore the cumulative crane and hoist demand time for the first five trade contractors is 35 + 25 = 60 hours/week. The sixth trade requires 15 hours of hoist per week and the cumulative total is therefore 60 + 15 = 75 hours/week, and so on. The combined cumulative crane and hoist demand histogram is then plotted (see Figure 4.14). It shows that two additional hoists would be needed to supplement one crane, assuming that the maximum capacity of the plant is 40 hours per week. The first hoist would need to be installed and made operational on week 4 and the second on week 6.

The final task in effective plant or equipment management is to control efficiency of the plant or equipment that has been committed. Idle times are wasteful and must be avoided at all cost. Plant or equipment that is no longer needed must be promptly returned to the supplier.

A number of useful tools can be employed for monitoring the efficiency of committed plant or equipment. They include calculation of resource utilisation factors, assessment of their utilisation using a multiple activity chart method (this will be examined in detail in Chapter 9), and creation and maintenance of a database of hired plant and equipment. Detailed information on the management of construction plant and equipment can be found in Harris & McCaffer (1991) and Chitkara (1998).

SUMMARY

This chapter has addressed the issue of resource management. It examined different patterns of resource distribution, particularly those commonly associated with construction projects. It then explained the concept of resource levelling and demonstrated its principles on a simple example. The latter part of the chapter addressed important issues of management of labour, materials, and plant/equipment. In the next chapter, the concept of the critical path method will be expanded by developing a number of overlapping models for a more realistic scheduling.

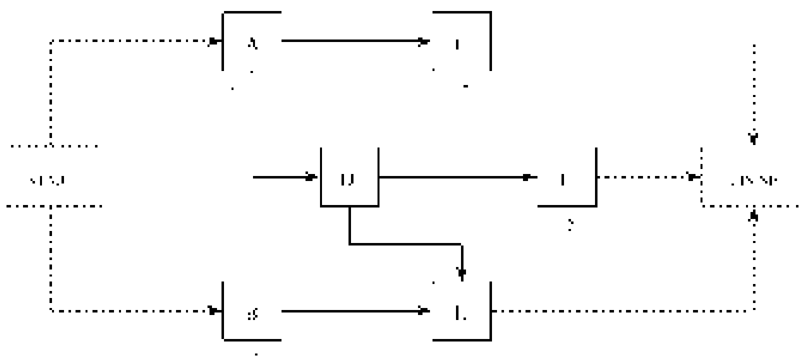
EXERCISES

Solutions to the exercises can be found on the following UNSW Press website: http://www.unswpress.com.au

EXERCISE 4.1

a) Calculate the precedence schedule given below. The schedule data are given in the following table.

b) Level the labour resource using the method of trial and error so that the labour demand does not exceed six workers. The project duration cannot be extended.

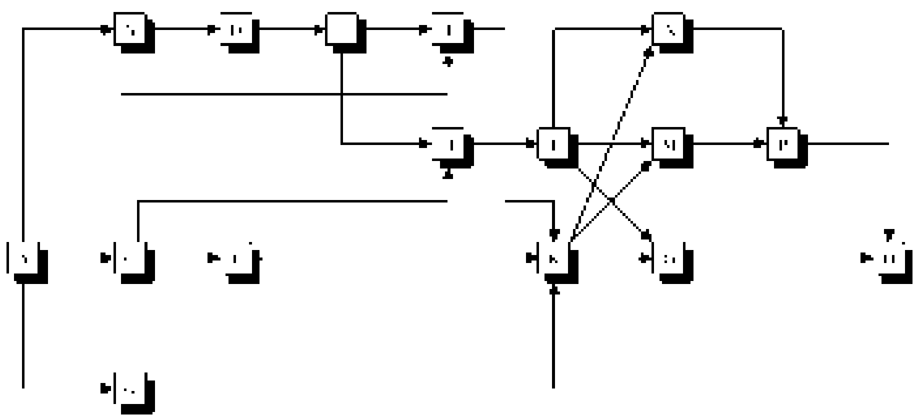


ACTIVITY	TIME IN DAYS	LABOUR RESOURCE RATE	LABOUR RESOURCE DAYS
A	6	5	30
B	2	4	8
C	7	2	14
D	3	3	9
E	1	2	2
F	2	2	4
Total			67

EXERCISE 4.2

a) Calculate the precedence schedule given below. The schedule data are given in the following table.

b) Level the labour resource using the method of trial and error so that the labour demand does not exceed eight workers. The project duration cannot be extended.



ACTIVITY	TIME IN DAYS	LABOUR RESOURCE RATE	LABOUR RESOURCE DAYS
A	2	4	8
B	2	5	10
C	8	1	8
D	3	3	9
E	1	1	1
F	10	3	30
G	8	3	24
H	3	5	15
J	3	2	6
K	4	4	16
L	4	2	8
M	1	3	3
N	2	4	8
O	8	2	16
P	2	2	4
Q	2	3	6
Total			172

EXERCISE 4.3

A high-rise commercial building of 34 storeys will be constructed on a one-week cycle per floor. The project will be serviced by tower hoists. Develop a hoist demand schedule from the following information. How many hoists will be required? Add 10 per cent for contingencies.

TRADE CONTRACT	ACTIVITY	NO. OF LOADS/ FLOOR	CYCLE/ FLOOR (MIN.)	ACTIVITY TIME/ FLOOR (HRS)	TOTAL TIME/ FLOOR (HRS)	CUMULATIVE TIME (HRS)
1	Formwork	100	15			
	Contingency	10%				
2	Reinforcement	40	15			
	Concrete	170	7			
	Conduits & cables	5	30			
	Contingency	10%				
3	Handrails	6	15			
	Contingency	10%				
4	A/C ducts	20	15			
	Sprinkler pipes	10	15			
	Contingency	10%				
5	Plumbing stock	5	30			
	Lift rails	3	30			
	Contingency	10%				
6	Bricks	15	15			
	Mortar	10	15			
	Windows	7	60			
	Door frames	3	30			
	Contingency	10%				
7	Electrical	8	60			
	Plaster	30	15			
	Glazing	8	60			
	Contingency	10%				
8	Ceiling frames	4	30			

	Wall and floor tiles	20	20
	Contingency	10%	
9	Toilet partitions	2	30
	Contingency	10%	
10	Plumbing fixtures	2	60
	Contingency	10%	
11	Ceiling tiles	8	30
	Lights	6	60
	Contingency	10%	
12	Lift doors	17	30
	Contingency	10%	
13	Doors	2	30
	Vanity units	3	60
	Venetian blinds	1	60
	Mirrors	3	60
	Contingency	10%	
14	Induction units	2	30
	Lift lobby finish	12	20
	Door hardware	4	15
	Contingency	10%	

CHAPTER 5

OVERLAPPING NETWORK MODELS

INTRODUCTION

The purpose of this chapter is to expand a sequential, finish-to-start relationship between preceding and succeeding activities in a critical path schedule and a broad spectrum of possible overlapped relationships.

The discussion of the critical path method has thus far assumed that for a pair of activities of which one is preceding and the other succeeding, the preceding activity must be fully completed before the succeeding activity can proceed. This relationship is referred to as finish-to-start (FTS). The assumption that the preceding activity must be fully completed before the succeeding one could begin was made in Chapter 3 to simplify the task of defining and developing the concept of the critical path method.

Now that the concept of the critical path method has been defined and developed, it is necessary to remove the assumption that work can only be scheduled sequentially. Many activities in a schedule can be overlapped in order to speed up the production process. It is advantageous for the planner to start the succeeding activity, where possible, before its preceding activity has been fully completed. For example, placing of slab reinforcement usually starts before the deck formwork has been fully completed. Overlapping not only models relationships between activities more realistically but it also reduces the overall duration of a schedule.

In the following sections of this chapter, the concept of the critical path method will be expanded by defining a number of overlapping models. These are:

- a start-to-start (STS) link
- a finish-to-finish (FTF) link
- a start-to-finish (STF) link
- combination of start-to-start and finish-to-finish commonly referred to as a compound link.

A pair of activities, one preceding and the other succeeding, can thus have one of five possible links: the traditional finish-to-start link and the four overlapping links. Each of these links will now be closely examined.

FINISH-TO-START LINK (FTS)

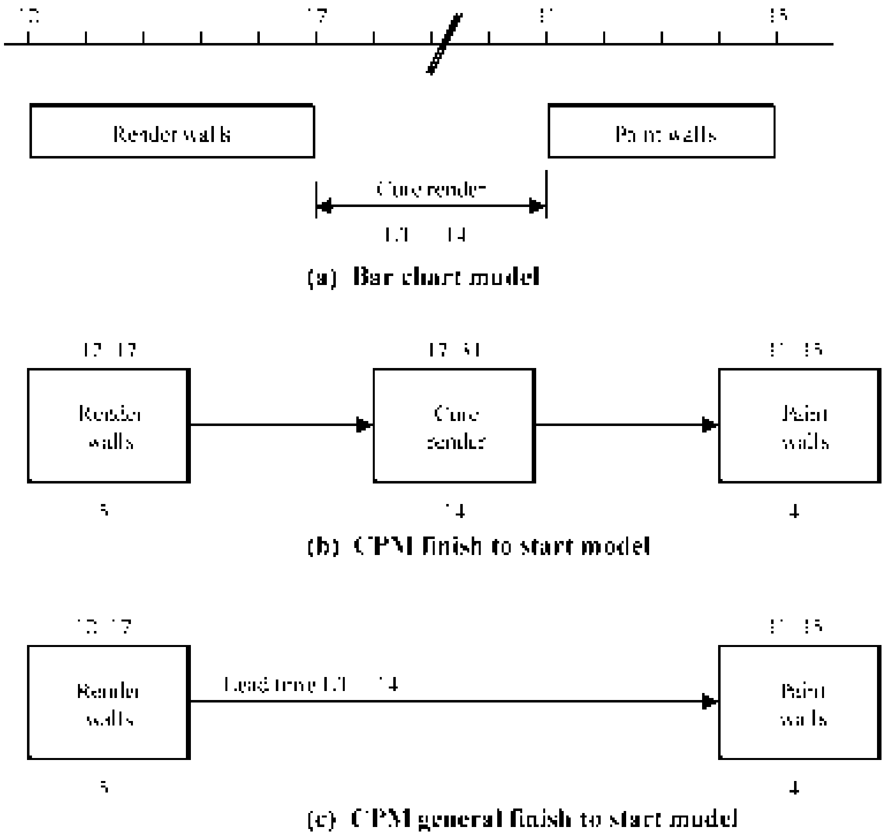
The FTS link is most frequently used in critical path schedules. It is the link around which the concept of the critical path method was defined in Chapter 3. In any pair of preceding and succeeding activities, the succeeding activity, J, may either start immediately after the completion of the preceding activity, I, or some time later. The start of the succeeding activity, J, may be delayed by unavailability of resources. Its start may also be delayed to allow the activity to gain the required physical properties through curing. For example, if the activity 'Render walls' in Figure 5.1(a) is completed today, the succeeding activity 'Paint walls' cannot start until the render has sufficiently cured, which is commonly specified as 14 days. The planner would need to treat this delay caused by curing as an extra activity in the schedule (see Figure 5.1(b)). Rather than treating delays caused by events like curing as extra activities, the planner may simply express delay as lead-time and note it on the relevant link in the schedule (see Figure 5.1(c)). When 'lead-time' replaces a 'delay activity', the formula for calculating the ESD of the succeeding activity, J, for the n number of preceding I activities is modified as follows:

$$ESD_J = MAX\ (EFD_I + LT_I)$$

Similarly, the expression of lag for the link I–J with lead-time becomes:

$$LAG_{IJ} = ESD_J - EFD_I - LT_I$$

Figure 5.1 Example of the finish-to-start link



START-TO-START LINK (STS)

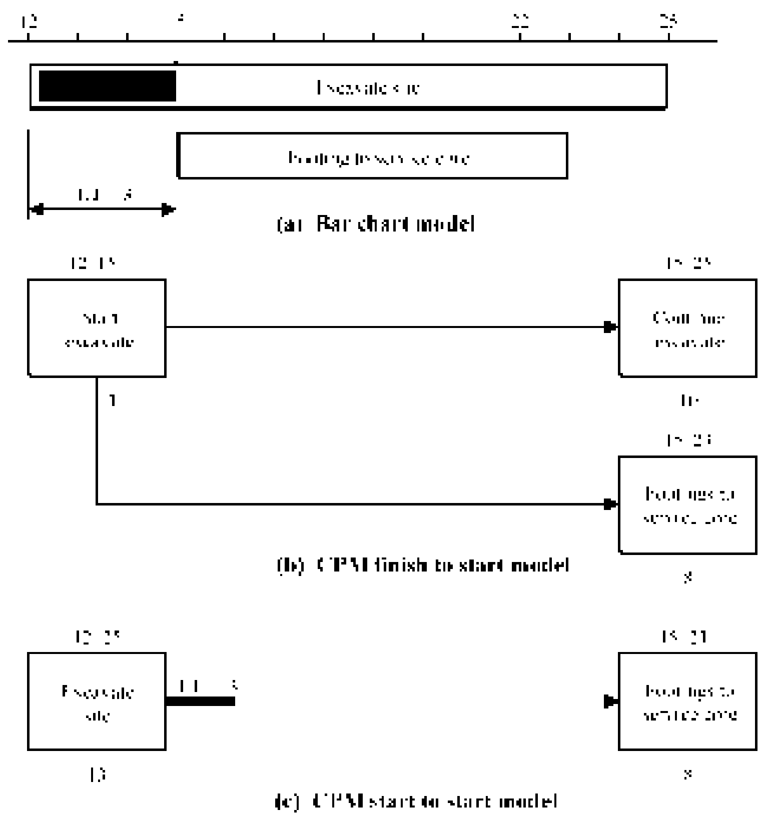
For a pair of activities, I and J, the succeeding activity, J, may sometimes begin after a portion of the preceding activity, I, has been completed. Beyond this point, activities I and J are totally independent of each other. Such a link between activities I and J is referred to as the start-to-start (STS) link.

Let's illustrate this overlap link on a simple example in Figure 5.2(a). The succeeding activity, 'Footings to service core', is scheduled to start three time-units after the preceding activity, 'Excavate site', has commenced. Thereafter, the work associated with these two activities will progress independently of each other and the finish of the preceding activity, 'Excavate site', will have no effect on the finish of the succeeding activity, 'Footings to service core'. This point is reinforced in Figure 5.2 (a) where the preceding activity, 'Excavate site', is scheduled to finish after the succeeding activity, 'Footings to service core', has been completed.

In the STS link, overlap occurs in the preceding activity, I ('Excavate site'), and is expressed as lead-time $LT_I = 3$. The bar chart in Figure 5.2(a) clearly shows the nature of the STS link.

If only FTS links are used in a precedence schedule, the relationship between the activities 'Excavate site' and 'Footings to service core' would need to be expressed with three activities as shown in Figure 5.2(b), where the activity 'Excavate site' is split into two separate activities, 'Start excavate' and 'Continue excavate'.

Figure 5.2 Example of the start-to-start link



However, using the STS link, only two activities are needed in a precedence schedule to show the relationship between the activities 'Excavate site' and 'Footings to service core' (see Figure 5.2(c)). For clarity, a simple protocol is adopted for identifying

STS links. It requires a portion of the link near activity I, where the overlap has occurred, to be widened. The amount of overlap is noted above the widened portion of the link as lead-time LT (Harris 1978).

In the STS link, the ESD of the succeeding activity, J, is calculated first from the ESD of the preceding activity, I, plus LT_I. Formulas for calculating the ESD of the following activity, J, and lag between activities I and J are expressed as:

$$ESD_J = MAX\ (ESD_I + LT_I)$$

$$Lag_{IJ} = ESD_J - ESD_I - LT_I$$

The validity of these formulas can easily be verified on the bar chart in Figure 5.2(a).

The STS link occurs on rare occasions only and should not be confused with the compound link that is characterised by the presence of both the STS and the FTS (finish-to-finish) links between a pair of preceding and succeeding activities. The compound link will be discussed later in this chapter.

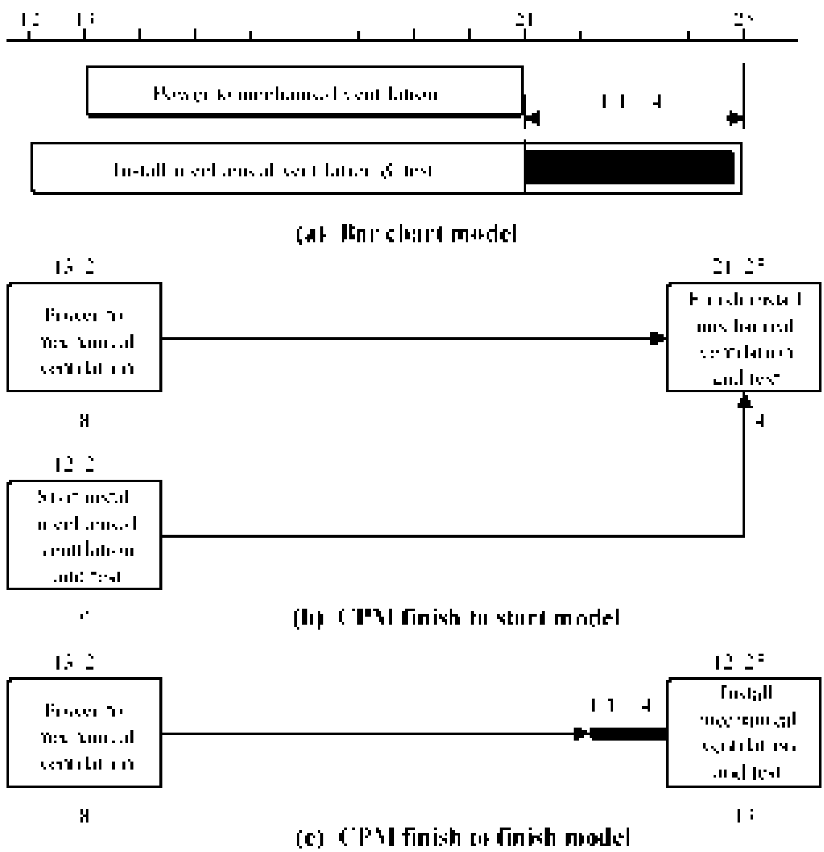
FINISH-TO-FINISH LINK (FTF)

When two activities have a FTF link, the succeeding activity, J, cannot be completed until its preceding activity, I, has been fully accomplished. This relationship is shown in a bar chart format in Figure 5.3(a). It is important to note that both activities I and J can start totally independently of each other. This is emphasised in Figure 5.3(a) by having the succeeding activity, 'Install mechanical ventilation and test', starting ahead of its preceding activity, 'Power to mechanical ventilation'. In the FTF link, overlap occurs in the succeeding activity, J.

If the relationship between the activities 'Power to mechanical ventilation' and 'Install mechanical ventilation and test' is shown in a precedence schedule using the FTS link, the succeeding activity, 'Install mechanical ventilation and test', would need to be split into two separate activities, 'Start install mechanical ventilation and test' and 'Finish install mechanical ventilation and test'. In total, a schedule would have three activities; see Figure 5.3(b).

Using the FTF link, a precedence schedule would have only two activities, as shown in Figure 5.3(c). The widened portion of the link near activity J signifies the presence of the FTF link. The amount of overlap is noted as a lead-time.

Figure 5.3 Example of the finish-to-finish link



The FTF link requires that the EFD of the succeeding activity, J, is calculated first from the EFD of the preceding activity, I, with the addition of LT_J. The ESD of activity J is then calculated as EFD_J – durationJ.

Formulas for calculating the EFD of the following activity, J, and Lag between activities I and J are expressed as:

$$EFD_J = MAX\ (EFD_I + LT_J)$$

$$Lag_{IJ} = EFD_J - EFD_I - LT_J$$

The validity of the above formulas can easily be verified on a bar chart in Figure 5.3(a).

START-TO-FINISH LINK (STF)

The STF link represents a complex relationship between a pair of preceding and succeeding activities, I and J. The main characteristic of the STF link is that activities I and J start and finish independently of each other. However, they come together at a certain point in their duration where a lead-time portion of the preceding activity, I, must be completed so that a lead-time portion of the succeeding activity, J, can be accomplished. This relationship is shown graphically in the bar chart in Figure 5.4(a).

The STF link frequently occurs between activities referred to as 'services'. For example, the activity 'Electrical wiring' often starts near the beginning of the project and continues almost up till the project's completion. Other 'services' activities such as 'Installation of lifts', 'Air conditioning', 'Hydraulics', 'Fire protection' and the like proceed independently from the activity 'Electrical wiring', but at a specific point in their duration they require access to electric power so that their installation and testing can be completed.

The relationship between the activities 'Electrical wiring' and 'Install lifts and test' could be modelled using FTS links. However, each activity must first be split into two in order to correctly represent the link between those two activities. This is illustrated in Figure 5.4(b).

Using the STF link, a precedence schedule only requires two activities to define the relationship between the activities 'Electrical wiring' and 'Install lifts and test' (see Figure 5.4(c)). The STF link generates two overlaps, one related to the activity 'Electrical wiring' and the other to the activity 'Install lifts and test'. They are noted as lead-times.

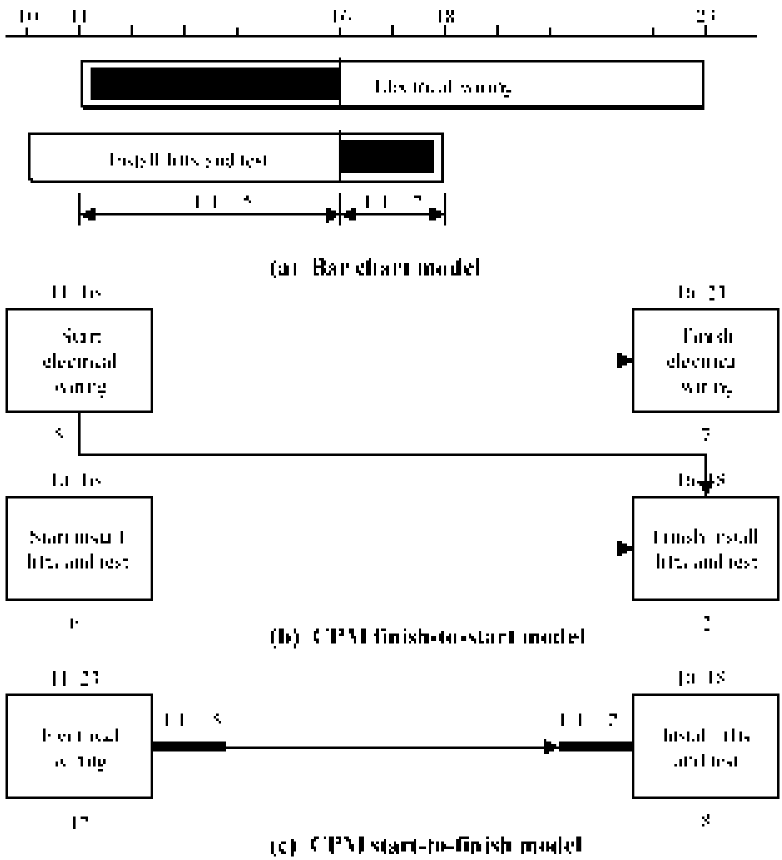
The nature of the STF link requires that the EFD of the succeeding activity, J, is calculated first from the ESD of the preceding activity, I, with the addition of both lead-times $LT_I + LT_J$. The ESD of the succeeding activity, J, is calculated next by deducting duration of activity J from the value of the EFD. Formulas for calculating the EFD of the following activity, J, and Lag between activities I and J are expressed as:

$$EFD_J = MAX\ (ESD_I + LT_I + LT_J)$$

$$Lag_{IJ} = EFD_J - ESD_I - LT_I - LT_J$$

The bar chart in Figure 5.4(a) confirms the validity of the formulas.

Figure 5.4 Example of a start-to-finish link



A COMPOUND LINK

A compound link between a pair of preceding and succeeding activities, I and J, consists of both the STS and the FTF links. This is the most commonly occurring overlap and is illustrated in the bar chart in Figure 5.5(a). This graph shows that the succeeding activity, ‘Wall lining’, cannot start until a portion of the preceding activity, ‘Install timber stud walls’, has been completed, which is given by a lead-time of four. This part of the relationship between the two activities is modelled by the STS link. From this point onwards, both activities are performed concurrently, but a portion of the succeeding activity, ‘Wall lining’, cannot be finished until the preceding activity, ‘Install timber stud walls’, has been completed. This portion of the relationship is given by the FTF link with a lead-time of three.

Figure 5.5(a) shows the lead-time portion of the activity 'Wall lining' to be three time-units. It means that the last three time-units of the activity 'Wall lining' cannot start until the preceding activity, 'Install timber stud walls', has been completed. It should now be clear that the activity 'Wall lining' will be delayed by one time-unit. To correctly schedule the activity 'Wall lining', the planner would need to either split it into two, as shown in Figure 5.5(a), with a one-time-unit break between the two parts, or delay its start by one time-unit to maintain continuity of work. Let's examine the former alternative first.

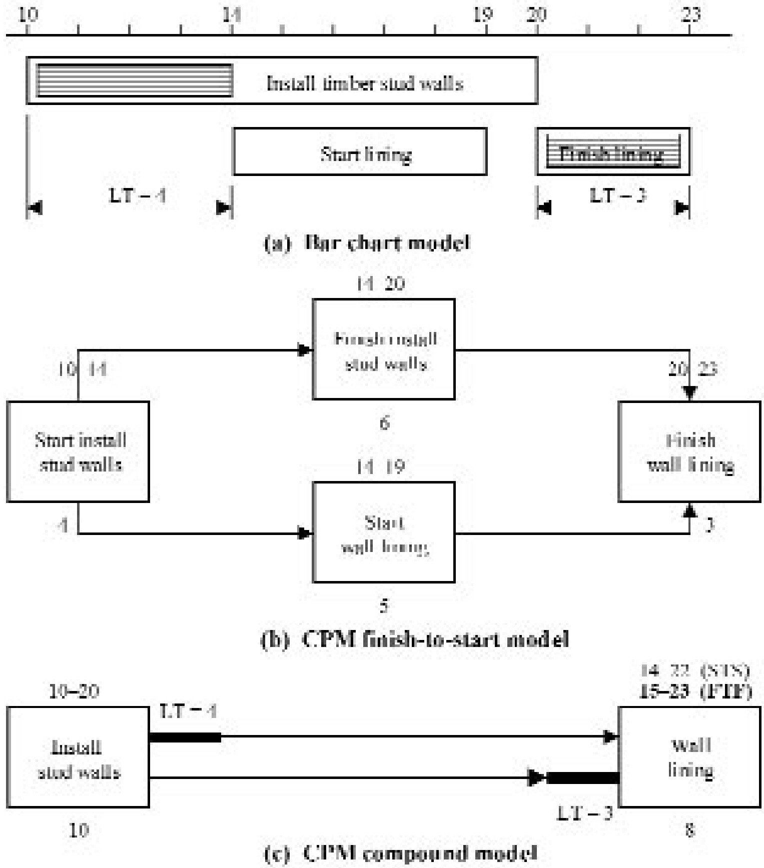
The contractor may want to begin the succeeding activity, 'Wall lining', as soon as the lead-time of the preceding activity, 'Install timber stud walls', has been reached. The work of the two activities then proceeds in parallel. However, if the rate of progress of the subcontractor performing the succeeding activity, 'Wall lining', is greater than that of the subcontractor performing the preceding activity, 'Install timber stud walls', discontinuity of work in the activity 'Wall lining' will occur. For the example in Figure 5.5(a), discontinuity occurs between time-units 19 and 20.

The compound relationship can be modelled in a critical path schedule using FTS links, but both the preceding and the succeeding activities would need to be split into two activities each, as shown in Figure 5.5(b).

Alternatively, the compound link can be created in a precedence schedule with two activities only, as shown in Figure 5.5(c) with both the STS and the FTF links present. Calculations of the ESD of the succeeding activity, 'Wall lining', will be performed separately for each of two links using the formulas derived on pages 103–107. For the link FTF, the value of the EFD of the activity 'Wall lining' will be calculated first, and the value of the ESD will be derived from this. The greater of the two values of the ESD is the ESD of the activity 'Wall lining'. In the example in Figure 5.5(c), the FTF link is dominant. However, if the lead-time of the activity 'Wall lining' is reduced to one time-unit, the STS link would then be dominant. If the lead-time of the activity 'Wall lining' is two time-units, both links have the same degree of dominance.

It was noted earlier that continuity of work in the activity 'Wall lining' would be ensured by delaying its start by one time-unit. It is interesting to observe that when a compound link is calculated (see Figure 5.5(c)), the succeeding activity, 'Wall lining', is automatically scheduled in a manner that ensures its continuity.

Figure 5.5 Example of a compound link



FREE AND TOTAL FLOAT IN OVERLAPPED NETWORKS

The formulas for free and total float derived in Chapter 3 are valid for use in overlapped networks. These formulas are:

$$\text{Free Float}_I = \text{MIN}\ (\text{LAG}_{\ I\,J_1\,J_2\,\ldots\,J_n})$$

$$\text{Total Float}_I = \text{MIN}\ (\text{LAG}_{\ I\,J_1\,J_2\,\ldots\,J_n} + \text{TF}_J)$$

In overlapped networks it is important to distinguish between the end activity and the terminal activity. The ‘end’ activity is the last activity in a CPM schedule, which may or may not determine its overall duration. On the other hand, the terminal activity may or may not be the last activity in a CPM schedule but it determines its overall duration. In networks that use FTS links only, end activities are those that have no further succeeding links. One or possibly more end activities will be critical and will thus determine the overall duration of the network. The end activity or activities that are critical are also ‘terminal’.

However, in overlapped networks, the end activity may have no further succeeding links, yet it may not be critical. In such a case, the end activity is not terminal since it does not determine the overall duration of the project; another activity will determine the overall network duration,which will be a true terminal activity. In Figure 5.6, activity H is the last activity in the schedule, but when the schedule is calculated, the true terminal activity that determines the schedule’s duration is activity G. This is illustrated in Figure 5.7. The reason why activity G is terminal will be discussed in the next section.

Overlapped precedence networks are often difficult to interpret. For example, it is not clearly apparent in Figure 5.7 that activity C is one of the end activities in the schedule. On closer examination of the schedule, it becomes obvious that activity C is in fact one of three end activities and as such it should be linked to the dummy activity END, and should have the value of its lag with the dummy activity END calculated. The reason why activity C is one of three end activities will be explained in section 5.8. Meanwhile, the reader may be able to deduce the reason by referring to Figure 5.9.

If the planner fails to identify all the relevant links in an overlapped schedule, the values of free and total float of some activities may be distorted. The following formula should be applied to check the validity of calculated float values in an overlapped precedence schedule:

$$FF_I \text{ and } TF_I \leq (LFD_{\text{Terminal activity}} - EFD_I)$$

The following example will demonstrate the calculation process applied to an overlapped schedule.

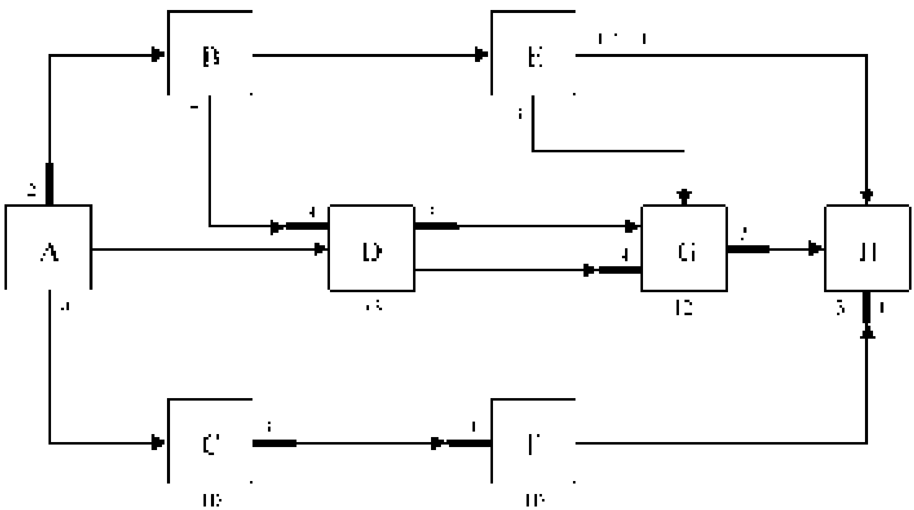
CALCULATING AN OVERLAPPED CRITICAL PATH SCHEDULE

The calculation process applied to overlapped critical path schedules follows the procedure defined in Chapter 3 under the concept of link lag (page 62–66). It involves the following steps:

- forward pass calculations
- calculation of lags
- identification of a critical path
- calculation of free and total float
- calculation of LSDs and LFDs
- plotting of a linked bar chart.

This calculation process will now be applied to a precedence schedule in Figure 5.6. Links between individual activities of the schedule represent the entire array of possible overlaps.

Figure 5.6 Example of an overlapped precedence schedule



Step 1. Forward pass calculations

The ESDs and EFDs of the activities in the schedule are calculated using formulas derived for each link type. Individual calculations are given below:

Link AB (STS)

$ESD_B = ESD_A + LT_A = 0 + 2 = 2$ $EFD_B = 2 + 7 = 9$

Link AC (FTS)

$ESD_C = EFD_A = 9$ $EFD_C = 9 + 10 = 19$

Activity D has two preceding links, one of which will determine its ESD and EFD values:

Link AD (FTS)

$ESD_D = EFD_A = 9$ $EFD_B = 9 + 13 = 22$

Link BD (FTF)

$EFD_D = EFD_B + LT_D = 9 + 4 = 13$ $ESD_D = 13 - 13 = 0$

Therefore, activity D has ESD = 9 and EFD = 22

Link BE (FTS)

$ESD_E = EFD_B = 9$ $EFD_E = 9 + 4 = 13$

Link CF (STF)

$EFD_F = ESD_C + LT_C + LT_F = 9 + 4 + 1 = 14$ $ESD_F = 14 - 10 = 4$

Activity G has three preceding links, one of which will determine its ESD and EFD values:

Link EG (FTS)

$ESD_G = EFD_E = 13$ $EFD_G = 13 + 12 = 25$

Link DG (STS)

$ESD_G = ESD_D + LT_D = 9 + 3 = 12$ $EFD_G = 12 + 12 = 24$

Link DG (FTF)

$EFD_G = EFD_D + LT_G = 22 + 4 = 26$ $ESD_G = 26 - 12 = 14$

Therefore, activity G has ESD = 14 and EFD = 26

Activity H also has three preceding links, one of which will determine its ESD and EFD values:

Link EH (FTS)

$ESD_H = EFD_E + LT_E = 13 + 1 = 14$ $EFD_H = 14 + 3 = 17$

Link GH (STS)

$ESD_H = ESD_G + LT_G = 14 + 2 = 16$ $EFD_H = 16 + 3 = 19$

Link FH (FTF)

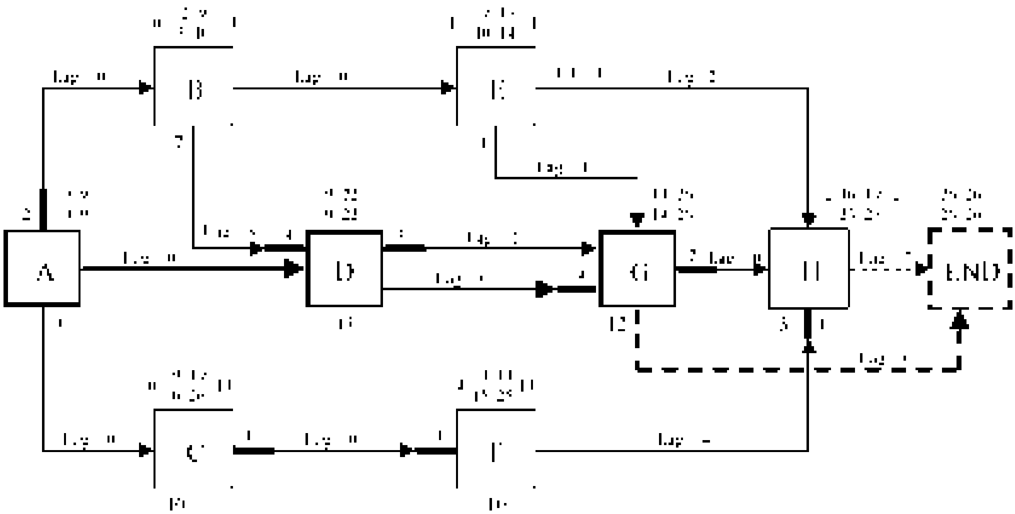
$EFD_H = EFD_F + LT_F = 14 + 1 = 15$ $ESD_H = 15 - 3 = 12$

Therefore, activity H has ESD = 16 and EFD = 19

The fully calculated schedule is given in Figure 5.7.

Although activity H is the last activity in the schedule, activity G is the true terminal activity. Since activities H and G are both end activities, they have links to a dummy activity, 'End'.

Figure 5.7 The fully calculated overlapped precedence schedule



Step 2. Calculate lags

Formulas derived for each link type are used to calculate lag values, which are as follows:

Link A–B (STS) $ESD_B - ESD_A - LT_A = 2 - 0 - 2 = 0$
Link A–D (FTS) $ESD_D - EFD_A = 9 - 9 = 0$
Link A–C (FTS) $ESD_C - EFD_A = 9 - 9 = 0$
Link B–E (FTS) $ESD_E - EFD_B = 9 - 9 = 0$
Link B–D (FTF) $EFD_D - EFD_B - LT_D = 22 - 9 - 4 = 9$
Link C–F (STF) $EFD_F - ESD_C - LT_C - LT_F = 14 - 9 - 4 - 1 = 0$
Link D–G (STS) $ESD_G - ESD_D - LT_D = 14 - 9 - 3 = 2$
Link D–G (FTF) $EFD_G - EFD_D - LT_G = 26 - 22 - 4 = 0$
Link E–H (FTS) $ESD_H - EFD_E - LT_E = 16 - 13 - 1 = 2$
Link E–G (FTS) $ESD_G - EFD_E = 14 - 13 = 1$
Link F–H (FTF) $EFD_H - EFD_F - LT_F = 19 - 14 - 1 = 4$
Link G–H (STS) $ESD_H - ESD_G - LT_G = 16 - 14 - 2 = 0$
Link G–END (FTS) $ESD_{END} - EFD_G = 26 - 26 = 0$
Link H–END (FTS) $ESD_{END} - EFD_H = 26 - 19 = 7$

Step 3. Determine the critical path

The critical path in a precedence schedule is a path of zero lags. The schedule in Figure 5.7 has only one critical path connecting activities A, D and G. The critical link between activities D and G is the FTF link.

Step 4. Calculate free and total float

Free and total float of the non-critical activities are calculated using the formulas derived on pages 111–112. Free float have already been calculated in the form of lags. They are as follows:

$FF_B = 0$ (the minimum lag value)
$FF_C = 0$
$FF_E = 1$ (the minimum lag value)
$FF_F = 4$
$FF_H = 7$

Total float of non-critical activities are calculated by working from the terminal activity and other critical activities back to the beginning of the schedule. Total float calculations are given below.

$TF_H = TF_{END} + LAG_{H\text{–}END} = 0 + 7 = 7$
$TF_F = TF_H + LAG_{F\text{–}H} = 7 + 4 = 11$
$TF_E = TF_H + LAG_{E\text{–}H} = 7 + 2 = 9$, or
$TF_G + LAG_{E\text{–}G} = 0 + 1 = 1$, therefore, $TF_E = 1$
$TF_C = TF_F + LAG_{C\text{–}F} = 11 + 0 = 11$
$TF_B = TF_E + LAG_{B\text{–}E} = 1 + 0 = 1$, or
$TF_D + LAG_{B\text{–}D} = 0 + 9 = 9$, therefore, $TF_B = 1$

The next step is to check the validity of the values of free and total float using the formula given on page 112 as:

FF_I and $TF_I \leq (LFD_{TERM.} - EFD_I)$

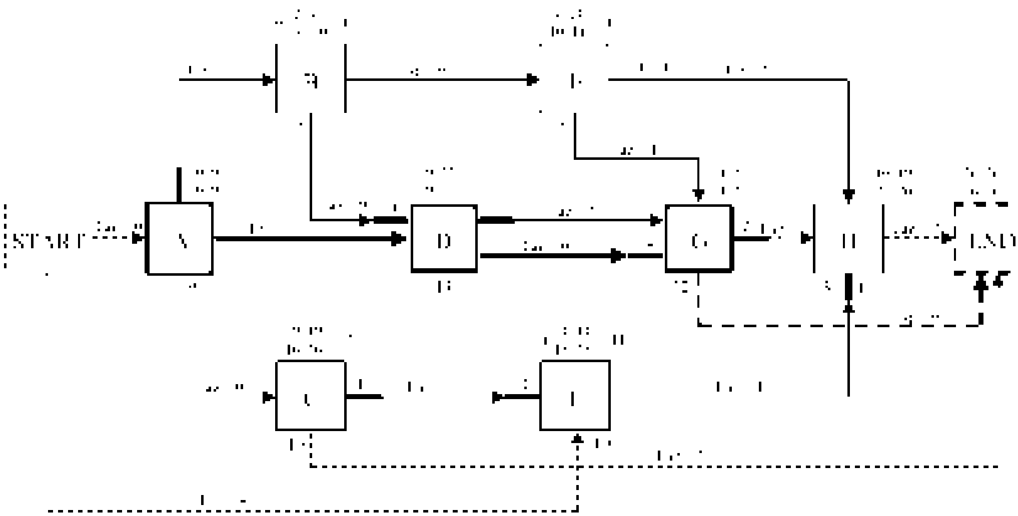
Then,

$FF_B = 26–9 = 17$ (OK), $TF_B = 26–9 = 17$ (OK)
$FF_C = 26–19 = 7$ (OK), $TF_C = 26–19 = 7$ (TF value must be reduced to 7)
$FF_E = 26–13 = 13$ (OK), $TF_E = 26–13 = 13$ (OK)
$FF_F = 26–14 = 12$ (OK), $TF_F = 26–14 = 12$ (OK)
$FF_H = 26–19 = 7$ (OK), $TF_H = 26–19 = 7$ (OK, right on the limit)

The total float value of activity C is incorrect. It should only be 7. The reason why the value of total float is incorrect is because activity C is in fact an end activity and its link with the dummy activity 'End' is missing. Careful examination of the STF link between activities C and F reveals the reason why. Because the end of activity C is not linked to any other activity, it must be an end activity. This can be confirmed by examining the bar chart in Figure 5.9.

The missing link C–End has been added to the schedule and its lag value calculated as 7 (see Figure 5.8). With this additional link, the value of total float of activity C is then 7 (for the link C–End).

Figure 5.8 The adjusted overlapped precedence schedule



The bar chart in Figure 5.9 reveals that activity F has no preceding link and should therefore be regarded as another start activity. Since the schedule now has two start activities, A and F, for clarity a dummy activity, ‘START’, is inserted into the schedule (see Figure 5.8). The value of lag START–F was calculated as 4.

Step 5. Calculate values of LSDs and LFDs

LSD and LFD values of the activities in the schedule can easily be calculated from the expression of total float given in Chapter 3 as:

$$TF = LFD_I - EFD_I$$

By rearranging the formula, the LFD of activity I is then:

$$LFD_I = EFD_I + TF_I$$

The LDS of activity I is then:

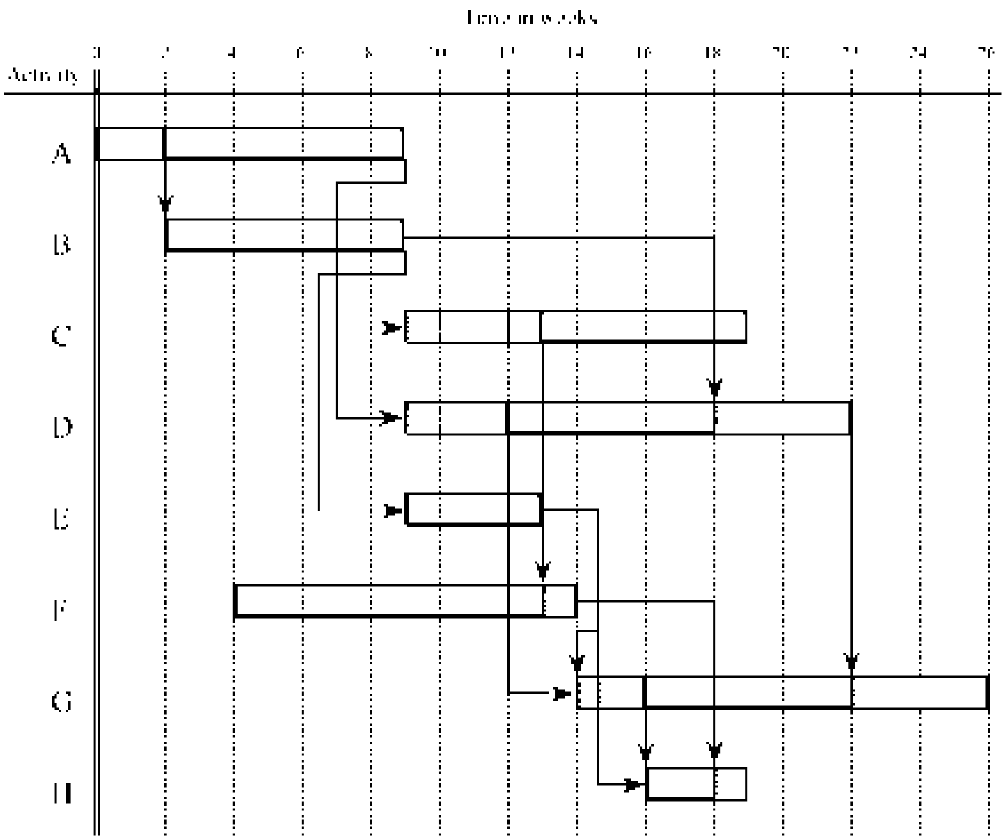
$$LSD_I = LFD_I - \text{Duration of activity I.}$$

The calculated values of LSD and LFD of the activities in the schedule are given in Figures 5.7 and 5.8.

Step 6. Plot a linked bar chart

While a precedence network is an excellent computational tool, it lacks the ability to clearly communicate the planning information, particularly when the network is overlapped. By converting a precedence network into the format of a linked bar chart, overlapped links between activities are clearly apparent (see Figure 5.9). Identification of all start and end activities is then a relatively simple task.

Figure 5.9 A linked bar chart of the overlapped precedence schedule



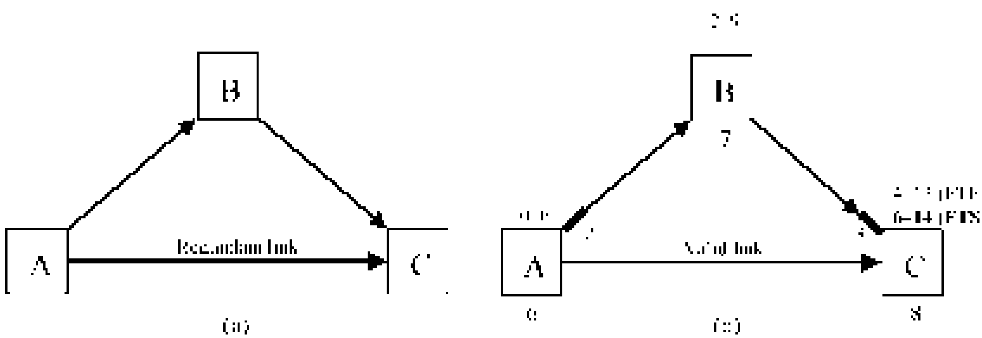
OVERLAPPING OF CRITICAL PATH SCHEDULES BY COMPUTER

Most commercially available CPM software contains built-in overlapping functions that allow the planner to construct realistic schedules. Some software, such as Primavera P3, provides the full range of overlapping models. Overlapping of critical path schedules using computers will be examined in Chapter 7.

REDUNDANT LINKS IN PRECEDENCE SCHEDULES

When three sequential activities, A, B and C, in a precedence schedule with only FTS links form a triangle, the link A–C is redundant (see Figure 5.10(a)). This is because the relationship between activities A and C has already been established by the link A–B–C.

Figure 5.10 A redundant and a valid link in a precedence schedule



However, when a precedence network is overlapped, the link A–C may or may not be redundant. Let's examine a simple precedence network in Figure 5.10(b) that contains some overlaps and check whether the link A–C is redundant. To determine this requires calculation of the schedule and determination of the ESD value of activity C. When the schedule is calculated, the ESD of activity C is either 4 (for the FTF link between B and C) or 6 (for the FTS link between A and C). By definition, the ESD of activity C must be 6 (the greater of those two values of ESD). It means that activity C cannot start until activity A is fully completed. The link A–C is therefore valid and must be included in the schedule.

SUMMARY

This chapter has introduced the concept of overlaps for use in critical path scheduling. A number of standard overlapping models were examined in detail and their implications illustrated on an example. By applying the defined overlapping models such as STS, FTF, STF and the compound overlap involving both STS and FTF, the planner is able to realistically schedule the production process.

The next chapter will examine the use of the critical path method as a monitoring and control tool.

EXERCISES

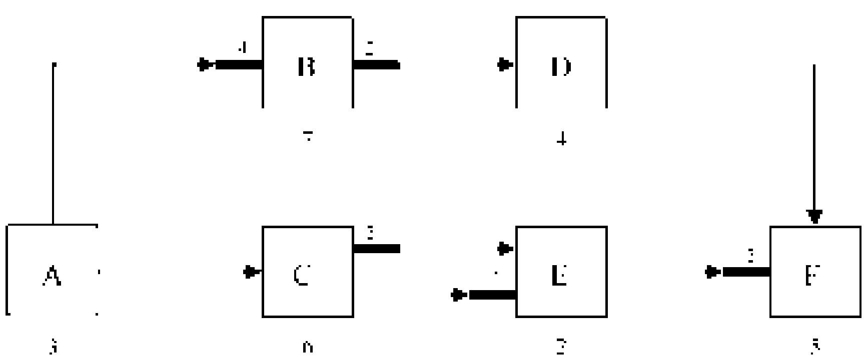
Solutions to the exercises can be found on the following UNSW Press website: http://www.unswpress.com.au

EXERCISE 5.1

An overlapped precedence schedule is given below. Calculate the schedule and determine:

1. the ESDs and EFDs of all activities in the schedule
2. lags of all links in the schedule
3. the critical path
4. free and total float of non-critical activities
5. the LSDs and LFDs of all activities in the schedule.

Convert the calculated precedence schedule to a linked bar chart.

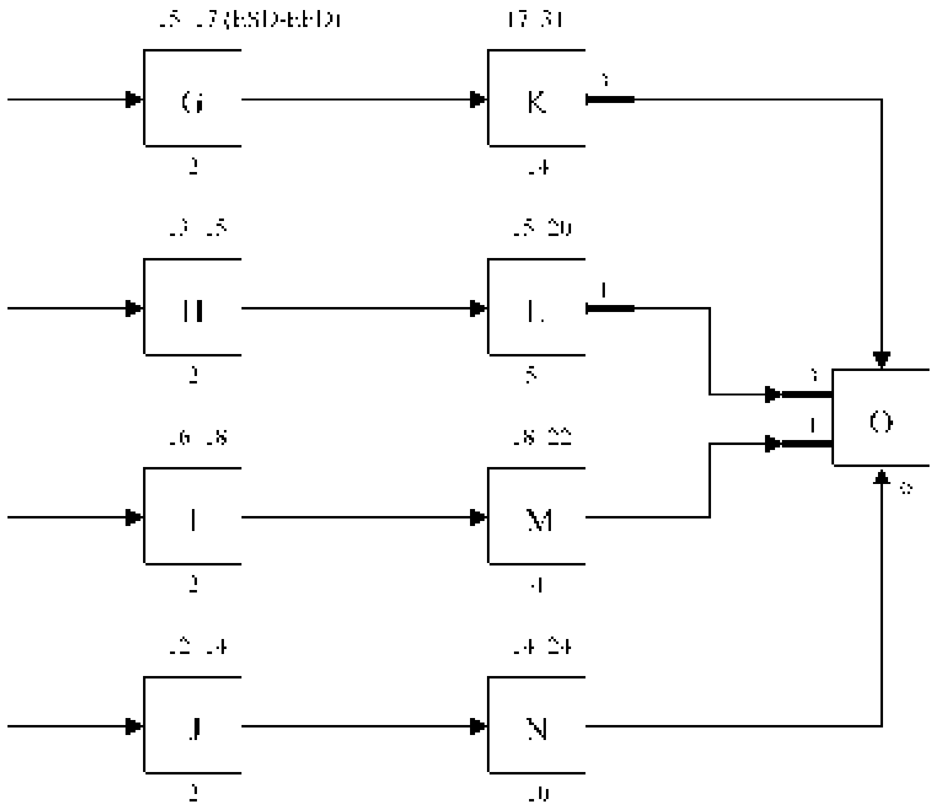


EXERCISE 5.2

A portion of an overlapped precedence schedule is given below. Calculate the schedule and determine:

1 the ESD and EFD of activity O
2 lags of all links in the schedule
3 free and total float of all activities in the schedule
4 the LSD and LFD of activities K, L, M, N and O.

Identify the true terminal activity.

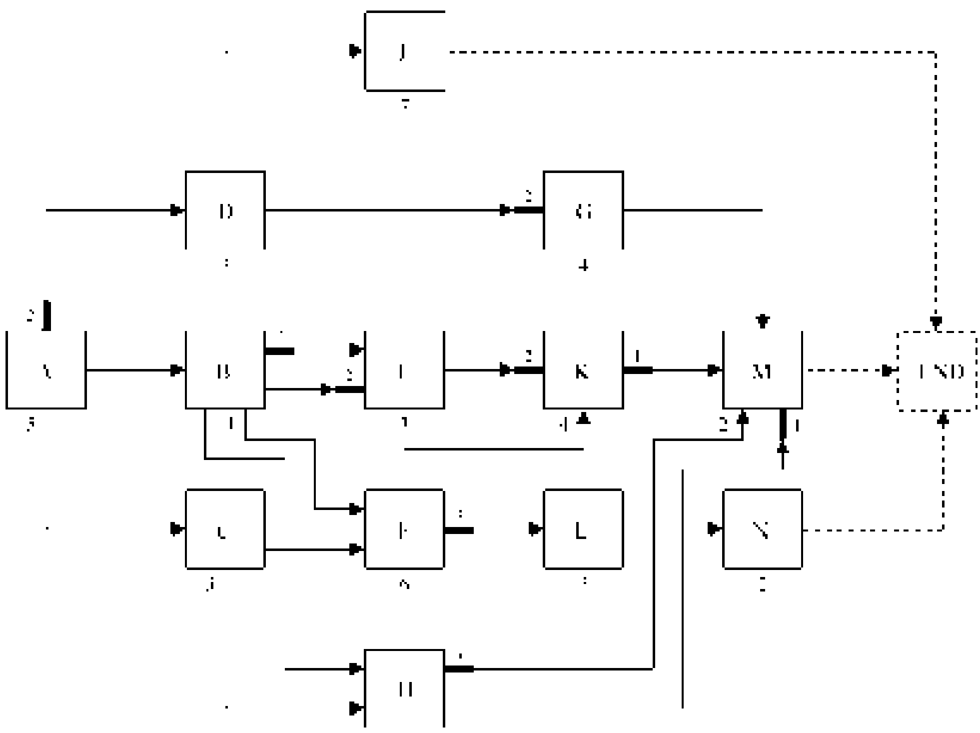


EXERCISE 5.3

An overlapped precedence schedule is given below. Calculate the schedule and determine:

1 the ESDs and EFDs of all activities in the schedule
2 lags of all links in the schedule
3 the critical path
4 free and total float of non-critical activities
5 the LSDs and LFDs of all activities in the schedule.

Convert the calculated schedule to a linked bar chart.



CHAPTER 6

PROJECT CONTROL

INTRODUCTION

Project control is the last element in the functional chain of management after work has been planned and organised. It completes a closed circuit or loop that will enable the project manager to detect deviations from the plan that could be related to organisational or production problems, inefficient use of resources, or the uncertain nature of the work in question. The project manager will be able to take corrective action by adjusting the production process and/or improving the use of resources.

The purpose of this chapter is to define project control from the scheduling point of view and explain its importance. The emphasis will be on time and resource control and cost–time optimisation. A method for compressing or accelerating critical path schedules will be described and demonstrated. The technique of earned value, which is an effective method of controlling the progress and performance of projects, will be discussed later in the chapter.

The main function of project control is to ensure successful attainment of the objectives that have been formulated in plans. Since plans are forecasts of future events, they are never truly accurate and the project manager must expect that deviations from the planned strategy will occur in the production process. An effective project control system will be able to detect any such deviations and will enable the project manager to formulate a remedial strategy.

PROJECT PERFORMANCE OUTCOMES

Project objectives defined in the planning stage impose specific performance outcomes that a project is expected to attain. These are usually related to time, cost and quality performance. Project control thus aims at defining performance outcomes and setting up a mechanism for their achievement.

Depending on the type and nature of a project, a control system may include additional performance factors such as control of change orders, production of documentation, and control of safety. Time progress control and resource productivity control factors will be the main focus of discussion in this chapter.

PROJECT CONTROL SYSTEM

The project control system ensures that the work meets the defined performance outcomes. It requires that the plans accurately replicate strategies developed for the execution of the project in accordance with the design documentation. It is able both to detect deviations from the plans that can be evaluated and to take periodic corrective action to bring the work into line with the plans (Harris 1978).

The type and complexity of a control system depends on the nature of a project and its size. A small project such as construction of a cottage would probably require no more than a simple bar chart schedule and a simple cost-reporting mechanism. Control of large projects, on the other hand, requires the development of a more complex system for measuring performance of a range of important factors. The main tools of such a control system are:

- target schedule
- cost budget based on the master cost estimate or master cost plan
- quality assurance plan
- reporting mechanism for the use of resources and other tasks.

A resource-levelled target schedule is an important tool of cost control. It determines a norm against which deviations in time and in the use of resources can be measured. The fundamental requirement is that a target schedule accurately represents the work that is to be accomplished in the time specified.

A cost budget, which is based on the master cost estimate or master cost plan, is the main tool of cost control. Apart from assembling information on costs incurred to date, it reports deviations from the master estimate and forecasts future expenditures. It also provides a basis for cash flow control.

A quality assurance plan defines the required quality performance outcomes and provides a mechanism for measuring them. For more information, see Oakland & Porter (1994), Dawson & Palmer (1995), Gilmour & Hunt (1995), and Oakland & Sohal (1996). Examples of reporting mechanisms for use of resources will be presented later in this chapter.

The project control system involves monitoring, evaluation, and adjusting or updating. These three important components of project control are graphically shown in Figure 1.1 in Chapter 1. A control system should be designed and implemented as a continuous process. It should be activated immediately after the start of production and should be maintained for the entire period of the project. The least expensive solution of a problem is its timely resolution. It means that the control system must be capable of reporting feedback information regularly and on time. This can be achieved through the application of a computer-based system.

MONITORING PERFORMANCE

Monitoring generates feedback about progress that has been achieved with regard to time, resources, costs, quality and other aspects of the project.

Monitoring time performance

Time performance of projects may be monitored visually, by direct communication with production personnel, or by formal meetings.

The visual assessment of progress assists the project manager not only in establishing the time performance but also in becoming aware of emerging problems, which may directly or indirectly affect progress. For example, the project manager may note an increasing volume of accumulated waste, the presence of bottlenecks, the inadequacy of storage facilities, or even inconsistency in the quality of finishes. Feedback on time performance may also be obtained through informal communication with production personnel. Regular site meetings provide the main forum for monitoring progress of work. The status of the project is determined from the schedule on which the actual progress achieved has been marked.

The time performance of large projects can also be monitored by focusing on one or a small number of key activities. For example, progress of a high-rise commercial building designed as a concrete frame is largely governed by the speed of the formwork activity. If the speed of forming columns, walls, beams and slabs slows down, so will the speed of other succeeding activities; the result may be delay in completing the project. In this case, it would be appropriate to determine from a project schedule the planned volume of formwork to be installed each day or each week. Monitoring would then compare against the plan the actual volume of formwork completed. It makes sense to include monitoring of performance of the key activities within the overall monitoring strategy.

Monitoring the use of resources

Feedback on the use of resources such as labour, materials and plant/equipment involves regular collection and recording of relevant information. It is essential that such information is generated accurately and on time.

Feedback information on the use of direct labour is generated by the time-sheets that a supervisor compiles for each week; from these, the labour cost is calculated. Time-sheets include highly detailed information on what each worker did during the monitoring period. Against each task performed by a worker the supervisor records an appropriate cost code. Every effort must be made to ensure completeness and accuracy, which is essential for accurate reporting of costs. An example of a time-sheet is given in Figure 6.1.

Since labour resources are committed to activities in the schedule, it is essential to monitor how these resources are being used. Time-sheets may help in revealing excessive overtime or periods of idle time. They also provide information on the total volume of the workforce working on the project each day.

A project schedule also helps to identify potential areas of inefficiency in the workforce by showing activities that have been delayed. The project manager is then able to determine whether or not such delays are caused by the workers.

Monitoring the use of materials involves keeping a record of both delivered materials and materials in stock. The quantity of delivered materials is detailed on delivery dockets that the supervisor or another authorised site person is required to verify. The supervisor assigns an appropriate cost code to each delivered item and this is detailed on a delivery docket for cost control purposes. The type and quantity of delivered materials is then recorded in a stock control ledger, which has entries for receipts and issues of materials.

Figure 6.1 Example of a time-sheet

PROJECT NAME:.....................................

Name of employee: .... Week ending: ....

Employee no. ... ... Supervisor: ... .

Employee category ... ... Date ... ...

Working hours	Work codes						
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
7–8							
8–9 9–10							
10–11 11–12							
12–13 13–14							
14–15 15–16							
16–17 17–18							
18–19 19–20							

Total normal working hours

Total overtime hours: ... ...

Monitoring the usage of plant/equipment requires the generation of a stock card database system and weekly plant/equipment time-sheets. A 'stock card' is prepared for each piece of plant/equipment that has been purchased or hired, showing the type, make and model, when purchased or hired, the name and details of the supplier, when due for service or return, and any other relevant information. With hired plant/equipment, the database should remind the supervisor of the impending due date for return. 'Weekly plant/equipment time-sheets' show the extent of use of each piece of plant/equipment that has been committed to the project. When cost-coded, this information becomes a part of a cost-reporting system.

The project manager may also rely on a schedule to monitor the efficiency of committed plant or equipment by assessing causes of delays and determining whether or not they may be attributed to the state of the plant or equipment.

EVALUATING PERFORMANCE

The purpose of evaluation is to analyse feedback data collected on performance in a particular period. The process of evaluation establishes what deviations, if any, have occurred and if they have occurred, what caused them and what strategies are needed to bring the project back to its predetermined level of performance.

Time performance evaluation

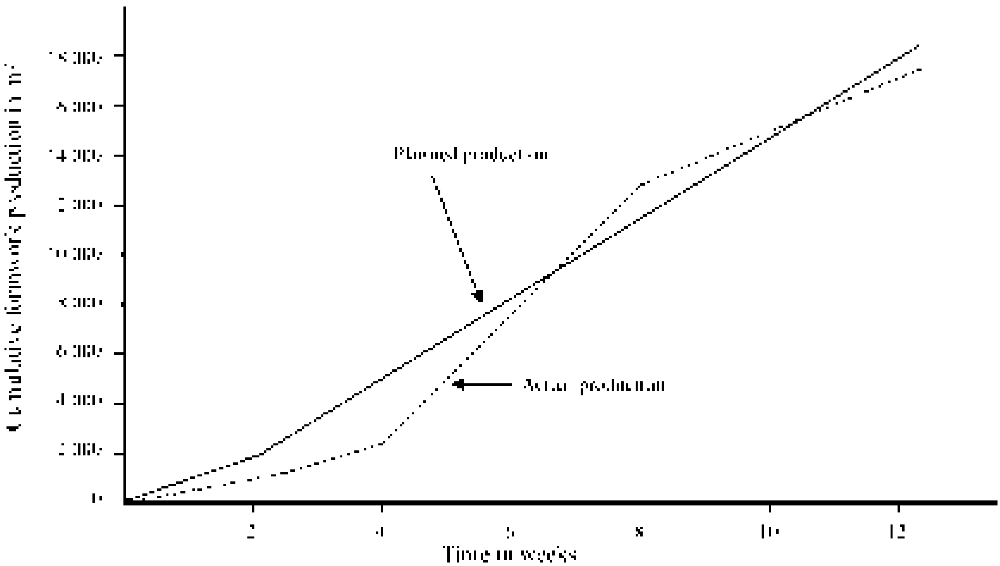
The feedback data on time performance reveals whether or not the project is on schedule and the status of each activity in the schedule. The project manager is able to determine what activities have been delayed and what caused their delay, what activities have been completed and what activities are in progress. For those activities that are in progress and for those not yet begun, the project manager may, based on the progress feedback, reassess their duration and adjust allocation of resources accordingly.

Evaluation of performance of key project activities, such as formwork, is best carried out by a trend graph. A trend graph is an X–Y chart that shows performance (in cumulative terms) in relation to a time-scale. As the name suggests, a trend graph shows visually the development of trends in performance, which may be positive or negative. The important thing to remember is that once a specific trend in performance develops, it usually continues unabated until management action alters it. This is illustrated in Figure 6.2, which shows the development of a negative trend of the actual formwork production in the first four weeks and the change in the trend caused by management action on week 4. The trend graph also shows another management action that was taken on week 8.

Resource performance evaluation

Apart from providing information for cost reporting, time-sheets of labour input also show the volume of overtime incurred or unproductive or idle periods. This may be indicative of insufficient or excessive volume of the labour resource or some other problem. Time-sheets also help to determine the total volume of the workforce employed on the project each day, which can be plotted as a histogram (see Figure 4.11). This information is crucial for reviewing the effectiveness of the personnel handling equipment, the volume of amenities and safety equipment on the site, and the adequacy of supervision. Since time-sheets provide data on the volume of incurred labour hours, this information can be plotted in a trend graph format together with the planned labour demand (see Figure 4.12).

Figure 6.2 Example of the trend graph for cumulative formwork production

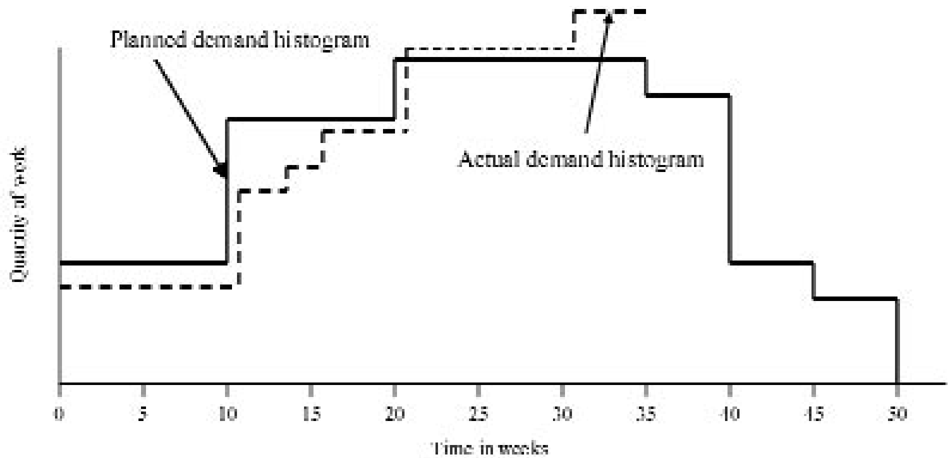


Delays in the project schedule may indicate inadequate allocation of the labour resource in some activities. The project manager would attempt to alleviate this problem through resource levelling. Alternatively, the project manager may study the distribution of resources and the flow of work using a multiple activity chart. This topic will be discussed in Chapter 9.

Performance evaluation of materials involves comparing incurred costs with the planned cost estimate. Deviations may point to errors in quantities, wastage, or even the possibility of pilferage.

The comparison of incurred costs and the planned cost estimate is also applied to evaluating the performance of plant or equipment. Comparing histograms of the planned and achieved resource demands is another way of evaluating such performance. This is illustrated in Figure 6.3.

Figure 6.3 Histograms of the planned and actual demand of a crane



The outcome of evaluation is the formulation of specific strategies or decisions aimed at bringing the project back on track. This could require a change to the design, which may lead to modifications of the production process itself, reallocation of resources, or injection of more resources. The cost and time impact of these actions is directly related to the magnitude of deviations between the planned and actual performance uncovered in monitoring.

ADJUSTMENTS/UPDATES

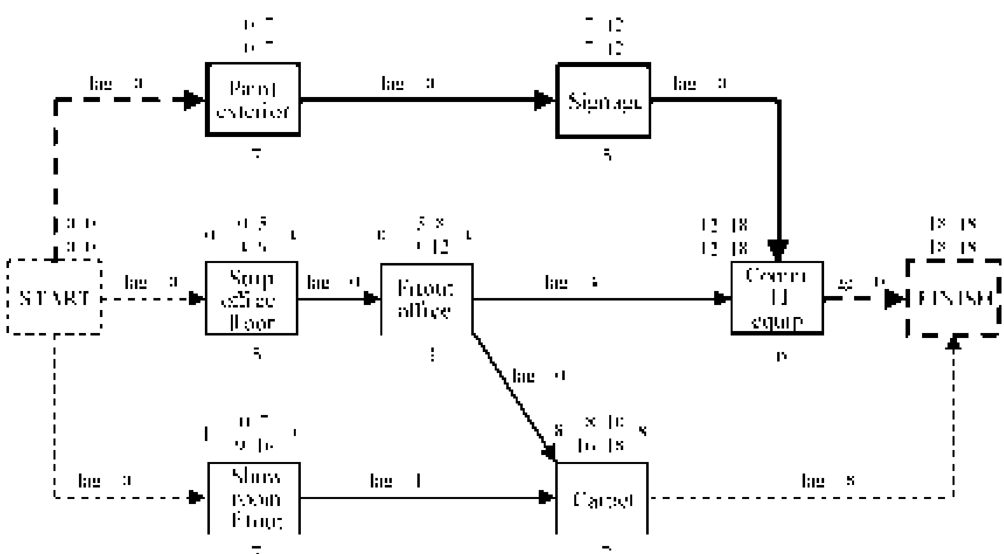
With all the feedback data in hand and decisions made on how best to improve performance of a project, the project manager proceeds to adjust or update production schedules, cost budgets, and other control charts, graphs and histograms. Where possible, the project manager will use computer-generated tools for planning and control such as a critical path schedule and a cost budget; these make updating much easier and they can facilitate control cycles more often than manually generated planning tools.

EXAMPLE OF MONITORING, EVALUATION AND ADJUSTING OR UPDATING OF A CRITICAL PATH SCHEDULE

Computer-generated critical path schedules are widely used for both planning and control of construction projects. Computers are, however, of little help in extracting feedback data on the project's progress and evaluation of that progess. These are the tasks that are performed manually, even though they are laborious and time-consuming. The main benefit of computers is in performing the updating or recalculating phase of the control cycle, which they can do almost instantaneously. Updating of a computer-generated critical path schedule will briefly be discussed in Chapter 7.

The aim of this section is to gain better understanding of the process of monitoring, evaluation and adjustment/updating through its application to a simple, manually generated critical path schedule. The project in question is office and showroom fitout of a small business enterprise. A precedence schedule of the project prior to the next progress review scheduled for week 7 is given in Figure 6.4

Figure 6.4 A precedence schedule of the fitout project prior to the progress review



A project control system operates on weekly cycles. It is now week 7 of the project period. A new control cycle has just begun. The process of monitoring established a status of progress of each activity in the schedule in terms of whether or not the activity has been completed, not yet started or is in progress (Table 6.1).

TABLE 6.1

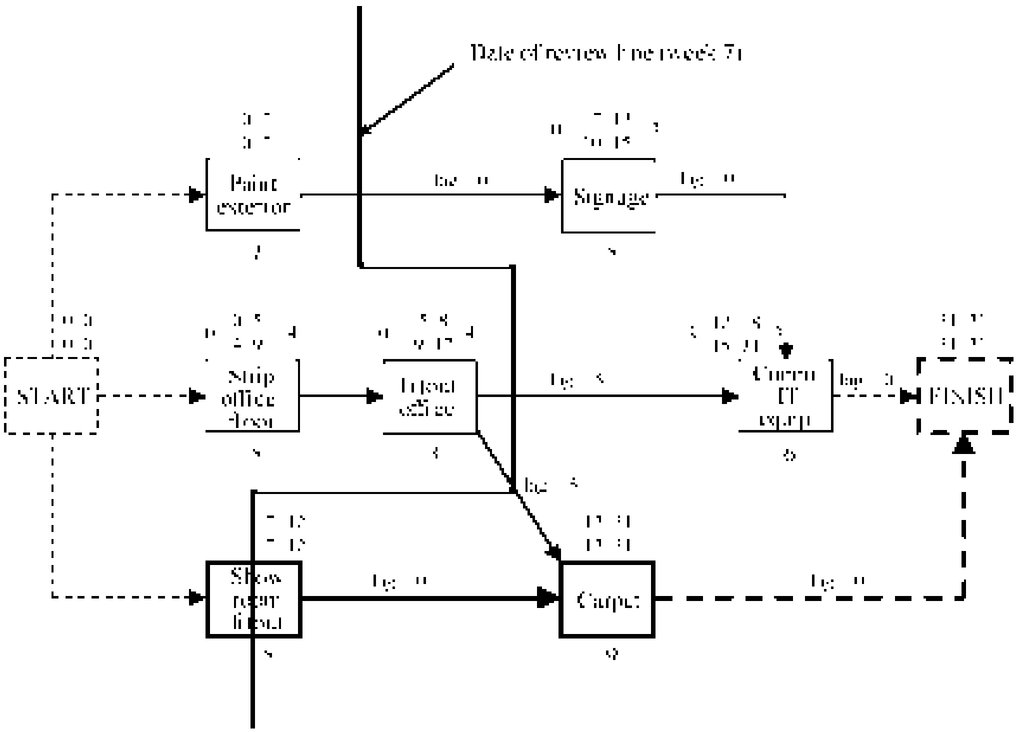
THE FEEDBACK DATA FOR THE FITOUT PROJECT

ACTIVITIES COMPLETED	ACTIVITIES NOT STARTED (DURATION REVISED)	ACTIVITIES IN PROGRESS (DURATION TO COMPLETE)
Paint exterior	Signage (5)	Showroom fitout (5)
Strip office floor	Carpet (9)	
Office fitout	Commission IT equipment (6)	

Evaluation of the performance of individual activities revealed, among other things, two serious problems. A substantial time overrun has occurred in the activity ‘Showroom fitout’, which was caused by the delay in obtaining the customs clearance for imported materials; and the activity ‘Carpet’ will now take significantly more time to complete because the floors have to be decontaminated before the carpet is installed. Consequently, the activity ‘Showroom fitout’ is estimated to take another five weeks to complete. The activity ‘Carpet’, which has not yet started, is now estimated to take nine weeks to complete rather than the original estimate of two. Durations of the remaining activities that have not yet started remain unchanged. Table 6.1 provides information on the revised durations of the activities, which are shown as a number in brackets.

The project schedule can now be updated. First, a line is drawn through the schedule to highlight the date of review, which is week 7. Because the precedence schedule is not drawn to scale, the line will not cut the schedule vertically. Rather, it will be drawn so that the completed activities are located to the left of the line and those that have not yet started to the right; those in progress will have the line passing vertically through them, as shown in Figure 6.5 Second, durations of the activities in the schedule are adjusted in accordance with information in Table 6.1. The schedule is now ready to be recalculated from the line that represents the date of review on week 7. The recalculated schedule is given in Figure 6.5. The outcome of the review on week 7 is the shift in the critical path and the extension of the project duration from 18 to 21 weeks.

Figure 6.5 A precedence schedule of the fitout project after update on week 7



COST–TIME OPTIMISATION

The typical characteristic of construction projects is that they are often completed late. There are many reasons for this, such as design changes, lack of planning and inappropriate use of planning tools, adverse climatic conditions, latent site conditions, and often simply unrealistic expectations.

The delay in completion of a project is usually accompanied by an increase in its cost, for which one or more members of a project team will be responsible. If the delay and the extra cost are the responsibility of the client, the main contractor is entitled to a claim under the contract for extension of time and for costs. If, however, the contractor is responsible for the delay in completing the project, the contractor may be liable to pay crippling liquidated damages to the client, in addition to being required to absorb any extra costs. The contractor would naturally attempt to make up for the delay, which is punishable under the contract by shortening the project period (see Uher & Davenport 2002 for more information).

The contractor may also want to complete the project ahead of the schedule in order to transfer the resources from the current project to a new one, which may be scheduled to start before the completion date of the current project. Another reason why the contractor would want to hasten completion is to earn a financial bonus from the client for completing the project ahead of schedule.

Accepting that some delays are likely to occur and/or that opportunities for time-saving may arise throughout the life of a project, it is necessary to deploy a process for effective management of delays or opportunities for time-saving. Such a process is referred to as 'compression' or 'acceleration'. Its main function is to shorten the project duration by injecting more resources at the minimum possible cost. The key principle of compression or acceleration is to find an optimum cost–time solution.

Before defining the process of compression or acceleration in detail, it is necessary to examine the relationship between cost and time.

Cost–time relationship

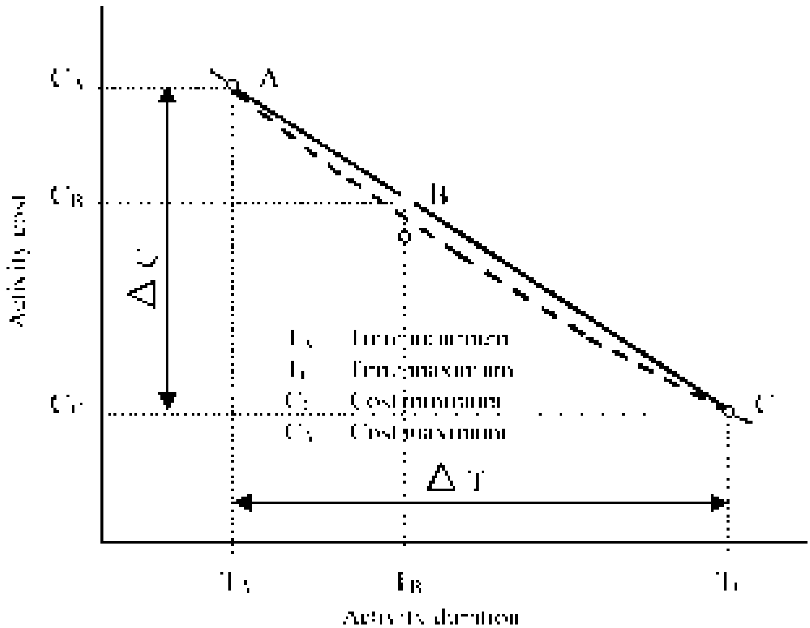
For any given activity, the cost of performing it is related to the period of its performance. The relationship between cost and time is indirect. This is because the time for performing the activity decreases as the cost related to the resource input increases. Figure 6.6 illustrates the relationship between cost and time for a particular activity, which is not only indirect but also non-linear, as shown by a curve between A and C. Point C (coordinates $T_C C_C$) in Figure 6.6 represents the minimum or the normal cost, and point A (coordinates $T_A C_A$) represents the minimum or the crash time.

It is possible without introducing much error to assume that the relationship between A and C is linear. Under this assumption, it is possible to express the value of the cost slope between the points of the normal cost C and the crash time A as:

$$\text{Cost slope} = \frac{\Delta C}{\Delta T}$$

where: $\Delta_C = C_A - C_C$
$\Delta_T = T_C - T_A$

Figure 6.6 An activity's cost–time relationship



The assumption of linearity in the shape of the cost slope makes it possible to determine, for a particular estimate of time, the equivalent estimate of cost. For example, the duration T_B corresponds to the cost C_B.

As evident in Figure 6.6, if a project schedule is to be accelerated, more resources must be injected to perform the work in a shorter time. The faster the rate of acceleration, the greater the need for additional resources and the greater the increase in cost.

Cost components

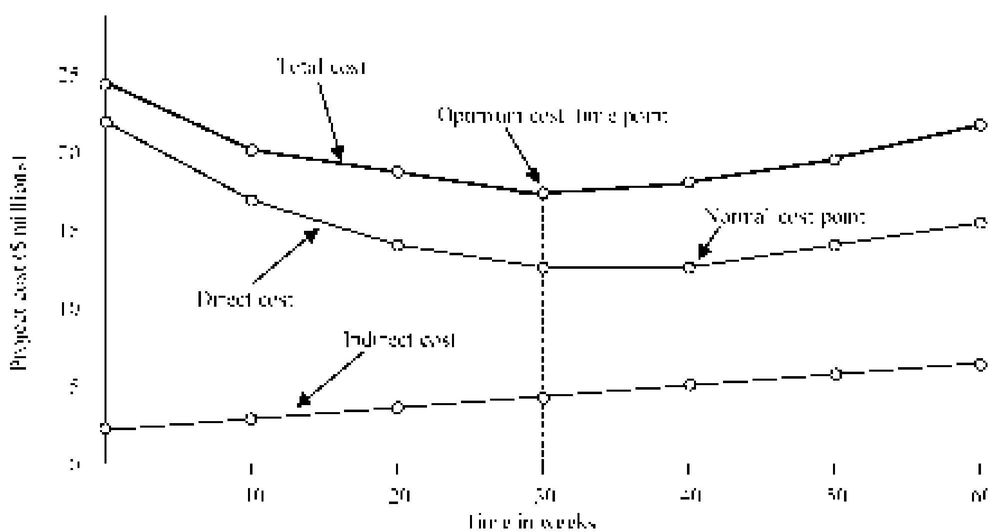
The total project cost is composed of a number of component costs. For simplicity, only two of these will be considered in compression/acceleration. They are direct costs and indirect or overhead costs.

Direct costs are associated with the cost of labour (including on-costs), materials and plant/equipment. The cost of each project activity is estimated as direct cost. Together, direct costs of individual activities constitute the direct cost of the project. An interesting characteristic of the project direct cost is that its magnitude increases with the decrease in the project period. This is illustrated in Figure 6.7. However, when the project duration exceeds the normal cost point, the project direct cost may also increase. This is due to inefficiencies in the use of resources when the schedule is unnecessarily long.

Indirect costs are those associated with general overheads. They are costs other than direct costs. Indirect costs may be fixed or variable over a period of time. When the production output is steady, the indirect cost may be constant or fixed, but when the volume of production fluctuates, the indirect cost may increase with the increase in the production output. In this case, the indirect cost is variable. For example, if the contractor has only one construction project in progress, the contractor's overhead cost would be fully borne by that project. With more projects in hand, the contractor's overhead cost would be shared in some way between those projects.

For the purpose of developing understanding of the process of compression/acceleration that will be discussed on pages 137–38, let's assume that indirect cost is fixed over a period of time. In cumulative terms, the indirect cost is a rising cost over a project period. Graphically, it is expressed as a rising, straight line (see Figure 6.7). The total project cost is then the sum of the direct and indirect costs (Figure 6.7). The lowest point on the total cost curve represents the point at which the cost and the time are at optimum. In Figure 6.7 the optimum point on the total cost curve has the time coordinate of 30 weeks and the cost coordinate of $17.5 million.

Figure 6.7 Project cost components



Cost–time optimisation of activities

The concept of cost–time optimisation can be applied to find an optimum relationship between the duration of an activity and its cost. Let's consider a simple example in Table 6.2 in which one specific activity, say 'Excavate', could be accomplished in four different periods depending on the type and volume of resources allocated to it. Direct costs have been estimated for each period of work. The indirect cost is assumed to be fixed.

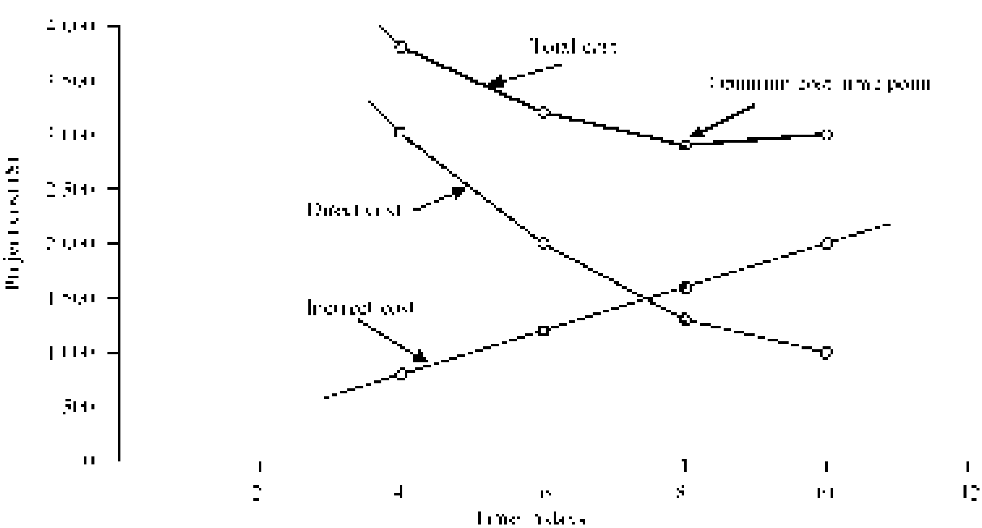
TABLE 6.2

ESTIMATES OF COST AND TIME VALUES FOR THE ACTIVITY 'EXCAVATE'

POSSIBLE ACTIVITY DURATION IN DAYS	DIRECT COST OF ACTIVITY $	INDIRECT COST/DAY $
10	1000	200
8	1300	200
6	2000	200
4	3000	200

The analysis of this example is illustrated in Figure 6.8. The lowest point on the total cost curve represents the activity's optimum cost–time point. Its coordinates are eight days' duration and $2800 cost.

Figure 6.8 The optimum cost–time point of the activity 'Excavate'



Compression or acceleration analysis

The preceding sections of this chapter have examined the relationship between project cost and project time. This cost–time relationship forms the basis of the concept of compression or acceleration. It should be noted that the terms 'compression' and 'acceleration' mean the same thing. Consequently, only the term 'compression' will be used from now on.

When it is necessary to shorten the project schedule, the concept of compression helps to reduce its duration at the least possible cost. Compression is based on four fundamental rules designed to keep cost and time at optimum:

1. Only critical activities may be compressed.
2. The critical activity with the lowest cost slope (that is, the cheapest critical activity) is compressed first.
3. The amount of compression of the critical activity must be smaller than or equal to the amount of total float of non-critical activities positioned on a path parallel to the critical path. If the amount of compression is equal to the amount of total float of such non-critical activities, those non-critical activities will become critical and they will form an additional critical path. If the amount of compression exceeds the amount of total float of such non-critical activities, the original critical path will be lost and those non-critical activities will become critical. If this occurs, the following Rule 4 will be contravened.
4. The original critical path and any other additional critical paths that have been created during the compression analysis must be retained throughout the analysis.

Rule 1 states the obvious: only critical activities are able to affect schedule reduction. Compressing non-critical activities will incur cost without any reduction in time.

Rule 2 stipulates that if there is more than one critical activity capable of being compressed, the one that costs the least amount of money to compress should be compressed first.

Rule 3 sets the limit of compression, and together with Rule 4 guards against the loss of the original critical path or any other critical paths that have been created during the compression analysis. The original critical path is the benchmark against which the compression analysis is carried out within the context of cost–time optimisation.

The compression process is repeated several times until all possible alternatives have been exhausted. It should be noted that not all critical activities are capable of compression. It is the task of the project manager to determine the compression capabilities of individual critical activities. As the compression analysis progresses and more non-critical activities become critical (according to Rule 3), such new critical activities will also be considered for further compression.

The compression procedure will now be demonstrated step by step by a practical example.

The problem

The contractor was awarded a contract to build a block of high-rise apartments in 43 weeks for the total contract sum of $9 190 000. The contract contains a liquidated damages clause of $20 000 per week. Since the client is a new developer with a strategy to invest in more construction projects over the next ten years, the contractor is aware of the need to perform well in order to secure more work from this client in the future.

The contractor's tender summary comprises:

Direct cost	$7 140 000
Indirect cost (fixed) @ $40 000 per week	$1 600 000
Profit margin	$450 000
Total tender sum	$9 190 000

The contractor's project manager has reviewed the tender documentation, particularly the cost estimate and the time schedule, and concluded that if the project is to be completed within the contract sum of $9 190 000, the duration would need to increase to at least 48 weeks. Apart from incurring extra overhead costs, the delay of five weeks would also invoke the liquidated damages clause. Furthermore, the contractor also needs to contemplate the impact that the delay in completing the project is likely to have on the future business relationship with the client. The revised project schedule is given in Figure 6.9.

The project manager has decided to assess the impact of compressing the schedule to its original duration of 43 weeks on the project cost. The project manager has been able to identify only five activities that are capable of being compressed and has determined the limits of compression, together with relevant compression costs. These are given in Table 6.3.

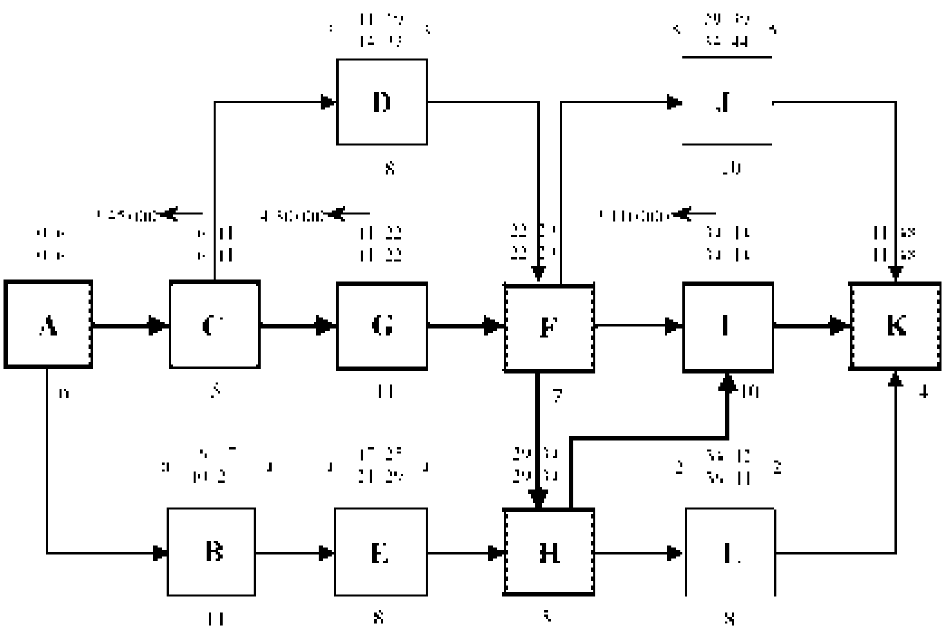
Please note that the difference between 'normal time' and 'crash time' is the amount of time by which the activities in Table 6.3 can be compressed.

TABLE 6.3

DATA FOR THE COMPRESSION EXAMPLE

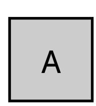
ACTIVITY	NORMAL TIME	CRASH TIME	COST OF COMPRESSION PER WEEK ($)
B	11	9	35 000
C	5	3	45 000
D	8	6	40 000
G	11	7	30 000
I	10	8	110 000

Figure 6.9 The project schedule before compression

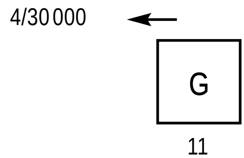


In Figure 6.9 and throughout the compression analysis, the following notations are used:

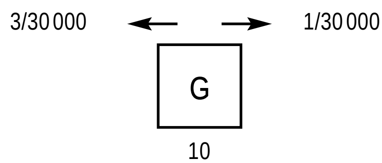
- When a critical activity in the schedule is shaded, it means that that activity is not capable of compression.



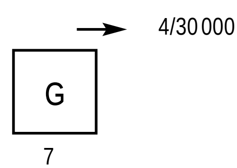
- The following notation indicates that activity G can be compressed by four weeks at $30 000 per week. The direction of the arrow is important here. When it points to the left, it indicates that four weeks are available for compression of activity G.



- The following notation indicates that activity G has been compressed by one week at $30 000 per week but may be compressed in the future by an additional three weeks. The fact that activity G has been compressed by one week is indicated by the arrow, which points to the right. The other arrow, which points to the left, indicates that activity G has three weeks available for future compression. Because activity G has been compressed by one week, its duration is now ten weeks.



- The following notation indicates that activity G has been fully compressed by four weeks at $30 000 per week. All the available time for compression has now been exhausted. Duration of activity G is now seven weeks.



The project in Figure 6.9 will now be compressed by applying the four compression rules. Let's start with the first logical compression.

First compression

Compression rule 1 states that only critical activities can be compressed. The critical activities in Figure 6.9 are A, C, G, F, H, I and K. Of those, only three are capable of being compressed (see Table 6.3). They are:

- activity C by two weeks at $45 000 per week
- activity G by four weeks at $30 000 per week
- activity I by two weeks at $110 000 per week.

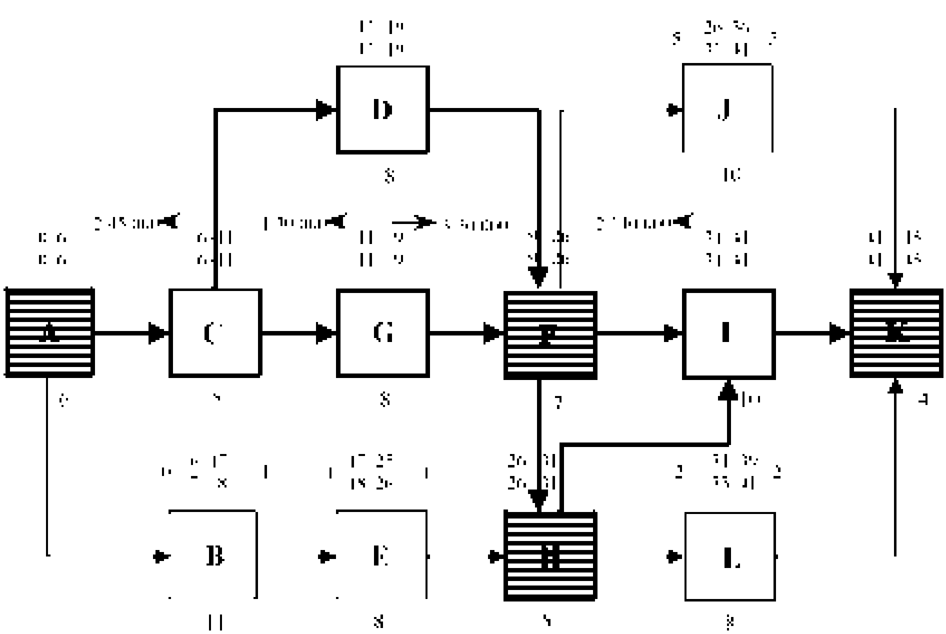
Compression rule 2 states that the cheapest critical activity should be compressed first. The cheapest activity (per week) to compress is activity G. It costs \$30 000 per week and may be compressed by up to four weeks.

Compression rule 3 places the limit on the extent of compression, which is governed by the amount of total float of non-critical activities that are positioned on a path parallel to the critical path. Two non-critical paths lie parallel to the critical activity G, which has already been selected for compression. They are C, D and F and A, B, E and H, with the minimum three and four weeks of total float respectively. It means that activity G can only be compressed by three weeks, which is the minimum amount of available total float. When compressed, activity D will become critical and so will the path C, D and F. The values of total float of activities B and E will be reduced from four weeks to one.

Therefore, activity G will be compressed in the first compression step by three weeks. The project schedule will now be recalculated to reflect the reduction in duration of activity G. The recalculated schedule is given in Figure 6.10. Its duration is now 45 weeks.

Project duration T_1 is	45 weeks
Cost of compression C_1 is	\$30 000 × 3 weeks = \$90 000

Figure 6.10 The project schedule after the first compression



Second compression

After the first compression step, activity D has become critical and since it can be compressed (see Table 6.3), it will be considered for compression together with the other critical activities in the second compression. The compression procedure defined in the first compression step will now be repeated.

The critical activities in Figure 6.10 that are capable of compression lie on two critical paths, the original one and the new one formed by activities C, D and F. To satisfy compression rule 4, which requires the existing critical paths to be retained, the amount of compression along one critical path must be matched by the same amount of compression along the other critical path. Let's identify critical activities that are capable of compression:

Since activity C lies on two critical paths (C, D and F and C, G and F), its compressing would shorten both critical paths by the same amount of time. Both critical paths would therefore be retained to satisfy rule 4.

Neither activity D nor G can be compressed on their own since this would result in the loss of one of the two critical paths. Consequently, activities D and G would need to be compressed together by the same amount of time. Activity I continues to be available for compression.

In summary, the following activities are available for compression:

- activity C by two weeks at $45 000 per week
- activities D and G together by one week at $70 000 per week
- activity I by two weeks at $110 000 per week.

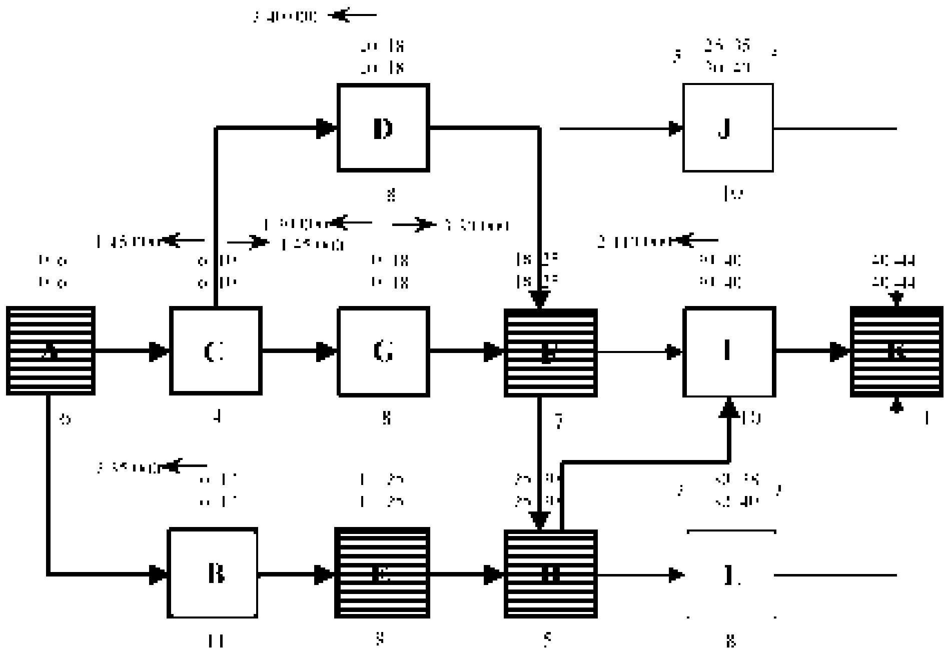
The cheapest activity (per week) to compress is activity C. Its compression costs $45 000 per week. It has two weeks available for compression.

The non-critical path A, B, E and H is parallel to the critical activity C. Compressing activity C will reduce the amount of total float of the non-critical activities B and E. Since the amount of total float is one week, activity C can only be compressed by one week. After compressing C, activities B and E will become critical. A path A, B, E. and H will also become critical. Duration of C is reduced to four weeks.

Therefore, activity C will be compressed in the second compression step by one week. The recalculated project schedule after the second compression is given in Figure 6.11. Its duration is now 44 weeks.

Project duration T_2 is	44 weeks
Cost of compression C_2 is	$45 000 × 1 week = $45 000

Figure 6.11 The project schedule after the second compression



Third compression

After the second compression, activities B and E have become critical, but only activity B is capable of compression (see Table 6.3). Only critical activities in the front part of the schedule are capable of compression. They are located on three parallel critical paths. The first path is A, C, D, F and H, the second is A, C, G, F and H, and the third is A, B, E and H. It is important to apply compression rule 4 here to ensure that all three existing critical paths in the front part of the schedule are retained after the third compression step.

Let's examine possible alternatives. Activity C cannot be compressed on its own because its compression would result in the loss of the critical paths A, C, D, F and H and A, C, G, F and H. In compliance with compression rule 4, activity C would need to be compressed together with activity B.

Next, activities D and G are considered. If they are compressed together by the same amount of time in the third compression step, the critical paths A, C, D, F and H and A, C, G, F and H would be lost. In compliance with compression rule 4, compressing activities D and G necessitates compression of B at the same time. The remaining alternative is to compress activity I.

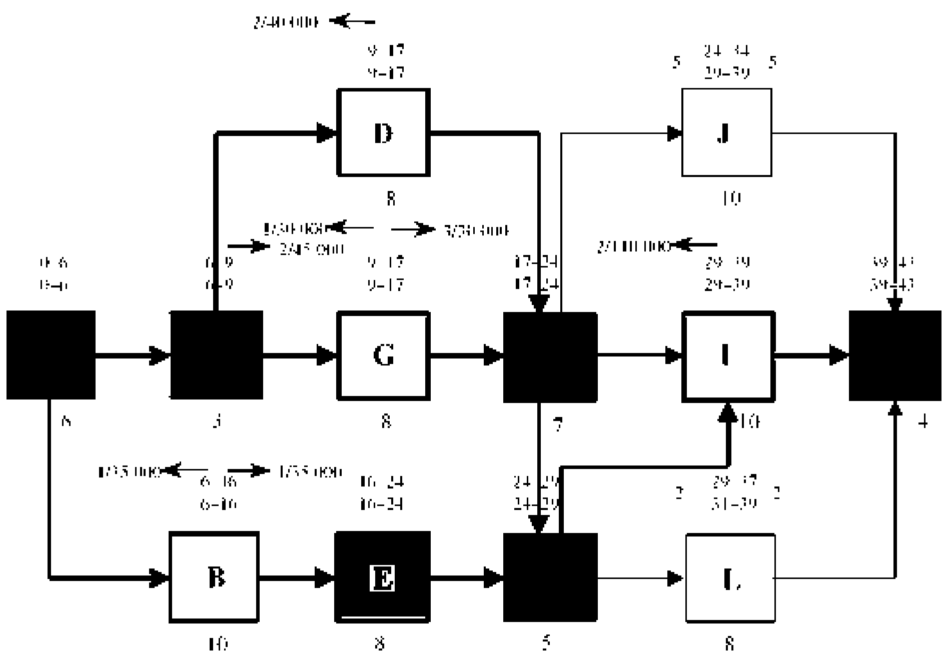
In summary, the following activities are available for compression:

- **activities B and C by one week at $80 000 per week (the cheapest alternative)**
- **activities B, D and G by one week at $105 000 per week**
- **activity I by two weeks at $110 000 per week.**

Therefore, activities B and C will be compressed together in the third compression step by one week. The recalculated project schedule after the third compression is given in Figure 6.12. The project duration is now 43 weeks.

Project duration T_3 is	43 weeks
Cost of compression C_3 is	$80 000 × 1 week = $80 000

Figure 6.12 The project schedule after the third compression



The project schedule has now been compressed to meet the original contract period of 43 weeks. If required, the project schedule may be compressed further. For example, in the fourth compression step, activities B, D and G could be compressed together by one week at $105 000 per week. In the fifth step, activity I could be compressed by two weeks at $110 000 per week.

Together with the starting scenario, the three compression steps that have brought the project schedule duration down to 43 weeks constitute four alternative solutions. Let's now calculate profit/loss outcomes for each of the four alternatives.

Before compression (T_n = 48 weeks)

Direct cost	7 140 000	
Indirect cost 48 weeks × $40 000	1 920 000	
Liquidated damages 5 weeks × $20 000	100 000	
Total cost		9 160 000
Tender sum		9 190 000
Profit		$30 000

After first compression (T_1 = 45 weeks)

Direct cost	7 230 000	
Indirect cost 45 weeks × $40 000	1 800 000	
Liquidated damages 2 weeks × $20 000	40 000	
Total cost		9 070 000
Tender sum		9 190 000
Profit		$120 000

After second compression (T_2 = 44 weeks)

Direct cost	7 275 000	
Indirect cost 44 weeks × $40 000	1 760 000	
Liquidated damages 1 week × $20 000	20 000	
Total cost		9 055 000
Tender sum		9 190 000
Profit		$135 000

After third compression (T_3 = 43 weeks)

Direct cost	7 355 000	
Indirect cost 43 weeks × $40 000	1 720 000	
Liquidated damages	0	
Total cost		9 075 000
Tender sum		9 190 000
Profit		$115 000

Two important issues emerge from the compression analysis of the above project schedule:

1. Compression reduced total float of the non-critical activities and turned most of them into critical activities. Only two non-critical activities, J and L, remained in the project schedule after the third compression. The loss of total float in a project schedule reduces its capacity to absorb future delays. It also reduces its capacity to achieve the effective use of resources through resource levelling.
2. The first two compression steps actually improved the overall project profitability in comparison to the starting situation. However, profitability declined after the third compression. Beyond this point, the more the project schedule is compressed, the higher is the cost of compression and also the project cost. This is because activities that could be compressed in the later compression steps 4 and 5 cost more to compress. A higher cost of the later compression steps is also attributed to the need to compress a group of critical activities.

With four possible alternative solutions in hand, what should the project manager do? There is no simple answer. In formulating an appropriate solution, the project manager would need to consider:

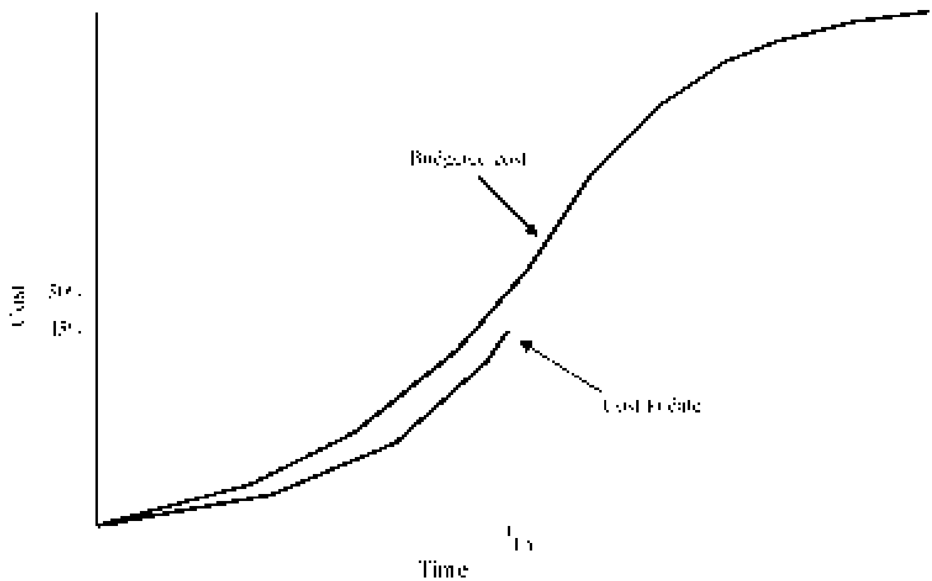
- the profit/loss outcomes of each compression step
- the likely damage to the contractor's reputation if the decision is taken to delay the contract
- the impact of the loss of total float and the increase in the number of critical activities on the ability to effectively manage the project
- the likelihood of securing time extension claims from the client that would, either partially or fully, offset the delay
- the current and future market conditions
- the level of construction activity in the future
- the project manager's own attitude to risk.

One plausible strategy that the project manager may consider is to inform the client of the problem and present the client with a range of alternative solutions including those developed through compression, together with an analysis of how such alternative solutions are likely to impact on both the client and the contractor. The client's response may help the project manager to formulate the most appropriate solution to this problem.

EARNED VALUE

The main objective of the control function, which is to measure the actual project performance and compare it to the plan, has already been discussed in this chapter. Time and cost are the two most commonly used performance measures, where time performance is assessed against a project schedule and cost performance against a cost budget. Assessing time performance independently from cost performance may provide misleading information about the overall project performance. This is illustrated in Figure 6.13.

Figure 6.13 Assessment of project cost performance



The actual cost performance measured at a particular point in time, T_n, is 45 per cent of the cost budget, whereas it was expected to be 50 per cent. The project manager may conclude that the cost performance is better than expected. But unless the project manager relates this information to the time performance, it is not possible to establish if the cost performance is good or bad.

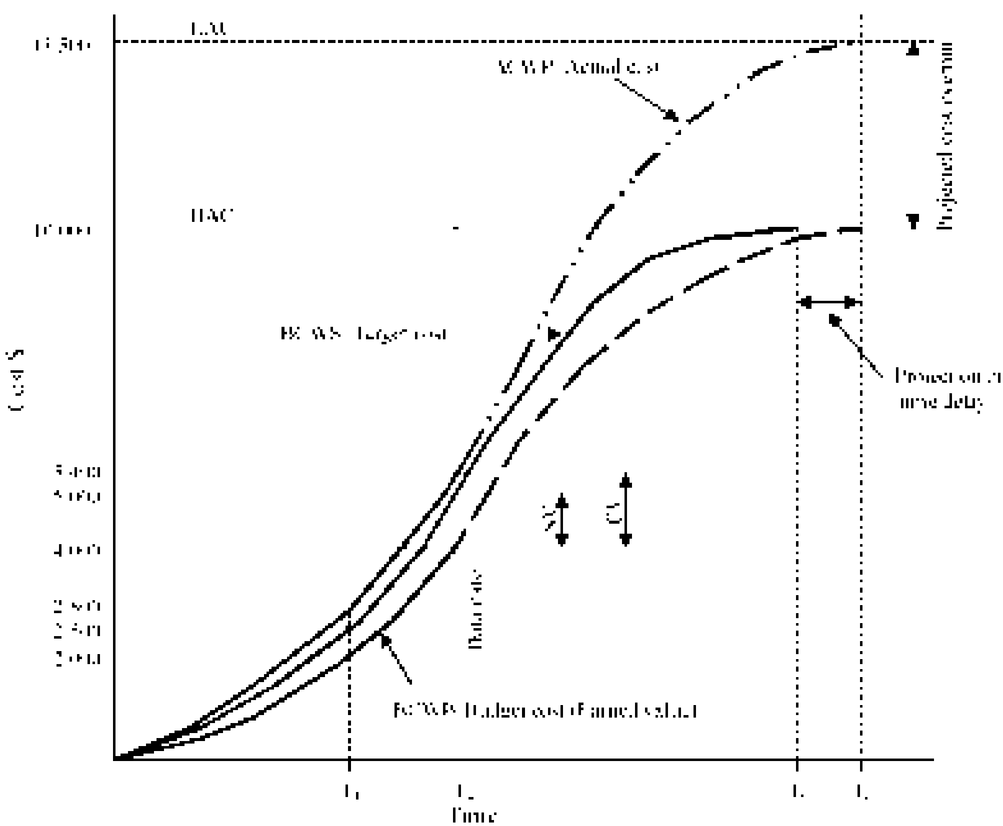
The concept of ‘earned value’ was developed to assist the project manager in assessing time and cost performance in an integrative manner. Earned value represents a uniform unit of measure of progress in terms of time and cost, and provides a basis for consistent analysis of project performance. The technique of earned value was developed in the United States in the 1960s and has largely been used by the US Department of Defence. Since the 1980s, it has been extensively applied in defence projects in Australia.

The technique of earned value

The technique of earned value assists in assessing current progress and performance, and forecasting future progress and performance. To understand the concept of earned value, it is necessary to become familiar with the key elements of earned value that are defined by specific acronyms. The acronyms of earned value have been adopted worldwide. They are illustrated in Figure 6.14.

The first element is 'budgeted cost for work schedule' (BCWS). It is the project target cost and is expressed in Figure 6.14 as an S-curve. For a scheduled project duration, T_s 'budget at completion' (BAC) is $10 000. This is the second element of earned value.

Figure 6.14 Earned value elements (adapted from Burke 1999: 205)



When a project gets under way, the control mechanism will generate feedback on progress at specific points in time known as ‘data dates’. At a data date, the project manager determines in percentage terms the actual progress achieved. It is referred to as PC or ‘percentage complete’. This is the fourth element of earned value. For example, at the data date T_1 in Figure 6.14, BCWS is \$2500. Let’s assume that the project manager assessed PC as 20 per cent. This information enables the project manager to calculate BCWP or ‘budgeted cost for work performed’ or simply ‘earned value’, which is the fifth element of earned value. For example, at the data date T_1,

$$BCWP_1 = PC_1 \times BAC = 20\% \times \$10\,000 = \$2000$$

Similarly, at the data date T_2, where BCWS is \$5000, PC was assessed as say 40 per cent. Then,

$$BCWP_2 = 40\% \times \$10\,000 = \$4000$$

The $BCWP_1$ and $BCWP_2$ values are the two points on the BCWP curve.

If the data date T_2 is the current date, the project manager will forecast BCWP for the remainder of the project. BCWP at completion will be equal to BAC, but the project period may be greater or smaller than T_s. In Figure 6.14 the project period for BCWP at completion is T_c.

While $BCWP_1$ at the data date T_1 is \$2000, the actual cost incurred may be different. Let’s assume that the actual cost is \$2800. Similarly, assume that the actual cost is \$5400 at the data date T_2, where $BCWP_2$ is \$4000. These two actual costs are referred to as ACWP or ‘actual cost for work performed’. They form an ACWP curve. ACWP is the sixth element of earned value.

In order to forecast ACWP at completion, the project manager calculates the value of EAC or ‘estimate at completion’, the seventh element of earned value, at the current data date. EAC is an estimate of the actual project cost at completion. It is calculated as follows:

$$EAC = (ACWP/BCWP) \times BAC \quad (1)$$

Since

$$BCWP = PC \times BAC \quad (2)$$

The equation (1) can be simplified as follows:

$$EAC = (ACWP/PC \times BAC) \times BAC = ACWP/PC$$

At the data date T_2,

$$EAC = \$5400/40\% = \$13\ 500$$

By extrapolation, the project manager is now able to draw an ACWP curve from the current data date to completion. By determining EAC and plotting an ACWP curve, the project manager is immediately alerted to potential time and cost overruns. This is probably the most important benefit of earned value.

When conducting periodic assessment of the project progress and performance, the earned value technique enables the project manager to determine, at specific data dates, schedule and cost variances, and schedule and cost performance indices.

The 'schedule variance' SV, the eighth element of earned value, is the difference between the earned progress BCWP and the budgeted progress BCWS. Although it is a measure of time variance, it is expressed in money units. The sign of the schedule variance indicates whether the project is ahead or behind the schedule. SV at the data date T_2 in Figure 6.14 is calculated as follows:

$$SV = BCWP - BCWS = \$4000 - \$5000 = -\$1000$$

The negative sign indicates that the project is behind the schedule. The schedule variance may also be expressed in percentage terms as follows:

$$SV\% = (SV/BCWS) \times 100\% = (-\$1000/\$5000) \times 100\% = -20\%$$

The 'cost variance' CV, the ninth element of earned value, is the difference between the earned value BCWP and the actual cost of the work. The sign of the cost variance again indicates whether the cost at a specific data date is greater or smaller than the original budget BAC. Let's calculate the cost variance as at the data date T_2.

$$CV = BCWP - ACWP = \$4000 - \$5400 = -\$1400$$

The cost variance is negative, indicating that the cost is over the estimate. In percentage terms, the cost overrun is 35%.

$$CV\% = (CV/BCWP) \times 100 = (-\$1400/\$4000) \times 100 = -35\%$$

Schedule and cost performance indices represent another measure of progress and performance of a project. The 'schedule performance index' SPI, the tenth element of earned value, is the ratio between BCWP and BCWS. For the data date T_2, SPI is:

$$SPI = BCWP/BCWS = \$4000/\$5000 = 8.0$$

When the value of SPI is smaller than 1, as is the case above, the project is behind schedule.

The 'cost performance index' CPI, the eleventh element of earned value, is the ratio between BCWP and ACWP. For the data date T_2, CPI is:

$$CPI = BCWP/ACWP = \$4000/\$5400 = 0.74$$

The value of CPI above is smaller than 1, which indicates that the project spending is over the budget.

Benefits of earned value

In summary, earned value is a highly appropriate technique for assessing and forecasting progress and performance of projects. Its numerous calculations can easily be handled by computer software such Primavera P3. Since the calculation of the estimate at completion, EAC is dependent on determining the value of percentage complete or PC, the project manager needs to exercise care in correctly assessing values of PC. Where possible, the project manager should assess the work completed to date quantitatively, for example in terms of the number of bricks laid. However, when expressing PC subjectively, for example in terms of the 50–50 rule, the fundamental requirement for the project manager is to be consistent. According to the 50–50 rule, when the activity starts, it is assumed to be 50 per cent complete, and when it is accomplished, it is assumed to be 100 per cent complete.

The technique of earned value enhances the cost performance analysis of a project through the application of a consistent methodology and by providing a uniform unit of measure. The key elements of earned value form the terminology that has been universally adopted. A comprehensive bibliography on earned value can be found in Christensen (2002).

SUMMARY

This chapter examined the function of project control. It defined the project control system in terms of monitoring, evaluation and adjustment. It then examined processes of monitoring and evaluation of time and resource performance. It also illustrated updating of a critical path schedule and examined the concept of cost–time optimisation. The application of cost–time optimisation in the form of compression was demonstrated by a practical example. Finally, this chapter described the technique of earned value and its benefits in controlling progress and performance of projects.

EXERCISES

Solutions to the exercises can be found on the following UNSW Press website: http://www.unswpress.com.au

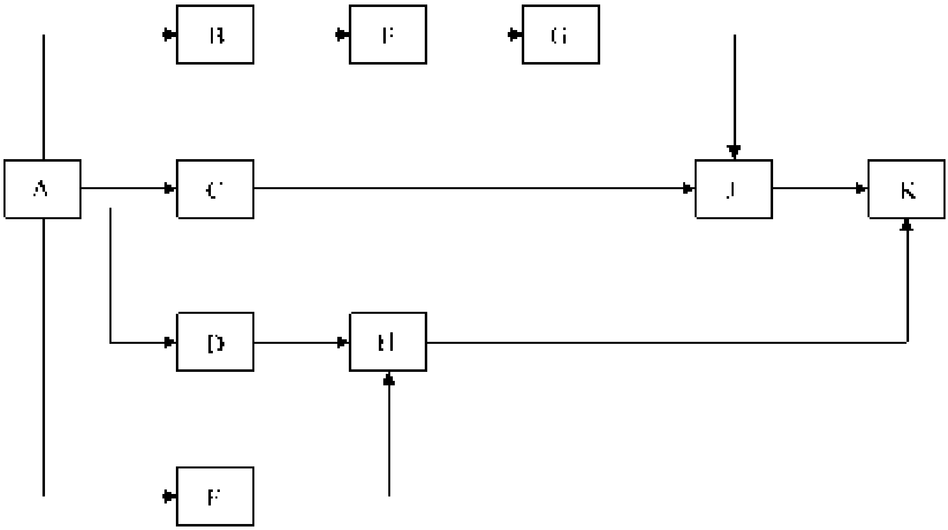
EXERCISE 6.1

A precedence schedule of a project is given below. Compress the schedule in accordance with the data given in the following table. The project indirect (overhead) cost is given as $200 per day.

1. **Determine a profit/loss outcome for each compression stage**
2. **Determine the optimum project time and cost point.**

ACTIVITY	NORMAL TIME IN DAYS	NORMAL COST IN $	CRASH TIME IN DAYS	CRASH COST PER DAY IN $
A	3	600	2	200/day
B	1	50	–	
C	5	3000	3	400/day
D	2	2000	–	
E	4	1200	2	100/day
F	1	300	–	
G	4	1600	2	400/day
H	10	4000	6	400/day
J	2	800	–	
K	4	2200	3	700/day

Note: Read the table in the following manner: activity A can be compressed by one day from three days to two days, etc.



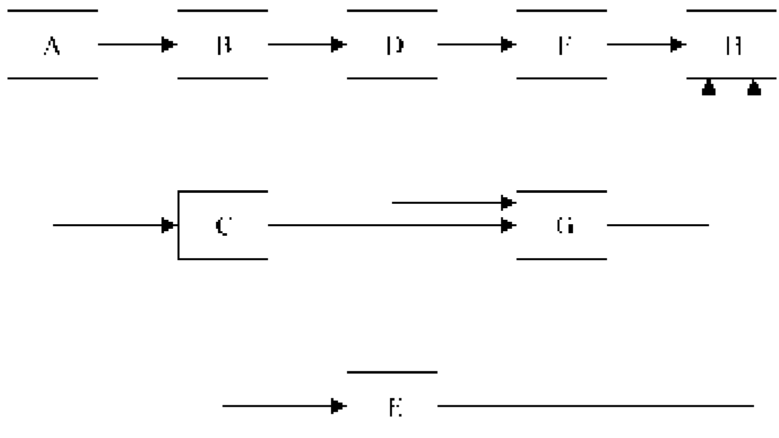
EXERCISE 6.2

A precedence schedule of a project is given below. Compress the schedule in accordance with the data given in the following table. The direct cost of the project is given as $10 000 and the indirect (overhead) cost as $100 per day.

1 Determine a profit/loss outcome for each compression stage
2 Determine the project cost when its duration is reduced to 17 days.

Activity	Normal time in days	Crash time in days	Crash cost per day in $
A	3	2	50/day
B	2	1	150/day
C	7	4	100/day
D	5	4	200/day
E	4	3	50/day
F	6	4	100/day
G	2	2	
H	5	5	

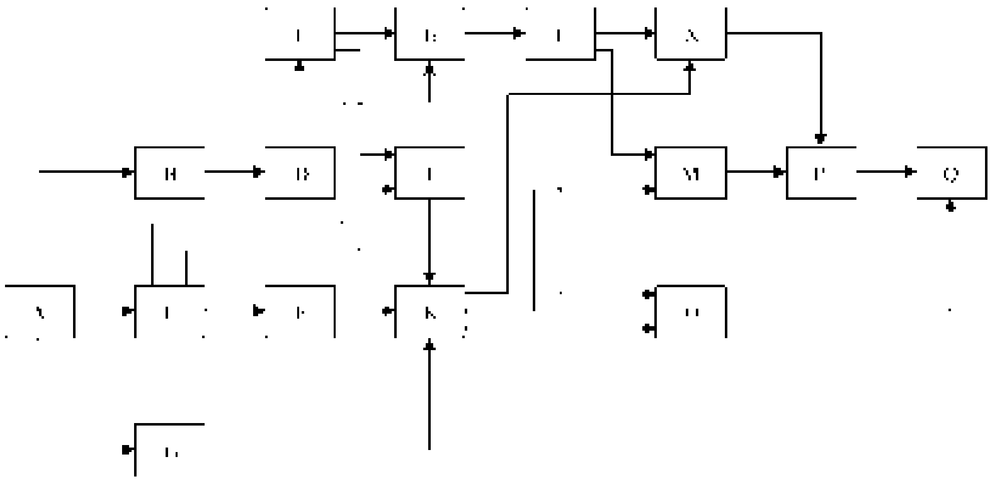
Note: Read the table in the following manner: activity A can be compressed by one day from three days to two days, etc.



EXERCISE 6.3

The contractor was awarded a contract for the construction of a small commercial building for the sum of $192 000. The contract period was agreed to be 108 days. The critical path schedule and the table of activities and costs for the project are given below.

Activity	Normal time in days	Crash time in days	Crash cost per day in $
A	10	10	0
B	20	20	0
C	40	40	0
D	8	8	0
E	30	20	400/day
F	30	25	350/day
G	48	48	0
H	24	18	250/day
J	20	15	300/day
K	15	11	600/day
L	12	9	200/day
M	10	5	300/day
N	6	5	50/day
O	9	7	800/day
P	4	4	0
Q	4	4	0



Before the start of the project, the contractor reviewed the tender schedule and realised that the specified completion date could not be met. The revised schedule indicates that the project will take 122 days to complete (a delay of 14 days).

The contract conditions include the liquidated damages clause set at $100 per day.

The contractor's tender price comprised:

Direct cost	166 000
O/h cost 108 days × $200/day	21 600
Profit	4 400
Total Sum	$192 000

Two weeks after the work on this contract has begun, the contractor was successful in securing another construction contract, but on a strict condition that the contractor would start the new contract before the completion of the current project (not later than on day 102 of the current project). The contractor expects to make $8000 profit on the new project.

Analyse the problem from the contractor's point of view and evaluate a range of alternative responses.

EXERCISE 6.4

For a building project, the following information was derived using the technique of earned value. For the given cases, calculate the values of EAC and interpret the project progress and performance (adapted from Burke 1999: 211). Assume that the data date is approximately at a mid-point of the project period.

CASES	BAC	BCWS	BCWP	ACWP
1	$10 000	$5000	$5000	$5000
2	$10 000	$5000	$4000	$4000
3	$10 000	$5000	$5000	$4000
4	$10 000	$5000	$6000	$4000
5	$10 000	$5000	$4000	$5000
6	$10 000	$5000	$6000	$5000
7	$10 000	$5000	$4000	$6000
8	$10 000	$5000	$5000	$6000
9	$10 000	$5000	$6000	$6000
10	$10 000	$5000	$3000	$4000
11	$10 000	$5000	$4000	$3000
12	$10 000	$5000	$7000	$6000
13	$10 000	$5000	$6000	$7000

CHAPTER 7

CRITICAL PATH SCHEDULING BY COMPUTER

INTRODUCTION

The purpose of this chapter is to briefly examine computer-generated critical path scheduling. Primavera Project Planner PC software will be used to prepare a critical path schedule for a residential project.

Although the critical path method is now the preferred scheduling technique, it has taken the construction industry a long time to accept it. Since then, its popularity has steadily increased. The first generation of the CPM software ran on large mainframe computers. The cost of computer processing was high, which restricted the use of CPM scheduling to large projects. The rapid advent of personal computers since the 1980s has reduced the cost of processing and revolutionised the use of CPM scheduling.

Today, there are many software products on the market to cater for a wide range of scheduling applications. They can generally be grouped into:

- a budget category of software that perform basis scheduling and cost reporting functions, for example Microsoft Project, Superproject and SureTrak
- a premium category of software that is able to perform more complex scheduling tasks and cost-reporting functions, for example Primavera Project Planner P3, Quicknet and Hornet
- a de luxe category of software that, apart from critical path scheduling, offers additional project management functions. For example, Artemis is a data-based software capable of cost estimating, while Timberline is complex information management software.

Most CPM software products express duration of activities as a single value estimate. Some, including Primavera P3 and Microsoft Project, have the capacity to perform Monte Carlo simulation of a critical path schedule through add-in simulation software. Such software enables the planner to express duration of activities as a distribution of values that can be fitted to one of a number of standard probability distributions. The simulation software generates random numbers, which are then assigned to relative probability distributions of individual activities. The outcome of each iteration run is the calculation of one value of the project duration. Hundreds or thousands of iterations produce the final outcome in the form of the normal distribution of project time, which is fully described by its mean and standard deviation. The concept of probability, risk and simulation will be discussed in more detail in Chapter 12.

An alternative approach to probability scheduling is PERT (program evaluation and review technique). It will be examined in detail in Chapter 13.

This chapter will explore the use of Primavera Project Planner P3 software in scheduling a small residential project. It will demonstrate the generation of time and resource schedules, the use of overlaps, the control function and the cost-reporting facility. Because the focus of this chapter is on demonstrating the use of critical path software, the reader should not expect to find detailed information on how Primavera P3 works.

BRIEF OVERVIEW OF PRIMAVERA PROJECT PLANNER P3 SOFTWARE

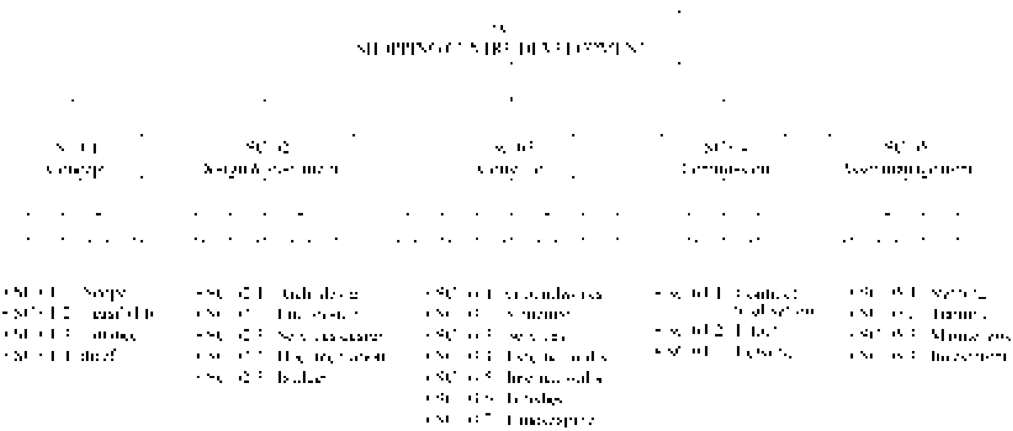
Primavera P3 is the leading CPM software with a widespread use throughout the world. It offers the full range of functions necessary for planning and control of projects. These include:

- time and resource scheduling
- resource levelling for a large number of individual resources
- modelling relationships through a full range of overlaps
- updating and network compression
- tracking progress in terms of time, cost and resources
- cost reporting.

Primavera P3 gives the planner an opportunity to accommodate different work patterns up to 31 calendars. It also helps to develop a hierarchy of work to be accomplished in the form of a work breakdown structure with appropriate codes.

With regard to WBS, Primavera P3 can create up to 20 levels of project structure. Figure 7.1 shows three levels of WBS of a shopping centre development project with appropriate codes. Naturally, more levels of WBS can be created as they are required. By sorting activities in a schedule according to their WBS codes, the planner can review information at different levels of detail.

Figure 7.1 A WBS for a shopping centre development project



Primavera P3 also provides a complex system of project and activity codes. Project codes are useful for tracking information on individual projects in the project group. Primavera P3 supplies ten default project codes that the planner can modify as required. By assigning activity codes, the planner can classify activities into specific groups for organising and sorting information in projects. Up to 20 activity codes can be specified, of which six are predefined by Primavera P3. They are:

- RESP (responsibility)
- AREA (area/department)
- MILE (milestone)
- ITEM (item name)
- LOCN (location)
- STEP (step).

If required, the predefined activity codes may be modified. For each activity code the planner defines specific values. For example, the planner has created a new activity code DEPT (department) with the following values:

- ESTM Estimating department
- CONS Construction department
- PRCH Purchasing department
- FINC Financial department
- HRMG Human resource management department
- CONT Contracts department

Primavera P3 generates ID codes that are assigned to individual project activities. Each activity's ID code can be up to ten characters long. It can be divided into four different parts, each with special meaning. This enhances the ability of the planner to organise, select and summarise activities. If the project belongs to a specific project group in Primavera P3 file structure, the first two characters in the field (positions 1–2) identify that project. The remaining three parts can be defined for different purposes. If the project doesn't belong to a project group, the first two characters are not reserved for identifying that project and the planner can use the entire field of ten characters to define up to four different ID parts. Following is an example of an ID code divided into four parts:

- part 1: project group (2 characters)
- part 2: project stage (2 characters)
- part 3: project member (2 characters)
- part 4: activity number (4 characters).

Activity ID codes are then assigned to each activity in the project using the above format. For example, the activity ID code M3DESE0468 would be interpreted as follows:

- 'M3' identifies the project as 'maintenance project 3'
- 'DE' refers to 'design stage'
- 'SE' refers to 'structural engineer'
- '0468' is the activity number.

Cost estimating requires the planner to prepare separate estimates for labour, materials, plant/equipment and other resources, and input them into a cost-accounting structure set up in Primavera P3. It consists of up to 36 categories of cost accounts.

Cost accounts can be up to 12 characters long and can be divided into a number of parts for a more detailed tracking and sorting of various cost components. They are identified by a one-character code, which is the twelfth character in the code. For example, a cost account '12350420600L' could be interpreted as follows:

- The first two characters, '12', identify the project within the project group.
- The next four characters, '3504', identify the item or activity within the project.
- The next one-character code, '2', identifies the work task.
- The next two characters, '06', identify the controller.
- The following two characters, '00', are spare or dummy characters.
- The twelfth character 'L' is reserved for the cost category.

Primavera P3 also offers a range of printed and plotted outputs. Some of the printed outputs will be illustrated in section 7.3.

SCHEDULING A RESIDENTIAL PROJECT USING PRIMAVERA P3

The project in question is a small residential building. A list of activities including durations and resources is given in Table 7.1.

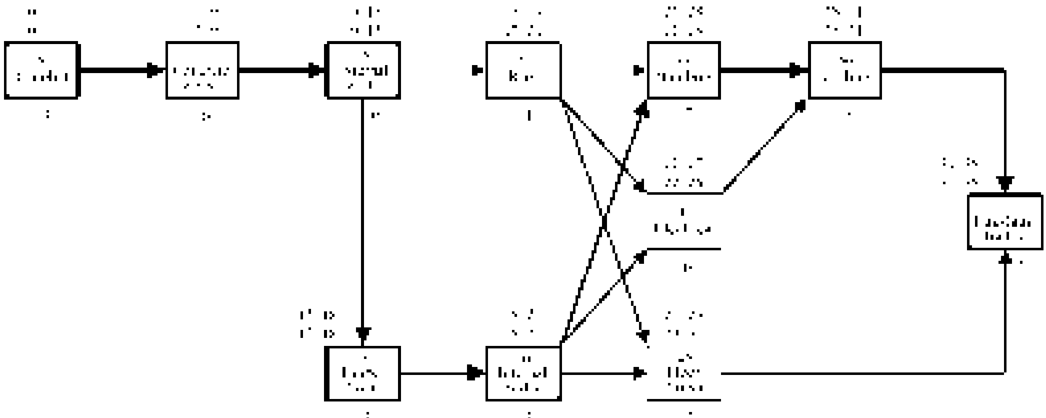
Resources can be assigned to activities either as lump-sum values or as rates per time-unit. For example, the activity 'Demolish' is assigned the supervisor's time in the form of a lump sum, that is, one person-day. Because the activity 'Demolish' is expected to take three days to complete, Primavera P3 assigns one-third of the supervisor's time to each day of the activity's duration. In comparison, the labourer is allocated to the activity 'Demolish' in the form of a rate, that is, one person per day. Primavera P3 then assigns one labourer for each day of the activity's duration, irrespective of how long the activity actual takes to complete.

TABLE 7.1 THE PROJECT DATA

Activities	Time in days	Project resources: Labourer	Carpenter	Subcontr.	Supervisor	Plant	All Labour
5 Demolish	3	1/day		5/day	1 person-day	1 Bulldozer/day 1 truck/day	7
10 Concrete	6	3/day	1/day		4 person-days	2 backhoe days 1 pump day 1 vibrator day	5
15 External walls	6			7/day	4 person-days	1 mixer per day 3 barrows per day 1 scaffold per day	8
20 Roof	4	1/day	2/day	3/day	2 person-days		7
25 Timber floor	3	2/day	4/day		2 person-days		7
30 Internal walls	3	2/day	4/day		2 person-days		7
35 Plumbing	7			14 person-days	2 person-days		3
40 Electrical	6			12 person-days	2 person-days		3
45 Floor Finish	2	2/day	3/day		1 person-day		6
50 Ceiling	3			2/day			2
55 Finishing	7	2/day	1/day	3/day	5 person-days		7

The logic of the construction sequence is defined in a manually produced and calculated precedence schedule in Figure 7.2.

Figure 7.2 A precedence schedule of the residential project



Create time schedule

Creating a new project and entering activities into Primavera P3 is a relatively simple task. Activities can be entered in a bar chart view that displays the activity form or in a PERT view. The reader should note that the term 'PERT' used in Primavera P3 describes a precedence network. It does not refer to the identical acronym used in this book that stands for 'program evaluation and review technique'.

For this simple example, neither project nor activity codes are considered. Activity IDs have been created as two-digit numerical codes. After all the activities have been logged in, they are linked to form the required relationships. At this stage of the schedule development, only finish-to-start links are used. Overlaps will be introduced later in this chapter.

The schedule will now be calculated using the time scheduler, which is only concerned with tasks while ignoring committed resources. Primavera P3 has calculated the project to be completed on day 39. Since Primavera P3 starts the project on day 1, week 1, the actual duration of the project in days is 38. The resulting time schedule can be viewed or printed in a number of different formats such as a linked bar chart, a time-logic diagram, a PERT network or a table. Figure 7.3 displays the time schedule in the form of a linked bar chart.

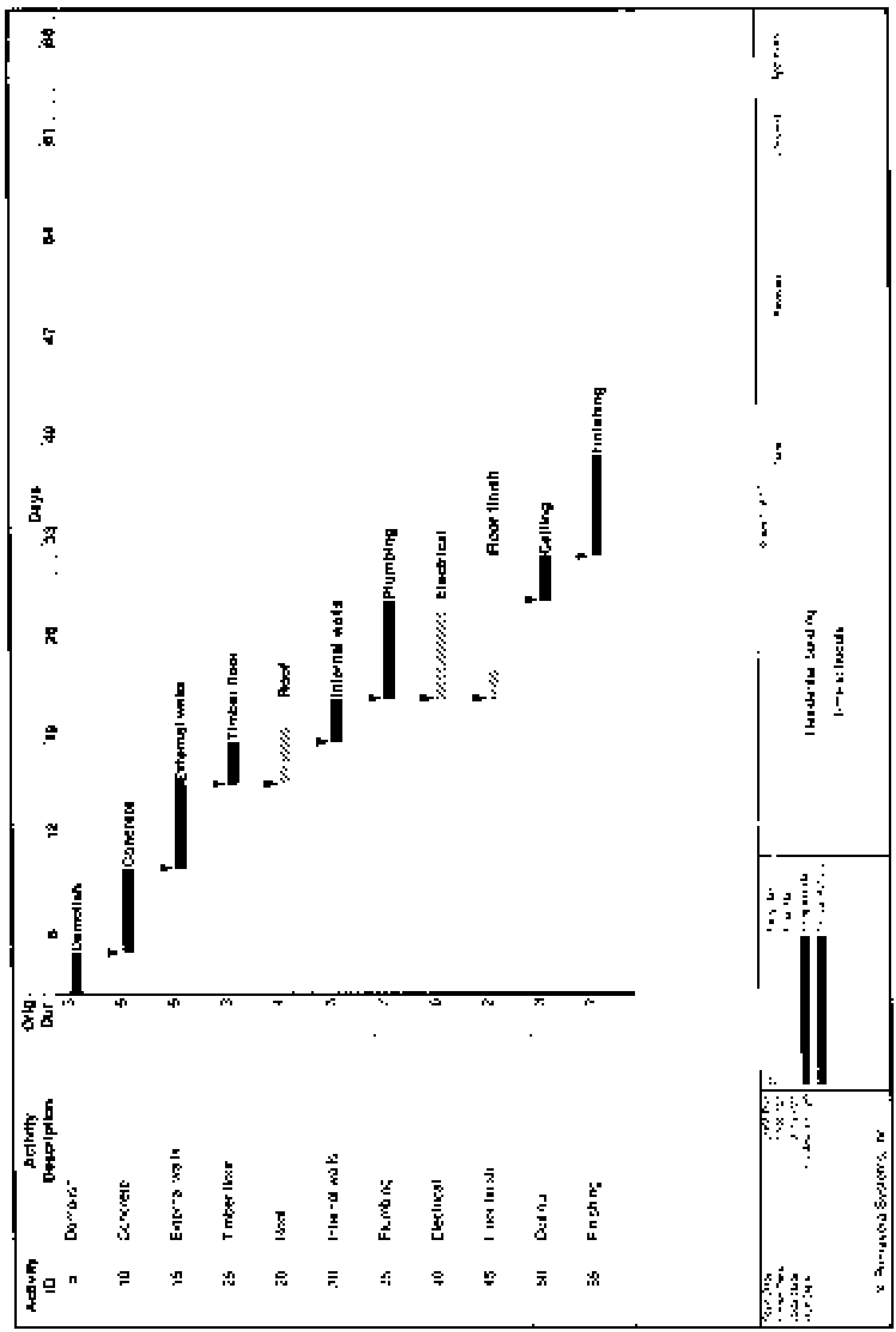
Create resource schedule

Primavera P3 levels resources according to the following rules:

- **Initially, resources are levelled within their normal limits by using up available total float but maintaining the project duration.**
- **If resources cannot be levelled within their normal limits, Primavera levels them within their total limits while maintaining the project duration.**
- **If Primavera P3 cannot level resources within their total limits, it will then extend the project duration.**

A 'normal limit' of a resource represents an optimum volume of that resource available for the execution of the work. A 'total limit' of a resource is the maximum volume of that resource available for the execution of the work.

Figure 7.3 The time schedule in the form of a linked bar chart



Limits imposed on the volume of required resources are specified in Table 7.2.

TABLE 7.2 NORMAL AND TOTAL RESOURCE LIMITS

RESOURCES	NORMAL LIMIT	TOTAL LIMIT
All labour	10	15
Backhoe	2	2
Barrow	3	3
Bulldozer	1	1
Carpenter	4	5
Labourer	3	4
Mixer	1	1
Pump	1	1
Scaffold	1	1
Subcontract labour	8	10
Supervisor	2	3
Truck	1	1
Vibrator	1	1

Before the schedule is resource-levelled, it is worth browsing through individual resources to examine their distribution and note their demand levels. For example, a resource histogram generated for 'Carpenter' in Figure 7.4 reveals that the demand for carpenters between weeks 3 and 4 exceeds both the normal and total limits. The activities causing this excessive demand are 'Timber floor' and 'Roof'. Unless more carpenters are assigned to one or both of these activities, Primavera P3 will delay the start of the non-critical activity 'Roof' until the total resource limit is met.

The importance of tracking the total number of people employed on construction sites was discussed in Chapter 4. The histogram of 'All labour' resource is given in Figure 7.5. It shows that the normal limit has been exceeded between weeks 3 and 4, but that the maximum labour demand is below the total limit of 15 people.

Figure 7.4 A resource histogram of the resource 'Carpenter' before levelling

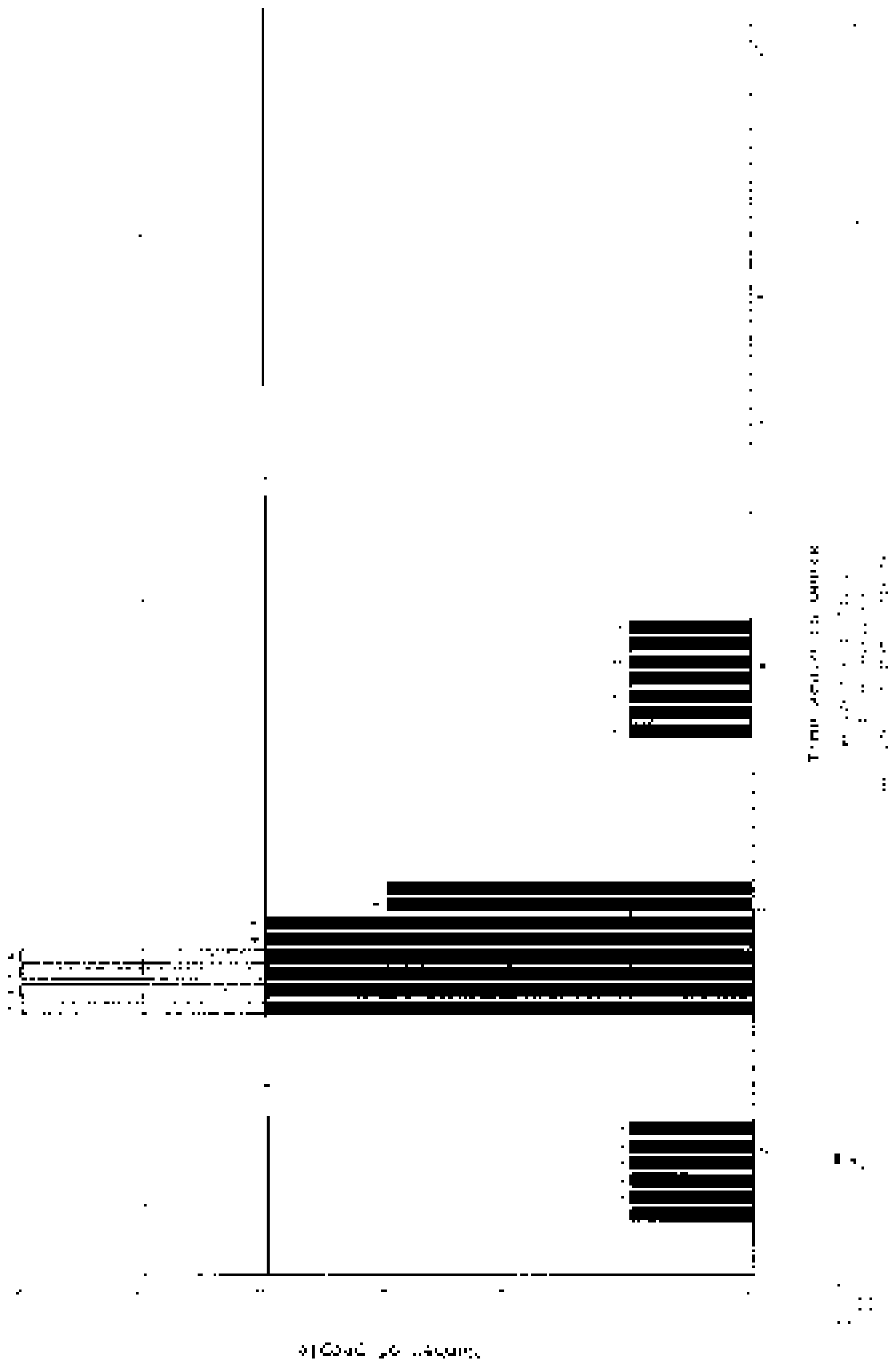
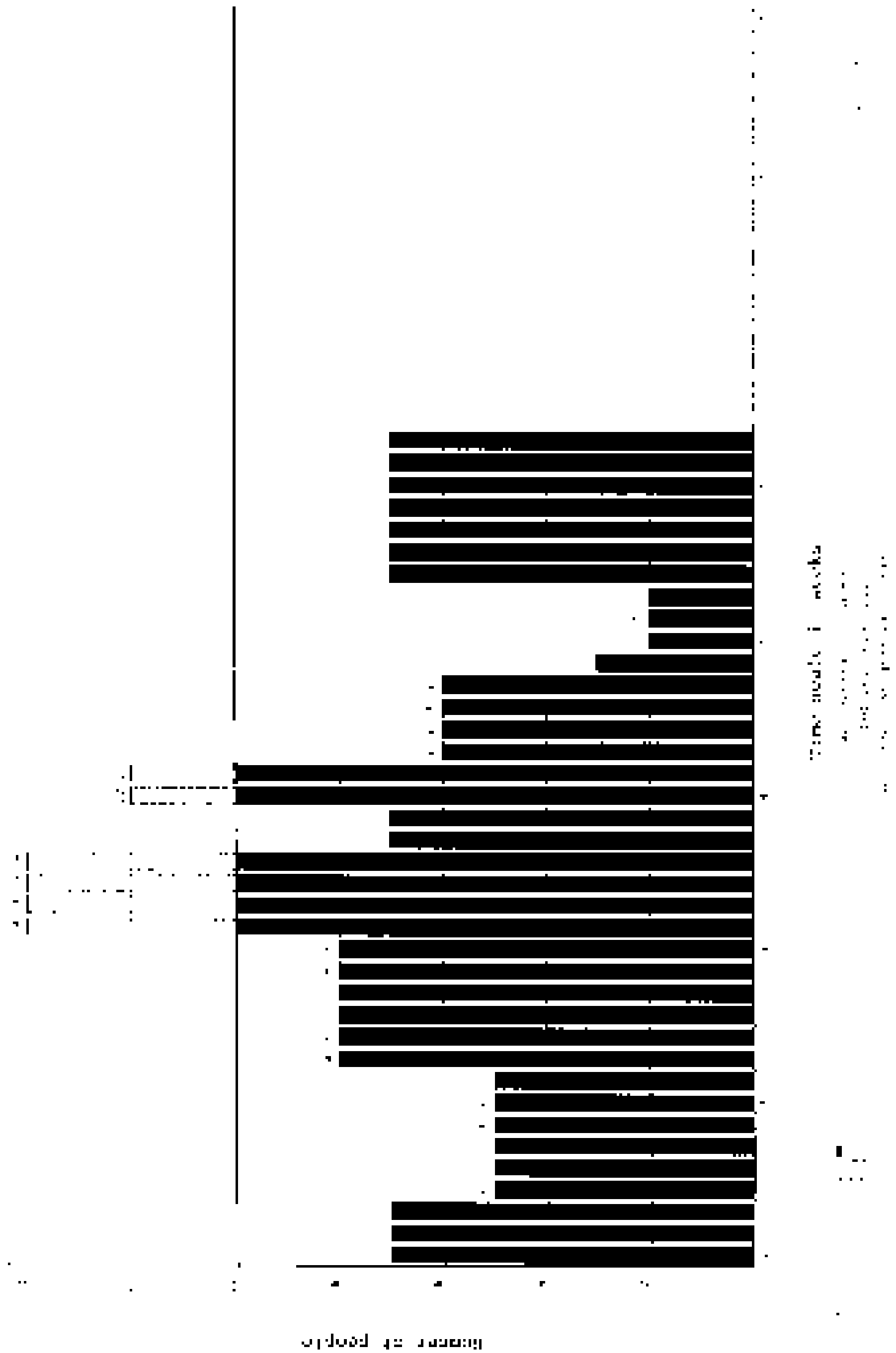


Figure 7.5 A resource histogram of the resource 'All labour' before levelling



Let's resource-level the schedule based on the defined limits of resources using the resource leveller in Primavera P3. The calculated project completion date is now day 43. Examination of the resource schedule in Figure 7.6 reveals that by observing the resource limits of the resource 'Carpenter', Primavera P3 delayed not just the activity 'Roof' but also the critical activity 'Internal walls'. Consequently, all the other activities scheduled beyond the activity 'Internal walls' were delayed. The resource histogram of the resource 'Carpenter' after resource levelling is given in Figure 7.7. It shows that the demand for the resource is now well within its normal limit.

Figure 7.6 The resource schedule in the form of a linked bar chart

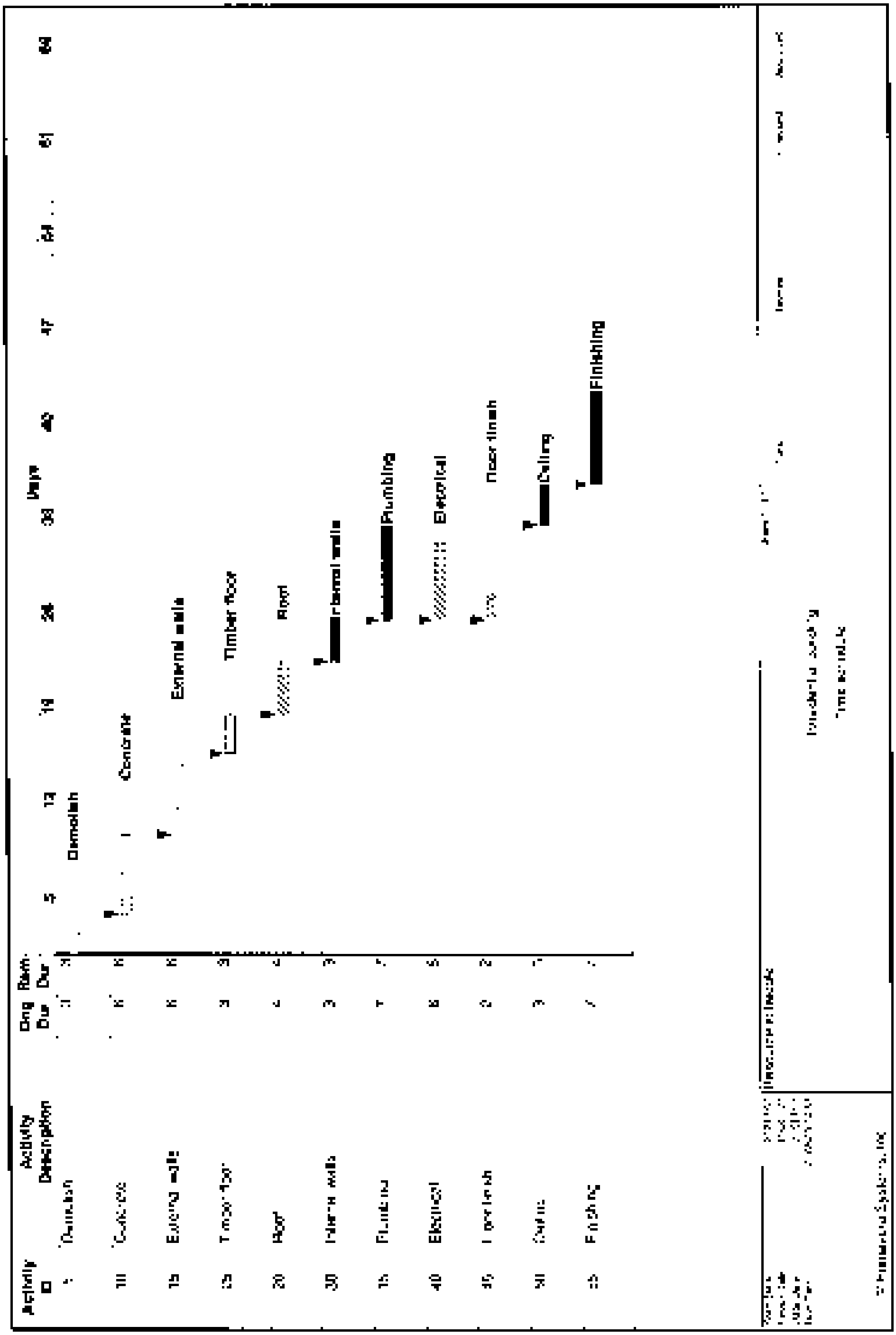
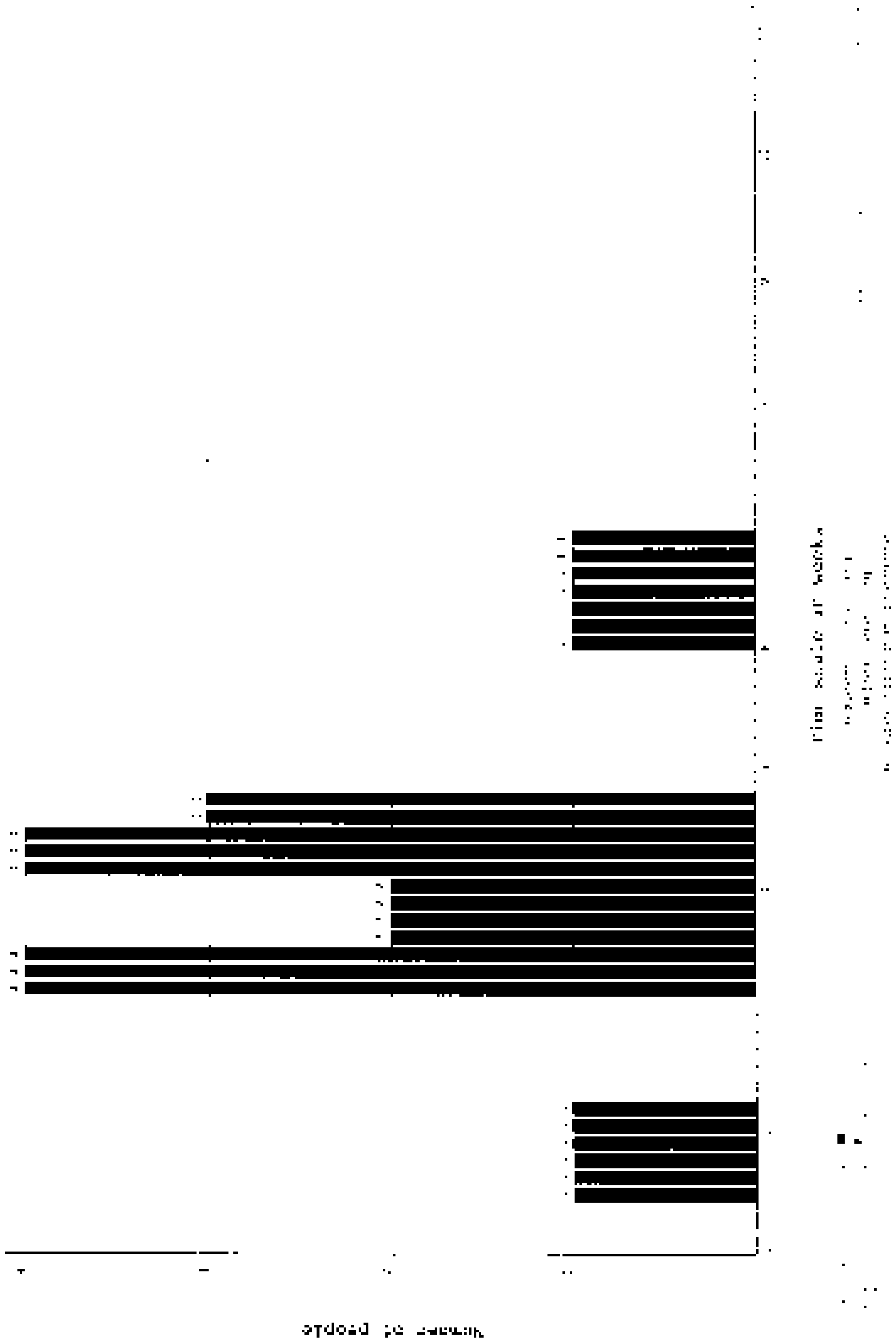


Figure 7.7 A resource histogram of ‘Carpenter’ after levelling



Cost estimating

For this residential project, five account categories have been set up as follows:

- L labour
- C contractor and subcontractors
- S supervisor
- P plant and equipment
- M materials.

Cost accounts have been set up for the following resources:

1201	labourer	1208	concrete pump
1202	carpenter	1209	vibrator
1203	subcontractor	1210	mixer
1204	supervisor	1211	wheelbarrow
1205	bulldozer	1212	scaffolding
1206	truck	1213	materials
1207	backhoe		

Individual cost components have been estimated for each activity in the project. They are given in Table 7.3.

TABLE 7.3 THE PROJECT COST DATA

	Costs						
Activities	Labourer	Carpenter	Subcontractor	Supervisor	Plant	Materials	Total Cost
5 Demolish	$420		$3 000	$160	$1500	$320	$5 400
10 Concrete	$2 520	$900		$640	$530	$1 300	$5 890
15 External walls			$8 400	$640	$1080	$6 750	$16 870
20 Roof	$560	$1 200	$2 400	$320		$4 150	$8 630
25 Timber floor	$840	$1 800		$320		$1 890	$4 850
30 Internal walls	$840	$1 800		$320		$5 240	$8 200
35 Plumbing			$2 800	$320		$1 740	$4 860

			Costs				
Activities	Labourer	Carpenter	Subcontractor	Supervisor	Plant	Materials	Total Cost
40 Electrical			$2 400	$320		$1 520	$4 240
45 Floor finish	$560	$900		$160		$2 670	$4 290
50 Ceiling			$1 200			$2 050	$3 250
55 Finishing	$1 960	$1 050	$4 200	$800		$3 250	$11 260
Total	$7 700	$7 650	$24 400	$4000	$3110	$30 880	$77 740

The cost rates for labour and plant are given in the following Table 7.4.

Table 7.4 The cost rates for labour and plant

Resources	Cost per day ($)
Backhoe	150
Barrow	10
Bulldozer	300
Carpenter	150
Labourer	140
Mixer	50
Pump	200
Scaffold	100
Subcontract Labour	200
Supervisor	160
Truck	200
Vibrator	30

Primavera P3 provides a wide range of cost reports including cost control, earned value, tabular and cost loading reports. Example of a cost report detailed by activity is given in Table 7.6.

Updating the schedule

As the project gets under way, the project manager regularly monitors performance and compares it to the planned or budgeted performance. From deviations and trends that have been detected and analysed, the project manager updates the schedule accordingly.

The process of schedule updating is a relatively simple task in Primavera P3. The revised data on duration of activities, resource requirements and costs, related to a particular point in time, are logged in. Let's assume that the schedule is being reviewed on day 27. The project manager's assessment of progress achieved to date, and the estimates of future progress in terms of time and cost, are given in Table 7.5.

TABLE 7.5 DATA ON PROGRESS OF THE PROJECT ON DAY 27

ACTIVITIES FULLY COMPLETED

ACTIVITY NUMBER	ACTUAL DURATION	ACTUAL COST
5	3	5 400
10	6	6 200
15	6	16 970
20	4	9 140
25	3	5 060
30	3	8 500

ACTIVITIES IN PROGRESS

ACTIVITY NUMBER	TIME TO COMPLETE	COST TO DATE	COST TO COMPLETE
35	6	800	4 170
45	1	2 650	1 860

ACTIVITIES NOT YET STARTED

ACTIVITY NUMBER	REVISED DURATION	REVISED COST
40	5	4 240
50	3	3 250
55	7	11 260

Once the revised time and cost information is logged in, the schedule is recalculated and new reports generated. A linked bar chart in Figure 7.8 and a cost report sample in Table 7.6 provide information on the outcome of the review on day 27.

Figure 7.8 The project schedule in the form of a linked bar chart on day 27

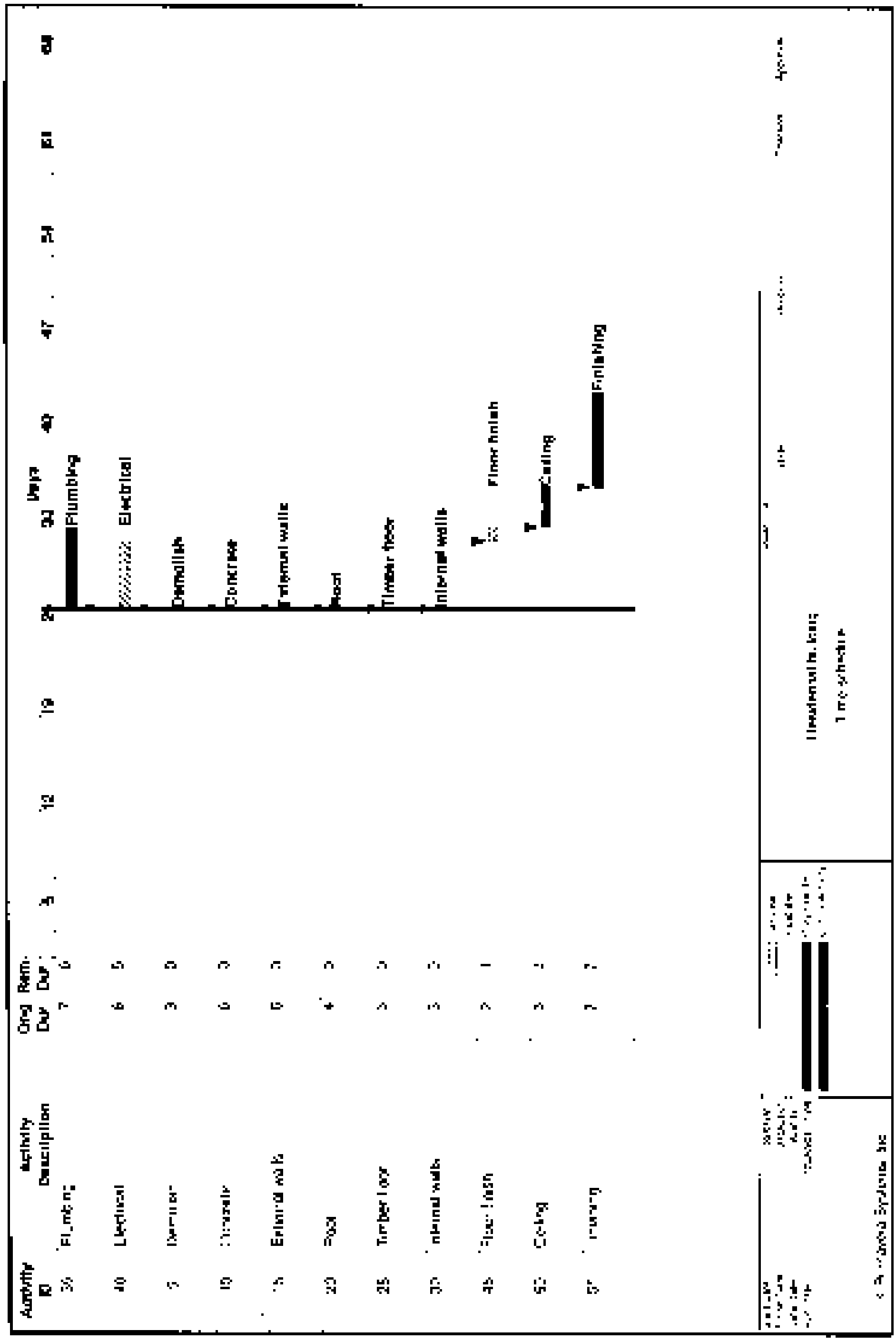


TABLE 7.6 A SAMPLE OF A COST REPORT FOR THE PROJECT REVIEW ON DAY 27

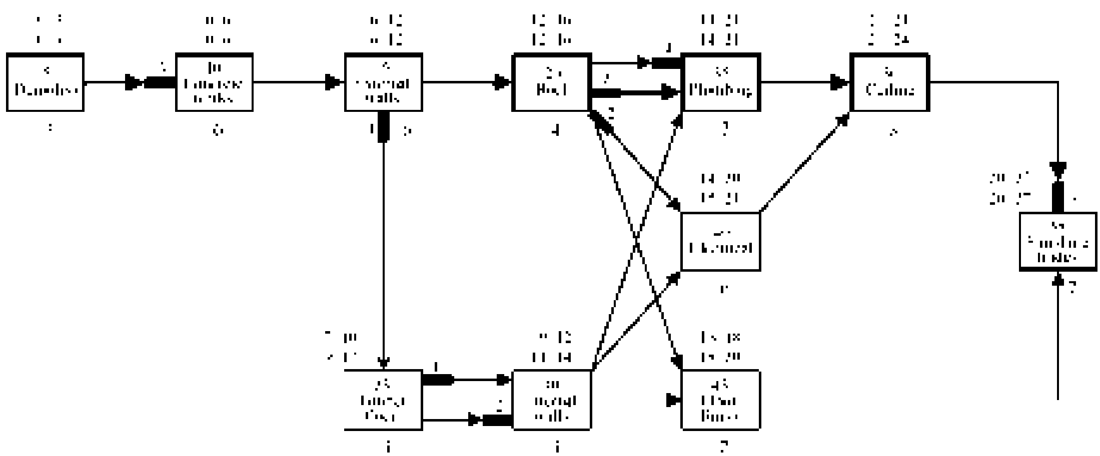
[illegible]

OVERLAPPING MODELS IN PRIMAVERA P3

In addition to the default FTS link, Primavera P3 is able to model STS, FTF and STF links, as well as a compound STS and FTF link. These overlapping models were discussed in detail in Chapter 5.

CPM schedules of small construction projects commonly involve FTS links only. Overlaps are rare due to their small size and a relatively small number of activities. While not entirely necessary, overlaps have been introduced into the residential project in question for demonstration purposes. They are illustrated in Figure 7.9. The manual calculation of the time schedule shows its duration to be 27 days.

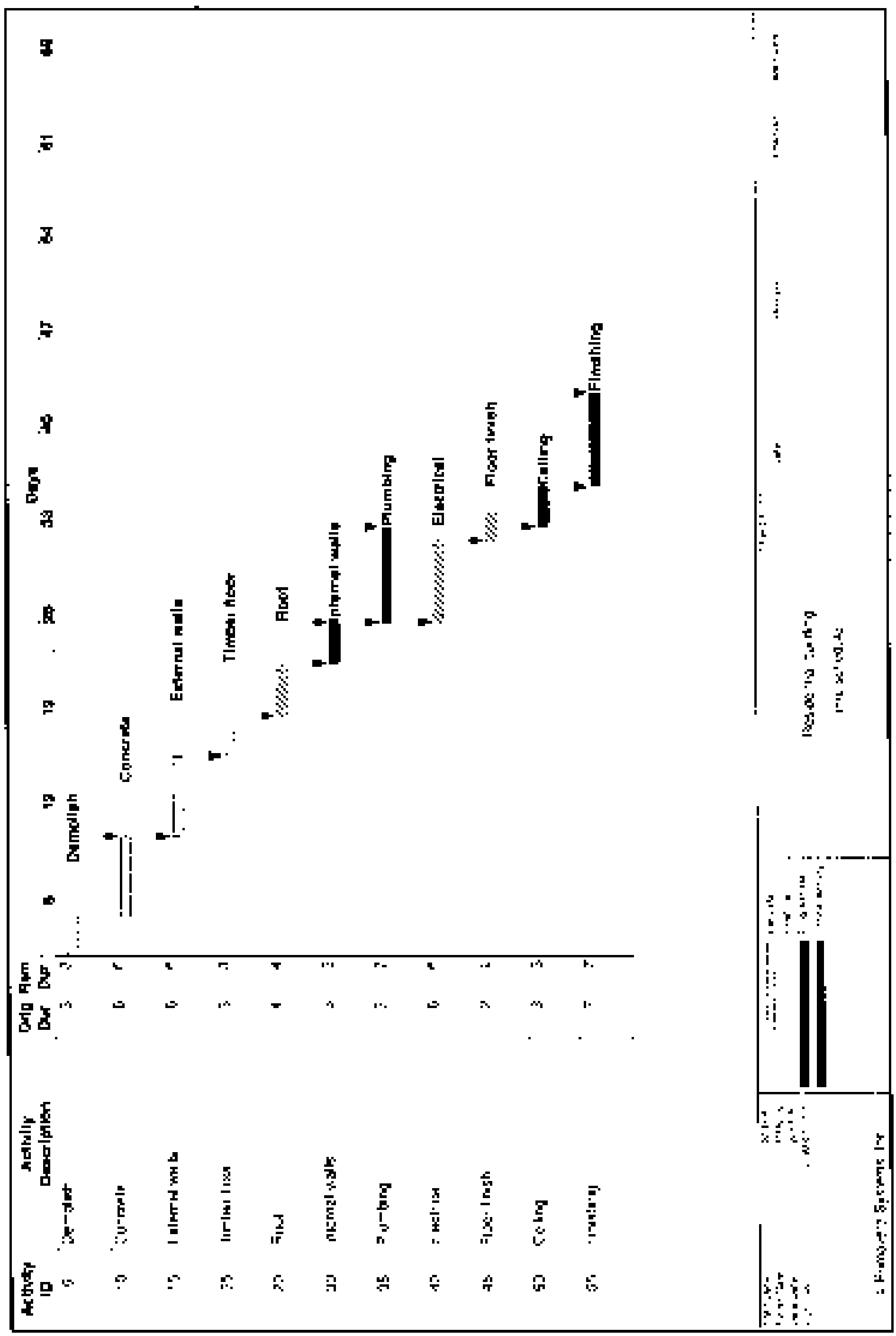
Figure 7.9 An overlapped schedule of the project



Primavera P3 adds overlaps by selecting an appropriate overlap from the 'Activity Detail' menu. A compound STS and FTF overlap requires the creation of two links, one for the STS and the other for the FTF link.

For the residential project in question, overlaps were added to the resource schedule. When the schedule was recalculated, its duration remained unchanged (day 42) (see Figure 7.10). This is because the resource schedule is calculated within the limits of available resources. In comparison, the overlapped time schedule in Figure 7.9 had its duration reduced to 27 days.

Figure 7.10 An overlapped linked bar chart



SUMMARY

This chapter examined some aspects of critical path scheduling using Primavera P3 software with regard to a small residential project. It explained the preparation and calculation of time and resource schedules, it defined activity and cost codes, and generated samples of cost reports. It also demonstrated the process of schedule updating. Finally, the chapter also illustrated the use of overlapping models in critical path scheduling.

It is important that those who use CPM software have, in addition to construction experience and the ability to operate the software, theoretical knowledge of critical path scheduling. This is essential for effective interaction with the software during the planning, monitoring and control stages. The planner must know what information to log in and how to interpret and respond to outputs. The planner is expected to be in full control of the scheduling process rather than being controlled or constrained by the CPM software.

CHAPTER 8

CRITICAL CHAIN SCHEDULING

INTRODUCTION

The concept of critical path was discussed in the preceding chapters. It is the most commonly used scheduling method in the construction industry. In recent years, however, the proponents of the 'theory of constraints' (TOC) have questioned the appropriateness of the critical path method (CPM) in project management, arguing in favour of an alternative approach derived from TOC, which is known as 'critical chain scheduling' (CCS). This approach may also be referred to as 'critical chain management' (CCM). In this chapter, the former term is used.

The purpose of this brief chapter is to examine the concept of critical chain scheduling, highlight its differences from the critical path method, and describe its benefits.

SHORTCOMINGS OF THE CRITICAL PATH METHOD

The proponents of CCS, including Goldratt (1997) and Newbold (1998), have identified a number of shortcomings of CPM that CCS is able to overcome. These are mainly related to excessive use of contingencies in time estimation, task orientation, frequent shifting of the critical path, and multi-tasking.

In traditional CPM scheduling, planners derive duration of activities deterministically as an average time estimate that has a 50 per cent probability of being achieved. This 'risky' estimate is then made safe by the inclusion of an allowance or contingency for uncertainty, which the planner adds to each activity. This contingency represents the planner's subjective perception of the risk to which each activity is exposed. Over hundreds of activities in a schedule, these individual activity contingencies add up to a substantial time contingency. Thereafter, top management of the firm usually adds another contingency to the schedule, which is intended to cover uncertainties surrounding the entire project. This contingency is referred to as project contingency and is commonly expressed as a percentage of the project period.

It would seem that with two layers of contingency built into a schedule, the probability of delays in delivering projects on time should be small. However, the reality is different, and construction projects continue to overrun on time. The proponents of CCS argue that excessive contingencies create feeling of 'safety' among the project team members and this may lead to complacence.

The proponents of CCS point to task orientation as another weakness of CPM. Indeed, CPM is task- or activity-oriented. The emphasis is placed on completing individual activities as planned. The project manager hopes that by accomplishing individual activities as scheduled, the project will be completed on time. Having sufficient time contingencies and float in non-critical activities may, however, lead to complacence; people's attention tends to shift away from those activities that have 'time safety' built into them to more urgent tasks. They may even reallocate resources away from such safe activities to those that need them urgently. This is known as 'student syndrome', which refers to the common practice among students of not attending to assignments until a last few days before their submission. The lack of focus on non-urgent tasks results in the loss of float. Non-critical activities then become critical and their further delay causes the project to overrun on time. It may be argued that the focus on tasks diminishes the focus on the overall completion date of the project, which is the most important issue as far as the client is concerned. A statement made by Frank Patrick (2002: 5) reinforces this view: 'We protect our project due dates by protecting task due dates with safety. Then, from the point of view of the project, we waste that safety due to the comfort it provides, and put the project promise in jeopardy'.

Efficient use of committed resources is an important aspect of critical path scheduling. This is achieved through resource levelling. When a schedule has been resource-levelled, each activity in the schedule becomes critical in terms of committed resources.

The loss of float in one specific activity may not by itself cause a delay to the overall schedule but it may alter the demand level for a resource that has been allocated to it. This may lead to extra costs, multi-tasking of committed resources, and/or a delay to the schedule. If resource allocation to critical activities is insufficient, such activities will be delayed unless more resources are urgently provided. This again will increase the cost and cause multi-tasking since resources from other activities will be diverted to activities in distress.

A resource-levelled schedule contains both task and resource dependencies. However, only task dependencies are shown in a critical path schedule as links. Resource dependencies are formed by resource levelling. Omission of some dependencies is likely to result in unexpected delays in activities. For example, a formwork subcontractor who is designing slipform equipment for the construction of the lift shafts realises that information on the location of reinforcing bars in concrete walls has not been provided. This is because a dependency between structural design and slipform design was omitted. The outcome of this omission is that slipform design will most likely be delayed if the structural engineer's resources cannot be mobilised immediately to address this problem. The most likely outcome is that the structural engineer will divert some of the design resources from other tasks to solving this problem. This potentially leads to multi-tasking of resources, which increases the risk of further delays.

References have previously been made to multi-tasking as a potential cause of delays. Multi-tasking is a common feature of CPM scheduling. It is characterised by employing resources across a number of different activities in a given period in order to achieve their maximum use. However, without clear priority of employment of such resources, as a safeguard, durations of activities are commonly made longer to ensure that the resources are able to accomplish the work. The extra time added to activities to compensate for multi-tasking may be lost due to the task orientation of the critical path method, which was briefly discussed earlier. A multi-tasked resource such an electrician, who is responsible for a wide range of activities associated with the installation and supply of the electrical service, is likely to be directed first to urgent tasks. If delays occur in the execution of such urgent tasks, non-urgent tasks lose their float and also become urgent. It follows that multi-tasking is likely to increase a risk of delays.

Knowledge of the location of the critical path is the essence of critical path scheduling. The project manager concentrates management efforts on preventing delays in critical activities in order to maintain the project schedule. When float is lost, non-critical activities become critical and form an additional critical path. Any further delay in their duration results in the loss of the original critical path. By the time the project manager contains the problem, which commonly requires reallocation of resources or injection of additional resources, another shift in the critical path may occur. The project manager's work then involves 'putting out fires' rather than managing. The outcome is rising cost and delay in completing the project.

By focusing largely on critical activities, the project manager may not recognise a high risk of future delays associated with non-critical paths. Just because non-critical activities have float does not guarantee that the amount of float is enough to safeguard against future delays.

The proponents of CCS believe that project schedules can be substantially reduced or the risk of time overruns minimised by the application of CCS. Before explaining how CCS works, let's first define the theory of constraints (TOC) from which CCS has emerged.

THEORY OF CONSTRAINTS

The theory of constraints was developed by Dr Eli Goldratt of the Avraham Y. Goldratt Institute (Goldratt 1997). It is a philosophy or a thinking process that helps management to develop appropriate solutions to problems that in turn improve the performance of projects. TOC is an integrated problem-solving methodology based on a holistic approach to problem solving. According to the TOC approach, components of the system being managed must be aligned and integrated with higher-level systems of which they are components. This requires effective management of project tasks and resources in consideration of defined project goals.

TOC is based on the premise that every organisation or system has at least one weak link or constraint that inhibits its ability to meet its goals. This weak link must be found and strategies developed for either eliminating it or learning to manage the work around it. The constraint is thus removed and the project is then uninhibited in achieving its goals.

The TOC thinking process provides specific tools for identifying such constraints and developing appropriate solutions. Since it brings many people together, it is also an effective communication tool that promotes team building. The TOC thinking process approaches problem solving strategically and tactically. Strategic problem solving attempts to find breakthrough solutions and requires a paradigm shift that may change the way in which the organisation operates. Tactical problem solving provides tools for resolving day-to-day problems; these tools are mainly communication, conflict resolution, empowerment and team-building tools.

Critical chain scheduling or CCS is the TOC-based technique for managing projects. Unlike the traditional CPM, CCS adopts a holistic approach to developing a project schedule. The main features of CCS will now be briefly discussed.

CRITICAL CHAIN SCHEDULING

The aim of CCS is to improve project performance by achieving a scheduled completion date, which in turn would very likely result in improved cost performance. Since it is a TOC-based technique, it is applied in a systematic and coordinated manner so that constraints preventing the achievement of project goals are identified and eliminated. This approach will also ensure that all the important dependencies among project activities have been identified and correctly built into a schedule.

From the CCS viewpoint, task orientation of the critical path method is a constraint. Another constraint is the excessive use of time contingencies that are added to individual activities as well as to the entire project. Proponents of CCS argue that these time contingencies and float may result in complacence, which may then turn into delays, multi-tasking and extra costs. CCS attempts to shift focus away from achieving individual tasks to meeting the scheduled completion date. It uses a radical two-pronged approach:

1. It takes the focus away from due dates of activities since most of them will not be completed on the scheduled date anyway. It adopts an approach that allows the work associated with tasks to take as long as it takes.
2. It removes time contingencies from individual activities.

How can a target date be met without exercising strict control over due dates of individual tasks and without any time contingency? Activities on a critical path and associated resources allocated to such activities must be given close attention since they control the project's duration. Let's refer to such critical activities as critical chain tasks. It is important to ensure that critical chain resources are available to start work when the immediately preceding activity has been finished. Rather than specifying the completion date of such a preceding activity, which without a time contingency has at most only 50 per cent probability of being met, it may be possible to arrange for a succeeding resource to be on standby and start working after the preceding activity has actually been completed. In this case the project manager would negotiate the amount of advance warning that the succeeding resource would require before starting the work.

With little emphasis placed on task dates and no time contingencies present in individual activities, the schedule is obviously very tight. Such a schedule offers no protection against risks to which the project may be exposed. But rather than safeguarding the due dates of individual critical tasks, CCS safeguards the end date of the project by adding a project buffer to the chain of critical tasks. The magnitude of this buffer is expected to be much smaller than the sum of individual time contingencies that the planner adds to critical activities in critical path schedules. Patrick (2002: 8) speculates that 'we can usually cut the total protection at least in half and still be safe'.

So far the discussion has evolved around critical activities or critical chains of tasks. Non-critical chains could be managed in much the same way as critical ones, but it may be rather tedious to arrange advance alerts for resources allocated to non-critical tasks. Instead, CCS uses buffers that are added to non-critical chains. They are referred to as 'feeding buffers' because they protect the start of the critical chain task from delays caused by the feeding of non-critical chains. The critical chain is thus protected not just by the project buffer but also by the feeding buffers. The feeding buffers also safeguard against frequent shifting of the critical path.

Multi-tasking has also been identified as a constraint of CPM. CCS reduces the occurrence of multi-tasking by shortening durations of activities. This requires the work to be done by the resource without any delay. When multi-tasking is minimised, the project manager is in better position to identify those resources that actually constrain the project.

A project schedule developed using the principles of CCS is expected to be 20–30 per cent shorter in duration than a schedule produced by the traditional CPM (Anon. 2002: 2). Once the project is under way, its progress requires regular monitoring and control. Project control in CCS is known as buffer management. At regular intervals the project manager tracks the consumption or the replenishment of project and feeding buffers. The buffers are usually broken up into three segments. The first contains a time allowance that is expendable and no action is required if some or all of it is actually consumed. When a time allowance in the second segment is beginning to be consumed, the project manager is required to develop a plan of action for recovering some or all of the time lost. If part of the third segment has been expended, the project manager will implement the planned action to recover the lost time.

From this examination of key features of CCS, some important benefits of CCS emerge. These include the following (Patrick 2002):

- shorter activity durations
- focus on the end date of the project rather than on due dates of activities
- the use of advance warning for commencement of resources
- prioritisation of resource use
- minimisation of multi-tasking
- project control by buffer management.

SUMMARY

This chapter examined the concept of critical chain scheduling, which is the implementation tool of the theory of constraints. The traditional critical path scheduling method was reviewed and its weaknesses identified. The theory of constraints was then briefly discussed followed by an examination of the concept of critical chain scheduling.

CHAPTER 9

MULTIPLE ACTIVITY CHARTS

INTRODUCTION

The purpose of this chapter is to examine the concept of a multiple activity chart (MAC) and demonstrate its application as a short-range resource-scheduling technique.

The critical path method is an excellent scheduling tool for developing production strategies within the limits of available resources. In medium to long-range scheduling, the work is broken down into specific activities, which are linked together to form a logical production sequence. Resources are then allocated to activities as required. In short-range scheduling, the process is often reversed. Because resources may already be committed, the project manager's task is to organise the work within the bounds of committed resources. For example, the project manager uses a weekly schedule to manage and control the project from day to day. Resources such as cranes, hoists and other plant, and labour such as subcontractors, have already been committed. In managing the project, the project manager allocates the work to be accomplished daily to the committed resources, so that the project period is maintained and the committed resources are used most efficiently.

In short-term scheduling, the critical path method is effective in organising the work but less effective in ensuring efficiency of committed resources. A resource-driven scheduling technique such as a MAC ensures maximum efficiency of committed resources.

A MAC represents the most detailed form of scheduling. When required, it allows the planner to schedule the work using a very fine time-scale, such as days, hours or even minutes. This allows the planner to find the most effective work method that maximises efficiency of committed resources.

A MAC is highly suitable for scheduling repetitive tasks. Most construction projects are repetitive in nature. Some projects comprise a number of separate buildings or structures that are either identical or substantially similar in design, for example individual houses in a large housing project, concrete bridge piers, or cooling towers in a power-generating plant. Some other projects such as high-rise commercial buildings or freeways comprise repetitive structural elements: structural floors of high-rise commercial buildings or sections of the road surface are similar or even identical in design and are constructed in much the same manner. Developing a CPM schedule that would repeat a detailed sequence of activities from floor to floor of a high-rise building is unnecessary. A MAC and a technique of line of balance are better suited to this task. The MAC's strength is in planning and organising the work of committed resources within one repetitive area of the project. The same planning strategy is then applied to other repetitive project areas. A line of balance then schedules the work of committed resources across all repetitive areas of the project. A technique of line of balance will be discussed in Chapter 10.

While MAC is an ideal technique for short-term scheduling, its application in the construction industry has been sporadic. This is because it is not supported by suitable computer software. The manual production of MAC schedules is not popular because it is time-consuming and costly. Nevertheless, MAC warrants closer examination because of the benefits it brings to scheduling.

FORMAT OF A MULTIPLE ACTIVITY CHART

A MAC is a two-dimensional chart. In the absence of the universal consensus on the format of this chart, its appearance may vary from country to country. In Australia, the time-scale is usually plotted on the vertical axis while committed resources are listed horizontally (see Figure 9.4). In the UK, however, the axes of the chart are usually reversed.

Irrespective of the format of a MAC, repetitive cycles of work are scheduled within committed resources that are displayed as columns. In this manner, both the production restraints, given by the logic of production, and the resource restraints, given by committed resources, are considered. The aim is to schedule the work in the shortest possible time while maximising the use of committed resources.

PREPARATION OF A MULTIPLE ACTIVITY CHART

The first step in developing a MAC requires the planner to identify repetitive work. Some projects tend to be repetitive in their entirety, some are substantially repetitive, and others, notably sports stadiums, theatres or even hospitals, may contain no repetitive work at all.

Once repetitive areas of the project have been identified, the planner then considers alternative methods of carrying out the work. In doing so, the planner seeks methods that simplify tasks, reduce labour congestion and maximise the use of resources. The planner then evaluates available alternatives and selects a preferred method. Since efficient use of resources is very important, in selecting a preferred method the planner may consider dividing a repetitive area of the project into smaller elements to further improve the use of resources. For example, from the construction point of view, a typical floor slab of a high-rise building may be divided into two, three or even more segments of similar size (see Figure 9.1). The planner will consider building each segment separately in order to achieve the best possible use of committed resources. Apart from developing a construction strategy, the planner will also compile detailed information on the quantity of materials and resources that will be committed to the work. The developed planning strategy for one repetitive area of the project will then be displayed as a precedence schedule (Figure 9.2).

In the next phase, the planner estimates the duration of repetitive cycles of work. Past experiences with similar projects and industry practice assist the planner in this task. Sometimes cycles may fall into 'natural' patterns of daily or weekly cycles. For example, a typical structural floor of a high-rise commercial building is commonly constructed on a weekly cycle. Sometimes the planner will need to estimate the duration of repetitive cycles of work from first principles. Once a construction contract is in place, however, the agreed contract period often dictates lengths of cycle times of work.

With this information in hand, the planner determines the size of labour crews for specific trades, and specifies the type and volume of plant/equipment (Table 9.1). The structure of a MAC schedule can now be defined in terms of resource groups that will appear in columns and an appropriate time-scale. Resource groups or columns in a MAC schedule may represent specific trades such as plumbing or formwork, and/or types of plant/equipment. They may also represent groups of activities performed by a specific resource. For example, one resource column may be defined as 'formwork to columns and slabs', while another one is 'formwork to beams and walls'.

With all the preparatory work complete, the planner is now ready to start scheduling. The best starting point is to identify key activities that signify the start and the finish of a cycle of work. These key activities are then entered in a MAC schedule. For example, construction of a repetitive slab segment of a high-rise commercial building is likely to start with the activity 'set out' and end when concrete has been poured on that segment (Figure 9.4). These two activities signify the start and the end of one repetitive cycle. The remaining activities of the work cycle are then scheduled in between. It is unlikely that the first attempt will achieve the best possible arrangement of work and efficient use of resources. The planner may need to repeat the exercise a number of times until the best possible solution emerges. This may mean varying the capacities of committed resources, regrouping resources, changing labour crew sizes, or even varying the cycle times of work, where this is possible.

When scheduling has been completed for one cycle of work, it will be repeated for the following cycles. After about two or three work cycles have been scheduled, a regular pattern of work of committed resources is established. Since a MAC schedule is a highly visual chart, the extent of use of resources becomes immediately apparent (Figure 9.5).

Before implementing a construction strategy detailed in a MAC schedule, the planner needs first to check its accuracy and adequacy. In particular, the planner needs to ensure that:

- the production logic has been maintained
- the contract requirements have been satisfied
- the resources are neither overcommitted nor under-used
- labour crew sizes are appropriate for the tasks
- committed plant/equipment has the required capacity appropriate for the tasks.

The process of MAC scheduling is best demonstrated by a practical example. Although the task of finding the best solution may appear to be tedious and time-consuming, the following example demonstrates the benefits of MAC in short-range scheduling.

EXAMPLE OF MAC SCHEDULING

The project in question is a high-rise office building designed as a concrete frame. The building has 40 levels of office space and five levels of underground parking. The office floors are similar in size and layout between levels 1 and 38. The plan of a typical floor is given in Figure 9.1.

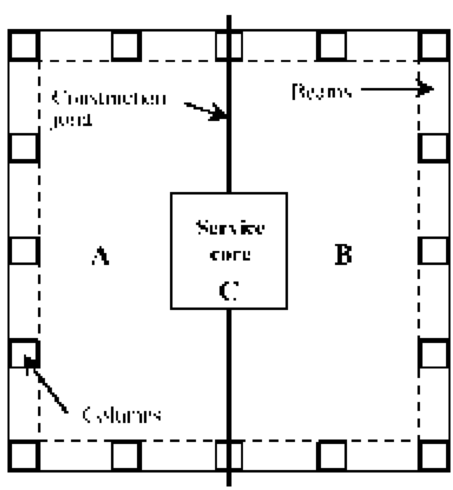
The contractor has been awarded a contract to construct this building in 85 weeks. The contractor's CPM schedule requires structural floors between levels 1 and 38 to be constructed in 38 weeks, which is equivalent to a one-week cycle per floor.

The contractor identifies activities relevant to the construction of a typical structural floor and allocates them to four subcontractors as follows:

- A steel-fixing subcontractor is required to tie reinforcing bars.
- A formwork subcontractor is responsible for erecting and stripping formwork, setting out floors, installing construction joints and trimming formwork.
- A concreter subcontractor is responsible for placing concrete.
- An electrical contractor is required to install in-slab services.

A contractor will erect one tower crane on the site that will service the four subcontractors.

Figure 9.1 A floor plan of the case study project



The contractor then develops a construction strategy to meet the required cycle time of one week and ensure maximum use of committed resources. It is unlikely that the latter objective will be achieved if each structural floor is built in one piece. But if these are divided into two or more segments and each segment is built separately, it may be possible to achieve continuity of the subcontractors' work by moving them from segment to segment.

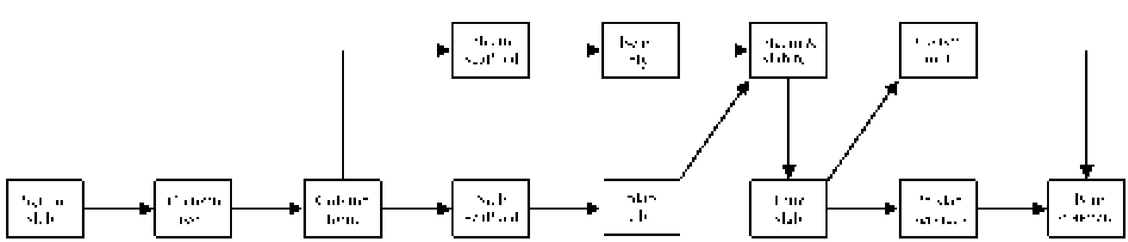
Let's assume that the contractor divides the structural floor into three segments A, B and C, where segments A and B are the mirror-imaged halves of the floor and the segment C is construction of the core (Figure 9.1).

The contractor decides to build slabs, columns and beams using conventional formwork, but selects slipforming for construction of the core. Slipforming is a well-known construction method of building concrete structures by continuously raising steel formwork during a concrete pour. The form is assembled at ground level and stays in one piece until the core has been completed. It climbs using its own jacking system. The contractor intends to keep building the core at least four levels above the structural slabs.

After the evaluation of alternatives, the contractor has adopted a strategy that requires construction of segment A to start first, followed by segment C and ending with segment B on each level of the structure. The contractor intends to move subcontractors from segment to segment, including to and from the core, to maximise continuity of work.

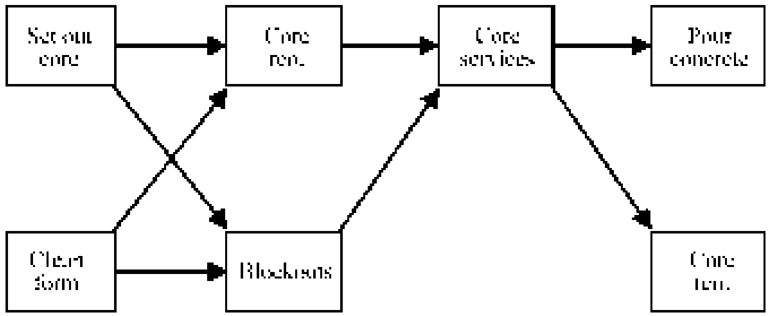
The contractor has prepared two CPM schedules of work. The first, in Figure 9.2, shows a construction sequence for segments A and B, which are identical except for a construction joint that is only required in segment A.

Figure 9.2 A schedule of work for segments A and B



The second, in Figure 9.3 shows construction of the core for segment C.

Figure 9.3 A schedule of work for segment C



Next, the contractor has determined appropriate crew sizes for the volume of work to be undertaken from the work content summary sheet given in Table 9.1.

TABLE 9.1 THE WORK CONTENT SUMMARY SHEET FOR THE PROJECT IN QUESTION

WORK CONTENT SUMMARY SHEET

SLAB		
Reinforcement		
Columns	32 person-hours	4 persons × 8 hrs
Beams and slab	96 person-hours	4 persons × 24 hrs
Formwork		
Columns	48 person-hours	4 persons × 12 hrs
Slab		
scaffolding	32 person-hours	4 persons × 8 hrs
slab plywood	32 person-hours	4 persons × 8 hrs
Beams	64 person-hours	4 persons × 16 hrs
Stripping		
plywood	64 person-hours	4 persons × 16 hrs
scaffolding	16 person-hours	4 persons × 4 hrs
Miscellaneous		
Set out	8 person-hours	2 persons × 4 hrs
In-slab services	16 person-hours	2 persons × 8 hrs
Construction joint	8 person-hours	2 persons × 4 hrs
Trim slab, beam	16 person-hours	2 persons × 8 hrs

WORK CONTENT SUMMARY SHEET (CONT'D)

CORE

Reinforcement	96 person-hours	4 persons × 24 hrs
Miscellaneous		
Set out	8 person-hours	2 persons × 4 hrs
Services	16 person-hours	2 persons × 8 hrs
Blockouts	40 person-hours	2 persons × 20 hrs
Clean form	32 person-hours	4 persons × 8 hrs

CONCRETE

One pour per day

This information helps the contractor to determine what activities will be performed by what resources, and the size of labour crew for each such resource. The contractor's decision is to use seven resource crews, each with the following work tasks:

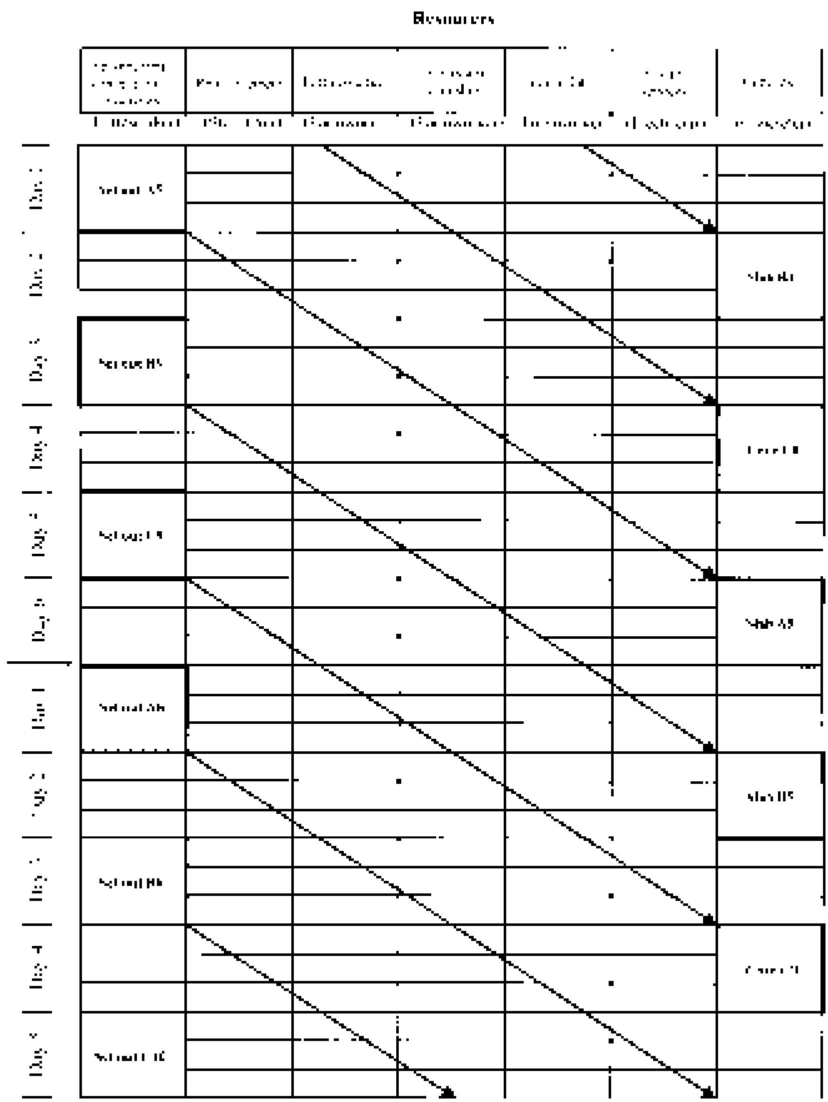
- Crew 1, of 2 persons: set out, trim formwork, construction joints, core blockouts
- Crew 2, of 8 persons: reinforce columns, slabs, beams and core
- Crew 3, of 4 persons: form columns, strip formwork, clean slipform formwork
- Crew 4, of 4 persons: form beams, trim formwork, strip formwork
- Crew 5, of 4 persons: form slab, strip formwork
- Crew 6, of 2 persons: install electrical services in slabs and core
- Crew 7, unspecified: pour concrete.

The first five crews are expected to stay on the job permanently until the structure has been finished. Because crew 6 performs one activity only per segment, its full use cannot be achieved. But this electrical crew is likely to be engaged in other parts of the project. The work of crew 7, placing of concrete, does not require continuity of work. Common work practice is to give sufficiently long notice to concrete placers to come to the site to place concrete as a one-off activity.

Let's assume that one production week is equal to six working days. Let's further assume that stripping of formwork takes place three floors below the working floor. It has already been decided that slipforming of the core will take place four levels above the working floor.

A MAC schedule with seven resource columns can now be prepared. Its time-scale is in days and hours. To ensure that a six-day cycle of work is achieved, the contractor initially schedules the first and the last activity in each segment per cycle. These are the key activities. For the project in question, the first activity of each segment is 'Set out' and the last 'Pour concrete'. Clearly, to meet the project's time objective, concreting of individual segments needs to take place every second day. This is illustrated in Figure 9.4, which provides a template of key activities in each segment. The pattern of work indicates that provided the remaining activities can be fitted in, all three structural floor segments will be completed in six days.

Figure 9.4 A MAC schedule with the key activities



The remaining activities can now be scheduled between the key activities. It should be noted that the scheduling process using a MAC should not start on level 1, the first typical floor, because its construction may take a little longer than on other typical floors. This is due to a 'learning curve' syndrome. Common practice is to start a few levels higher, where a regular cycle time of work is expected to be constant, and then schedule the first few floors by using the experience already gained. In this example, let's begin scheduling on level 5.

Scheduling individual activities within the constraints of time, committed resources and the defined logical pattern of work is not easy. The work is laborious and time-consuming, and may require a number of trials. One possible solution is illustrated in Figure 9.5. It shows that the work associated with building a typical structural floor can be completed within six days and with excellent use of committed resources. Please note that the nominated crew of eight workers in the resource columns 'Reinforcement' was actually split into two crews, of four workers each, to meet the work demand. A similar split in the resource crew occurred in the resource column 'Form beams, trim slab', but only on days 1 and 6 of the cycle.

There may be plausible alternative solutions and the reader is encouraged to seek them out.

As the structure rises, the increasing wind velocity is likely to adversely affect the crane's speed and efficiency. The length of vertical movement of materials and people is also going to increase progressively, possibly adding extra time to the cycle of work.

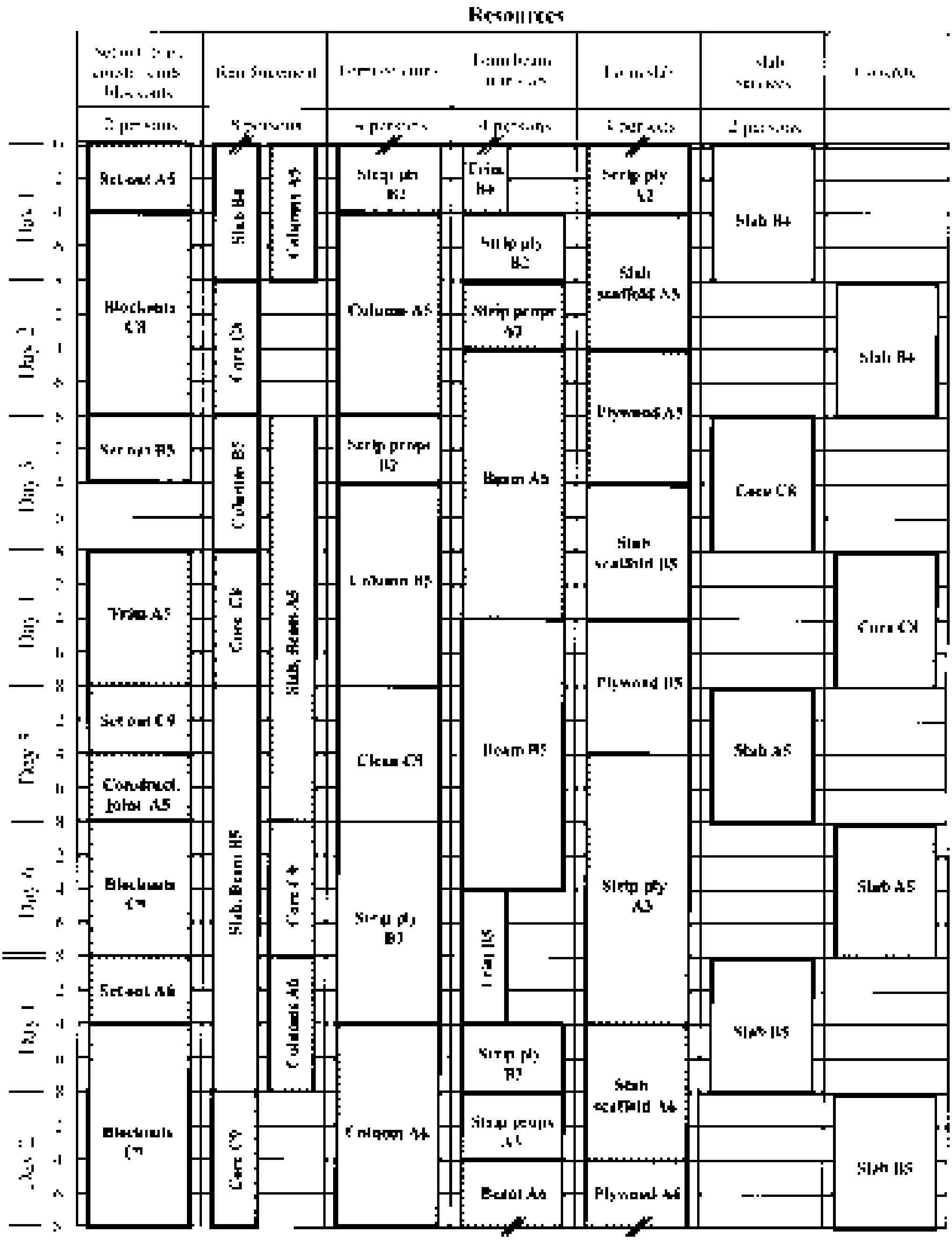
Since the work on levels 1, 2, 3 and 4 is likely to take longer than six days, the contractor will compensate for the learning curve syndrome by adding progressively more time to the cycle of work for lower floors. Similarly, the contractor will need to add more time to the work cycle for the last few floors, which are unlikely to be of the same design as the typical floor.

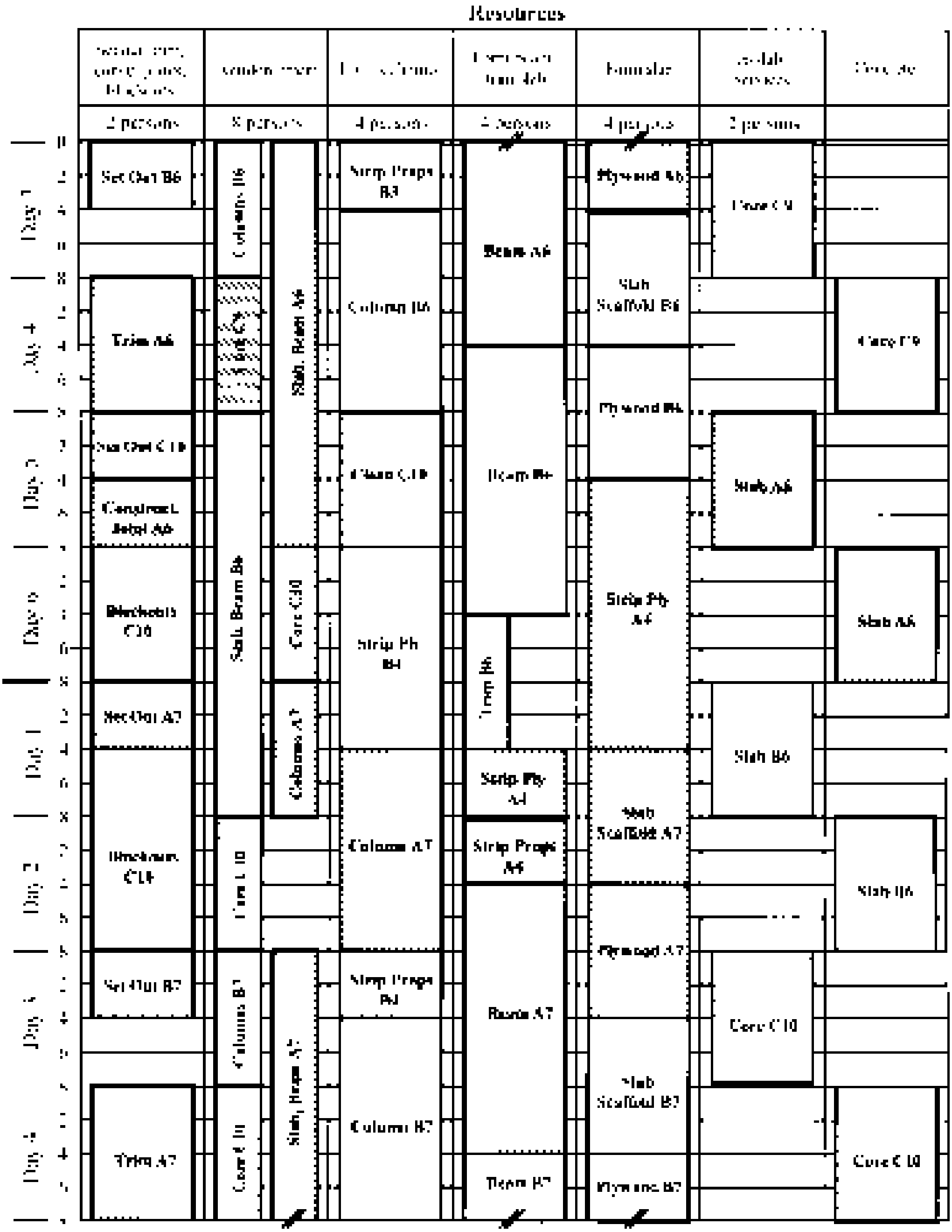
The arrangement of work shown in the MAC schedule in Figure 9.5 achieves the required performance goal of a six-day cycle per typical floor. Because MAC schedules are resource-based, they are largely intolerant of delays to activities. However, since the risk of delays during construction is commonly high, the contractor in question will need to implement a number of measures to ensure integrity of the MAC schedule. These may include:

- adding an appropriate time contingency to each activity or each cycle of work
- having additional resources on standby

- maintaining adequate supervision of the work
- committing to effective process of monitoring and control.

Figure 9.5 The completed MAC schedule





Specific scheduling outcomes achieved by using a MAC must be integrated with the overall CPM project schedule in order to maintain the planned flow of work and the provision of resources across the entire project. It is particularly important to ensure that materials are available in the required quantities and can be delivered in the specified time-frame, that the materials-handling equipment has sufficient capacity to service project activities, that the required labour resources are available, and that site amenities are adequate for the required labour force.

Let's assume that the contractor is able to reduce the cycle time of work related to the construction of structural floors from six to five days per floor by using the available resources better. In theory, the contractor would expect a significant reduction in the overall project schedule without unduly increasing the construction cost. However, unless the extra speed of building the structure is closely coordinated with other project activities, significant problems could develop. For example, materials may not be available for delivery at the new rate of demand, or the site materials-handling equipment may simply run out of capacity to service the project.

SUMMARY

The MAC is a highly effective short-range scheduling technique. It is particularly suited for scheduling repetitive work. Because it examines the work tasks at the highest level of detail, it is able to assist planners and project mangers in developing effective production methods that achieve efficient use of committed resources.

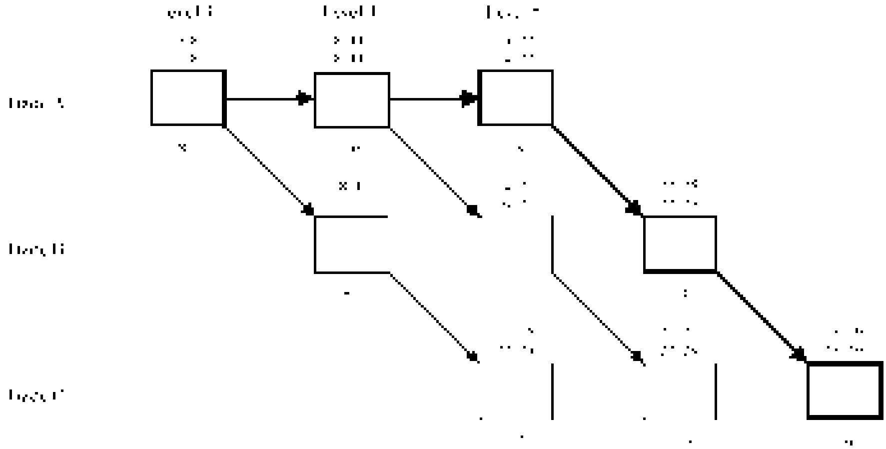
The lack of suitable computer software to support MAC severely restricts its use in the construction industry. The challenge for the construction and computer software industries is to develop a suitable program for MAC scheduling.

EXERCISES

Solutions to the exercises can be found on the following UNSW Press website: http://www.unswpress.com.au

EXERCISE 9.1

Three different trades are engaged in the construction of typical floors in a high-rise building. The work schedule is given below. Using a MAC, arrange the activities in the schedule so that the three trades are employed most productively. Assume that only one crew per trade is available.



EXERCISE 9.2

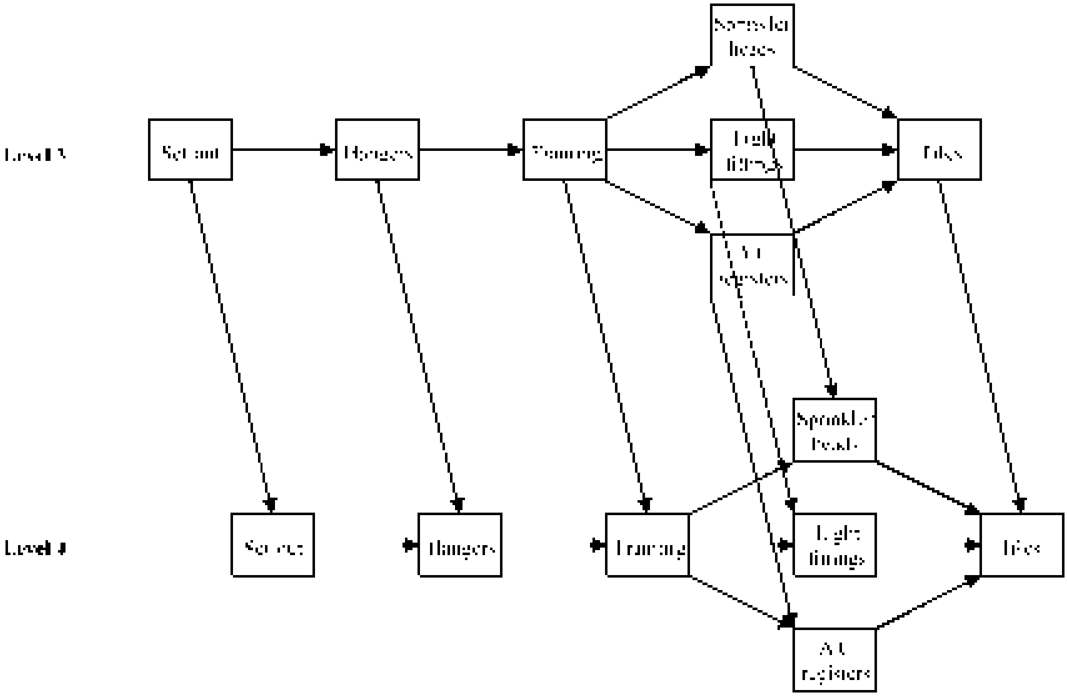
The following activities are associated with the installation of suspended ceilings on typical floors in a high-rise office building.

Crews	Activities	Planned production rates
Ceiling crew	Set out ceiling grid	8 person-hours
	Fix ceiling hangers @ 2 m centres	0.1 person-hour/hanger
	Fix ceiling framing	50 lin. m/person-hour
	Fix ceiling tiles	12.2 m^2/person-hour
Sprinkler head crew	Fix sprinkler heads @ 3 m centres to previously installed sprinkler pipes	3 heads/person-hour
Lights fitting crew	Fit light fittings into ceiling grid @ 3 m centres	6 fittings/person-hour
A/C register fitting crew	Airconditioning registers @ 4 m centres	3 registers/person-hour

The area of a typical floor is 30 m × 20 m.
Suspended ceilings are built to a 1.0 m × 0.5 m grid.

Determine appropriate crew sizes for the four crews of workers and then prepare a schedule of work using a MAC. Ensure that the resources are used efficiently.

A construction sequence of activities involved in the installation of ceilings is given in the following precedence schedule.



EXERCISE 9.3

A crane is being used to lift pallets of concrete bricks into the building. One crew of labourers unloads concrete bricks from the truck onto pallets and the other unloads pallets in the building. These crews of labourers are also responsible for hooking and unhooking pallets to the crane. One set of slings only is available for use. Following is a list of activities and their standard times expressed in minutes:

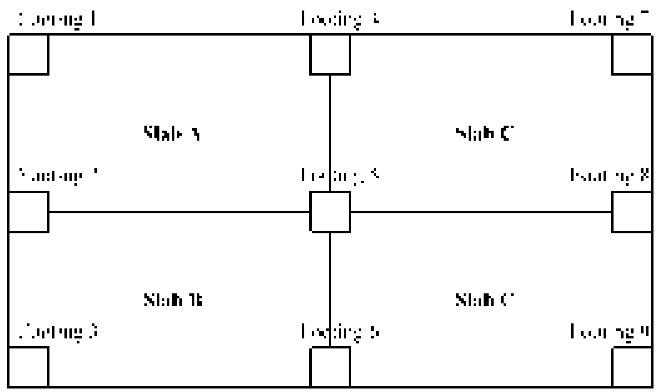
ACTIVITIES	STANDARD TIMES IN MINUTES
Remove bricks from truck and fill one pallet	6
Lift full pallet into building with crane	2
Unload pallet in building	5
Lower empty pallet with crane	1
Hook one pallet onto crane	0.5
Unhook one pallet from crane	0.5
Lift crane hook (without pallet)	2
Lower crane hook (without pallet)	1

There are three pallets available, each holding 100 bricks. They are located on the ground floor adjacent to the 'unloading area' for trucks. One truck can hold 800 bricks.

Using MAC, illustrate a method of getting bricks into the building. How long will it take to unload the first truck? What is the cycle time of work measured for three pallets?

EXERCISE 9.4

A footing plan for a building project is shown below. Specific activities, durations and crews are given in the following table.

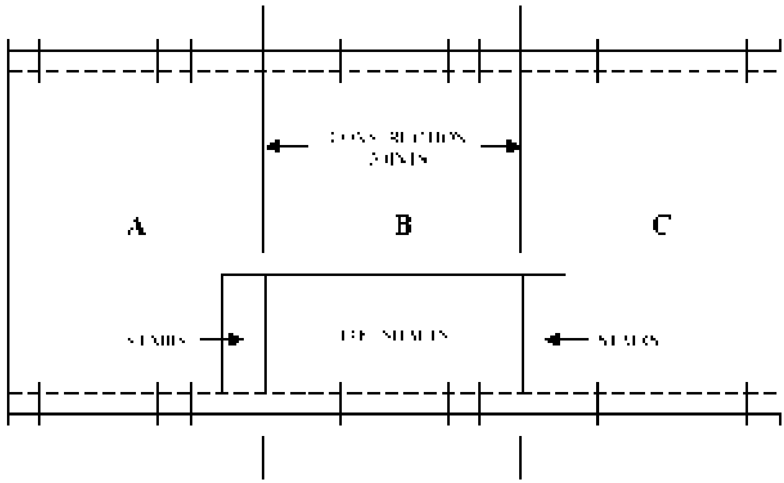


Crews	Activities	Time in hours
Excavator	Excavate footings	3 each
	Trim slab areas before reinforcing	2 each
Reo. fixer	Reinforce footings	2 each
	Reinforce slab areas	1each
Concretor	Pour footings	1 each
	Pour slab areas	2 each

Prepare a MAC schedule showing the most efficient method of building the footings.

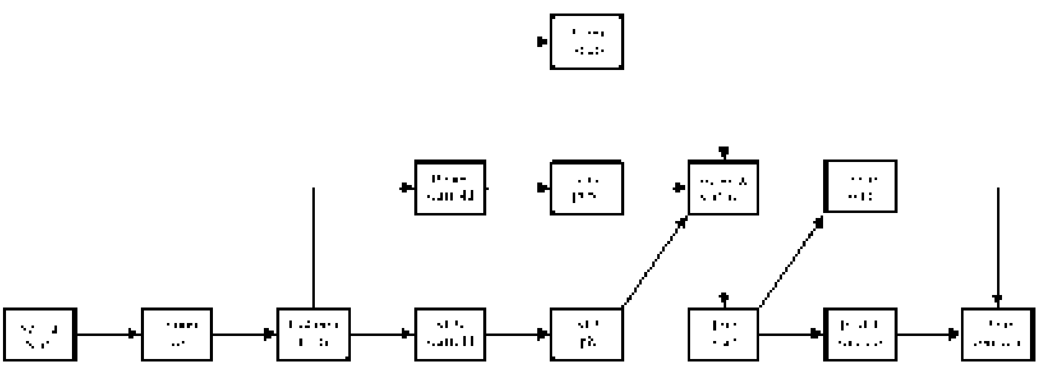
EXERCISE 9.5

The following plan shows the layout of a typical floor in a high-rise concrete frame building. Prepare a short-range MAC schedule for construction of the structure (slabs, columns, walls, beams and stairs) and some miscellaneous items detailed in the 'Work content summary sheet'.



The structural engineer has provided for two construction joints in the floor structure. These may be conveniently used for breaking up the floor into three segments A, B and C.

Segment C is identical to A except for a construction joint. Segment B is similar to segments A and C, with somewhat smaller floor area but larger wall area. For the purpose of this question, assume that the construction sequence for each segment is largely the same. A precedence schedule of the construction sequence for one segment is given below.



The activities related to the construction of a typical floor together with resource demand levels are given in the following 'Work content summary sheet' table.

WORK CONTENT SUMMARY SHEET (FOR ONE SEGMENT)

Reinforcement		
Columns	32 person-hours	4 persons × 8 hrs or 8 persons × 4 hrs
Beams and slabs	96 person-hours	4 persons × 24 hrs or 8 persons × 12 hrs
Formwork		
Columns	70 person-hours	7 persons × 10 hrs
Stairs/walls	42 person-hours	7 persons × 6 hrs
Slabs		
scaffolding	24 person-hours	3 persons × 8 hrs
slab plywood	24 person-hours	3 persons × 8 hrs
Beams	128 person-hours	8 persons × 16 hrs or 4 persons × 32 hrs
Miscellaneous		
Setout	8 person-hours	2 persons × 4 hrs
In slab services	16 person-hours	2 persons × 8 hrs
Constr. joint	8 person-hours	2 persons × 4 hrs
Trim slab, beam	16 person-hours	2 persons × 8 hrs
Concrete		
One pour per day		

Note: Stripping of formwork is not considered.

CHAPTER 10

THE LINE OF BALANCE TECHNIQUE

INTRODUCTION

The purpose of this chapter is to overview the line of balance technique (LOB) and examine its capacity to schedule repetitive construction tasks.

The repetitive nature of construction projects was already discussed in Chapter 9 in relation to the technique of a multiple activity chart (MAC). It was explained that construction projects such as large housing estates, high-rise commercial buildings, highways, tunnels, pipelines, bridges and the like consist of numerous highly repetitive elements. Such projects are commonly referred to as repetitive or linear construction projects. It was also suggested that a CPM technique is less appropriate for scheduling repetitive projects. Other techniques such as multiple activity charts and line of balance are preferred. A MAC was described as a highly effective short-range planning technique, particularly suited for scheduling repetitive tasks. LOB is effective in medium to long-range scheduling.

Mattila & Abraham (1998) and Al-Harbi et al. (1996) described techniques that may be used for scheduling repetitive projects:

- the critical path method (CPM)
- optimisation methods such as the dynamic programming model, the linear scheduling model (LSMh) and the repetitive project modelling (RPM)
- graphic techniques such as the line of balance (LOB), the vertical production method (VPM) and the linear scheduling method (LSM).

Scheduling of repetitive tasks using CPM requires a large number of activities. Visualisation and interpretation of CPM schedules with a large number of activities is often difficult. CPM scheduling has already been addressed in previous chapters of this book.

Optimisation methods treat scheduling of repetitive projects as a dynamic process. They look for efficient solutions in terms of cost and time while maintaining the constraints related to the production rate and continuity of work of committed resources. Optimisation methods will not be discussed in this book.

The graphic methods plot repetitive activities as diagonal lines on a X–Y graph with time on the horizontal axis and location on the vertical axis. The slopes of the lines represent production rates of the activities. LOB, VPM and LSM techniques are very similar and are often treated as being the same. VPM (O'Brien 1975) is best suited to scheduling repetitive activities in high-rise building projects while LSM (Mattila & Abraham 1998) is more applicable to truly linear construction projects where activities are repetitive for the entire project duration, such as pipeline or highway construction.

LOB embraces the features of both VPM and LSM, and in addition creates a control graph from which the planner can determine how many repetitive segments and sub-segments will be completed at specific times.

A technique of LOB will now be examined in detail and its link to MAC emphasised. First, the main features of LOB will be given. The concept of delivery program in LOB will then be introduced, after which a process for developing a LOB schedule with single and multiple crews will be discussed.

CONCEPT OF LINE OF BALANCE

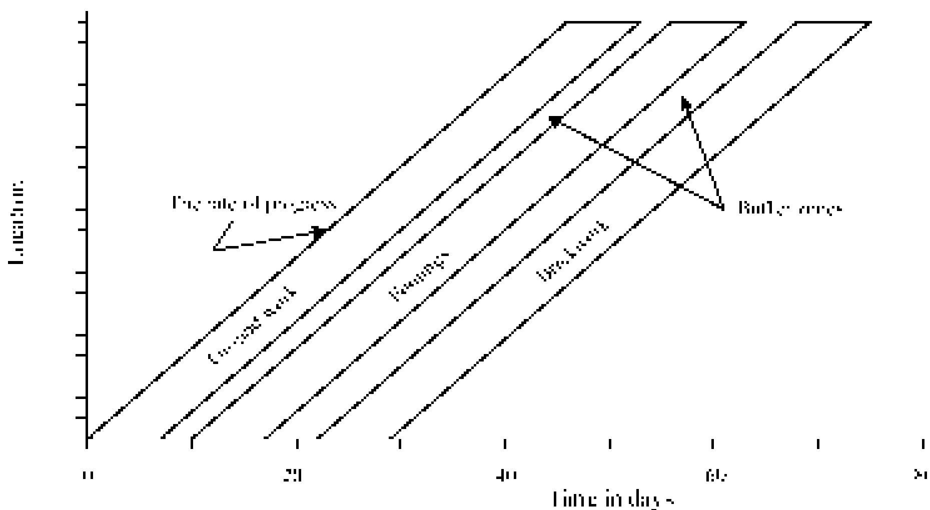
LOB is a relatively simple technique suitable for medium to long-range scheduling of repetitive projects. It is a resource-based scheduling technique with the prime concern of ensuring continuity of work and efficient use of committed resources.

LOB relies on information generated by a MAC. The task of a MAC is to organise the work at the highest possible level of detail in order to determine work cycles of repetitive processes, and to ensure the most efficient use of resources in such repetitive cycles of work. LOB then links repetitive cycles of work together to form an overall schedule.

Construction of repetitive projects is normally carried out by sequencing discrete activities, which are identical in each repetitive segment. For example, a large housing project comprises many similar or identical houses. Construction of one house is commonly broken up into activities or groups of activities referred to as packages. Crews of workers perform the tasks associated with activities or packages. The project is then constructed by arranging the work of each crew to proceed continuously and sequentially from the first to the last house. A MAC assists in defining sizes of crews for each activity or package. Sometimes one crew per activity or package is sufficient, sometimes multiple crews may be required to achieve the desired rate of progress.

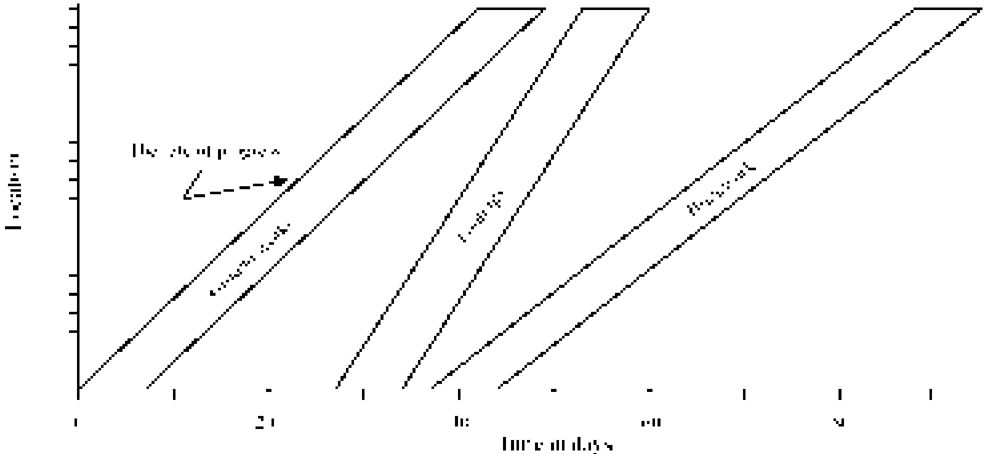
If individual activities or packages in each repetitive segment have the same rate of progress, they are arranged to progress one after the other from the first to the last house. This is illustrated in Figure 10.1. A gap between individual activities is a buffer zone, which serves as a time contingency of each activity.

Figure 10.1 A LOB schedule of activities with the identical cycle times



A uniform rate of progress of individual activities is rarely achieved. A more realistic scenario is to expect rates of progress to vary from activity to activity. Activities of such varying rates of progress are then linked together so that continuity of work of each crew is maintained. This is illustrated in Figure 10.2.

Figure 10.2 An LOB schedule of activities with different cycle times



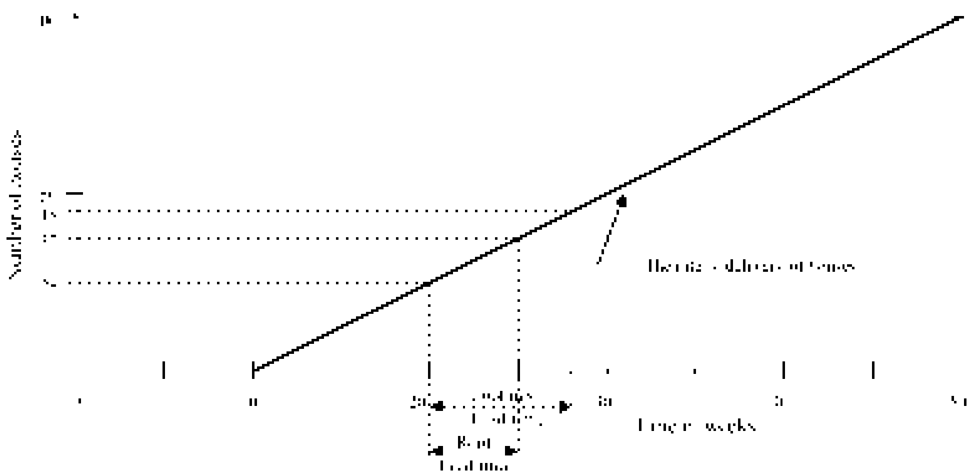
The rate of progress of each activity or package may or may not remain constant over the project period. For example, pipeline construction may progress at a constant rate if the ground conditions are unchanged but may increase or decrease with the change in ground conditions. In constructing high-rise buildings, cycle times of work from floor to floor are likely to increase in duration as the structure rises. This is largely due to the extra time needed to lift materials and transport people to the rising structure, and possibly also to the increasing intensity of wind.

CONCEPT OF DELIVERY PROGRAM IN LOB

The rate of progress of repetitive projects is often controlled by a contract. For example, the contract requires the contractor to deliver at least two fully completed houses each week over the contract period of 50 weeks. Let's assume that there are in total 100 houses to be constructed under this contract. Let's further assume that the first house will take ten weeks to complete. It means that the remaining 99 houses will need to be delivered between weeks 10 and 50, which is equivalent to approximately 2.5 houses delivered per week. This is illustrated in Figure 10.3. The contractor would then need to develop a construction strategy that would meet the required delivery rate of houses. This will be addressed later in the chapter.

Having established the delivery rate of completed houses, it is possible to use the delivery rate graph to establish, at specific intervals, the planned production output of houses and their individual activities. As construction gets under way, the planned volume of output will be used as a control tool against which the actual production will be assessed. But first, let's define the concept of 'lead-time'.

Figure 10.3 The delivery rate graph



The concept of lead-time helps in determining the number of houses and individual activities that will need to be completed at specific intervals. It is a period (in weeks, days or other time-units) by which a particular activity must precede the end activity if the delivery of a repetitive unit is to be made on time.

A bar chart schedule in Figure 10.4 illustrates the concept of lead-time. The schedule shows a sequence of building a house in ten weeks. When the time-scale is reversed at the foot of the bar chart, lead-times for each activity can be determined. For example, the activity 'Footings' has eight weeks of lead-time. It means that when this activity is completed, it will take another eight weeks to complete the house. Similarly, the activity 'Clean-up' has zero lead-time, which suggests that when it is completed the house is fully completed.

Let's use lead-times to plan production output levels. For example, how many houses and their individual activities will be completed on week 20 using the rate of delivery graph in Figure 10.3? When the last activity 'Clean-up' is completed, lead-time is zero, which is the lead-time of a fully completed house. A vertical line drawn at week 20 intercepts the rate of delivery line. The intersection point represents the number of completed houses, which is read off the vertical axis as 25. The volume of completed activities on week 20 are determined in much the same manner. Let's take the activity 'Footings' first. Because its lead-time is eight weeks, a vertical line is draws eight weeks to the right from week 20, which is week 28. The interception point on the rate of delivery line corresponds to 45 completed footings, read off the vertical axis. Similarly, since the activity 'Roof' has a lead-time of five weeks, a vertical line is drawn at week 20 + 5 = 25 and corresponds to 37 completed 'Roof' activities on week 20. This process is then repeated for the remaining house activities. The planned production output of each activity is presented graphically in Figure 10.5. The actual production output is then marked up on the graph. In this format, the difference between the planned and actual production output is clearly apparent.

Figure 10.4 A construction schedule of one house with lead-times

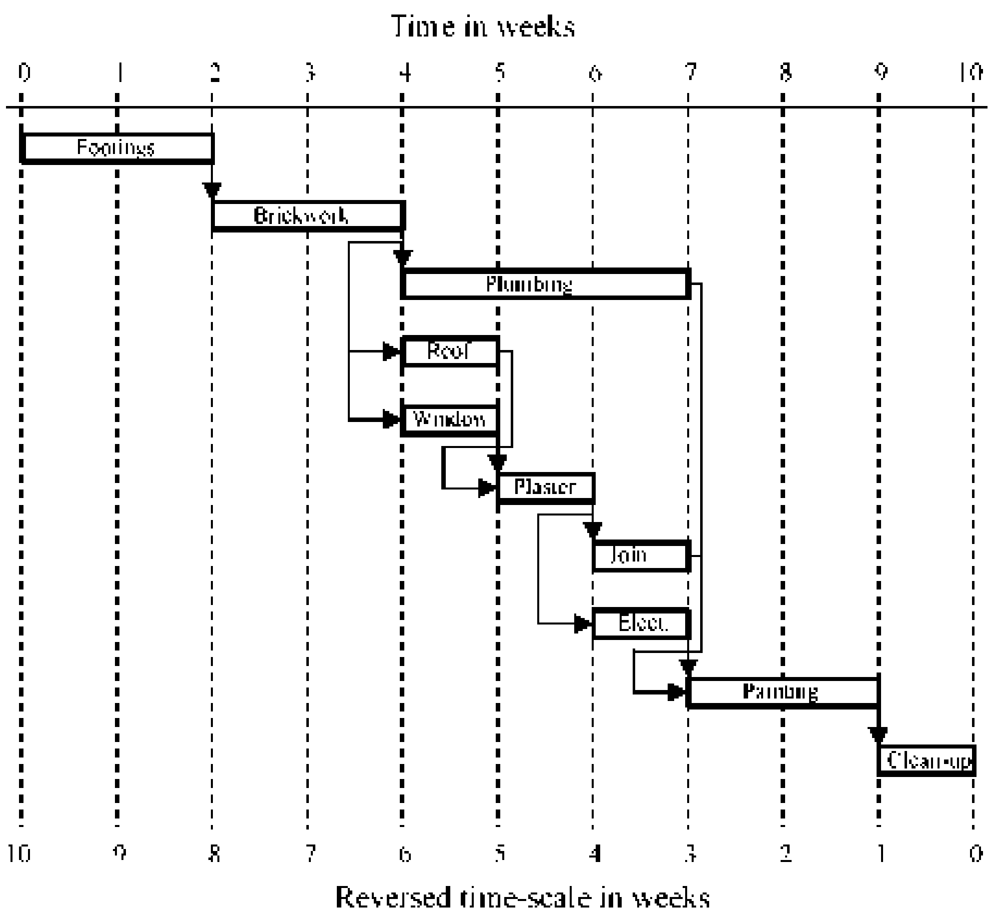
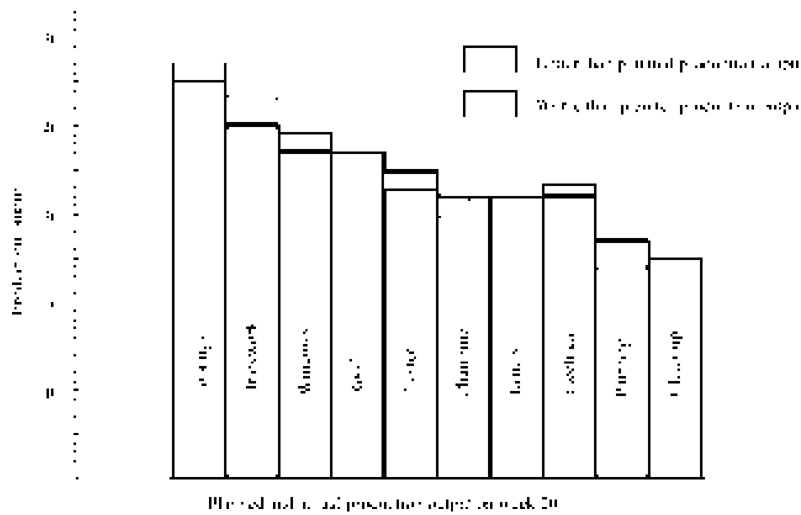


Figure 10.5 The planned and actual production output graph



DEVELOPING A LOB SCHEDULE

The fundamental aspects of preparing a LOB schedule have already been discussed and have been illustrated in Figures 10.1 and 10.2. A LOB schedule shows graphically the arrangement of repetitive activities from location to location for the entire project. Start and finish dates of such repetitive activities are determined in a LOB table.

Let's demonstrate the process of calculating start and finish dates of repetitive activities in a tabular form for the following project. The project in question is a high-rise commercial building with 20 typical floors. Because no specific date has been given for the completion of the fit-out of 20 typical floors, there is no need to be concerned with the required rate of delivery of individual packages.

The building is designed as a concrete frame structure, comprising columns, walls and slabs. LOB will be used to schedule activities associated with the fit-out of the 20 typical floors. The fit-out work has been broken up into seven trade packages, each performed by one crew of subcontractors. It is assumed that construction of structural floors proceeds well in advance of the fit-out activities. A precedence schedule of fit-out activities related to a typical floor is given in Figure 10.6.

Figure 10.6 A precedence schedule of the fit-out project

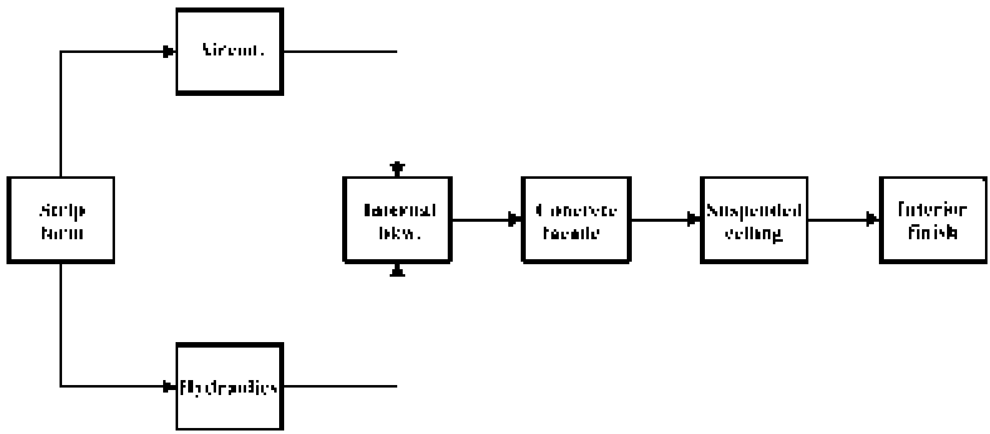


Table 10.1 shows in the first two columns a list of trade packages and their respective cycle times determined by a MAC.

TABLE 10.1 THE LOB TABLE OF THE FIT-OUT PROJECT

TRADE PACKAGES	DURATION PER CYCLE OF WORK	TOTAL DURATION IN DAYS	START OF WORK PACKAGE IN DAYS	FINISH OF WORK PACKAGE IN DAYS
1. Strip formwork	6	120	0	120
2. Airconditioning ducts	8	160	6	166
3. Hydraulics	5	100	25	125
4. Internal brickwork	7	140	33	173
5. Concrete facade	5	100	78	178
6. Suspended ceiling	6	120	83	203
7. Interior finishes	8	160	89	249

The total duration of the work associated with each repetitive trade package over 20 typical floors is calculated in the third column. The table shows that cycle times of work of the individual packages vary between five and eight days. To ensure continuity of work of subcontractors, a succeeding package that has a slower rate of progress than its immediately preceding package, or the same rate will be scheduled as soon as the first cycle of work of its preceding package has been completed. If everything goes according to the plan, this succeeding package will not interfere with the work of the preceding one. However, if a succeeding package has a faster rate of progress than the preceding one, its start would need to be delayed sufficiently to prevent interference with the preceding package.

Let's now calculate start and finish dates of the trade packages in columns 4 and 5. 'Strip formwork' is the first package in the production cycle. It starts on day 0. Since its total duration is 120 days, it will finish on day 120.

The start of the next two trade packages, 'Airconditioning ducts' and 'Hydraulics', depends on the completion of the preceding package, 'Strip formwork'. Let's schedule the package 'Airconditioning ducts' first. Because its duration per cycle of work is longer than that of the preceding package 'Strip formwork', it can be scheduled to start as soon as the first 'Strip formwork' activity has been completed, which will be on day 6. This package will be completed on day 166.

The cycle of work of the package 'Hydraulics' is faster than that of the preceding package, 'Strip formwork'. It means that it cannot be scheduled to commence as soon as the first 'Strip formwork' activity has been completed because it would continually interfere with it. Rather it will be scheduled from the finish date of the last 'Strip formwork' activity. This last 'Strip formwork' activity is scheduled for completion on day 120 and therefore the last 'Hydraulics' activity will be completed five days later on day 125. The first 'Hydraulics' will then start on day 15. Its progress will be uninterrupted and it will not interfere with its preceding activity.

The next package to schedule is 'Internal brickwork'. Its start is dependent on completion of two preceding packages, 'Airconditioning' and 'Hydraulics'. Let's consider these two preceding packages one at a time. With regard to 'Airconditioning', the 'Internal brickwork' package is faster per cycle of work. It will therefore be scheduled from the finish of the last 'Airconditioning' activity. Because the last 'Airconditioning' activity is scheduled for completion on day 166, the last 'Internal brickwork' activity will be finished seven days later, on day 173. The start date of the 'Internal Brickwork' package will then be day 33. With regard to 'Hydraulics', 'Internal brickwork' is slower per cycle of work and will therefore start as soon as the first 'Hydraulics' activity has been completed, which is on day 30. The package 'Internal brickwork' will then be completed on day 170. This is three days before its other preceding package, 'Airconditioning', would be completed. Clearly, the start and finish of the package 'Internal brickwork' is governed by its preceding package, 'Airconditioning'.

The start and finish dates of the remaining trade packages are determined in the same manner. The first fully fitted out floor will be ready on day 97, which is the finish date of the first 'Interior finishes' package. The delivery rate of the remaining fully fitted out floors is one every eight days thereafter (this rate is equal to the cycle time of the last package, 'Interior finishes'). The total project duration is 249 days.

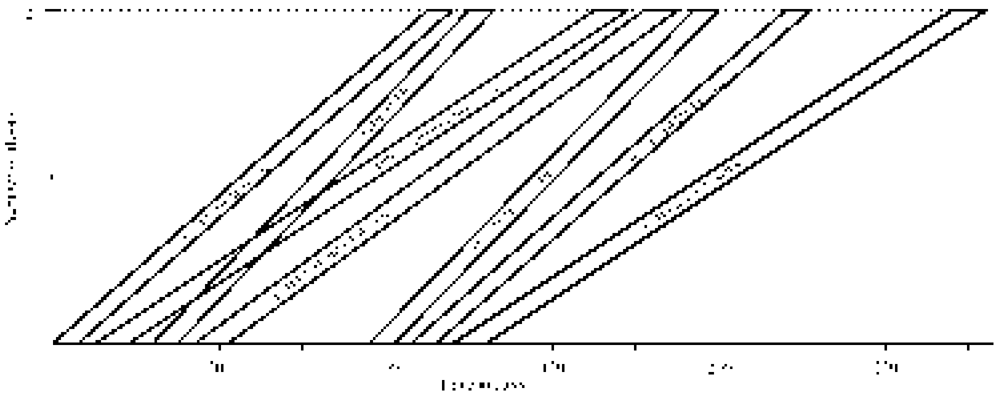
The trade packages have been scheduled to ensure continuity of work from start to finish. Because unforeseen risk events may cause delays in some activities, the prudent planner will safeguard against delays by adding time contingency to the schedule. This is commonly done in the form of a buffer zone inserted between activities. With a buffer zone of say six days between each package, the project would be completed on day 279 with the first fully fitted out floor ready on day 127 (Table 10.2).

TABLE 10.2 THE LOB TABLE WITH BUFFER ZONES OF SIX DAYS

TRADE PACKAGES	DURATION PER CYCLE OF WORK	TOTAL DURATION IN DAYS	START OF WORK PACKAGE IN DAYS	FINISH OF WORK PACKAGE IN DAYS
1. Strip formwork	6	120	0	120
2. Airconditioning ducts	8	160	12	172
3. Hydraulics	5	100	31	131
4. Internal brickwork	7	140	45	185
5. Concrete facade	5	100	96	196
6. Suspended ceiling	6	120	107	227
7. Interior finishes	8	160	119	279

The LOB schedule of the project with buffer zones of six days is graphically shown in Figure 10.7. In this visual form, the impact on project period by slow packages is clearly apparent. If it is possible, for example, to reduce the cycle time of work of the package 'Interior finishes' to six days, the project duration would be shortened by around 20 days, and if all the packages had the same cycle time of, say, six days, approximately 60 days would be saved.

Figure 10.7 The LOB schedule of the fit-out project



DEVELOPING A LOB SCHEDULE FOR PROJECTS REQUIRING MULTIPLE CREWS

Tight construction schedules often require the planner to allocated more than one crew of workers to undertake a repetitive activity in order to speed up production. The following example will demonstrate a process of developing a LOB schedule with multiple crews.

A large housing project comprises 100 identical houses. The project must be completed within 60 weeks and the contractor is required to deliver three houses per week from week 25 onward. A precedence schedule showing the construction sequence of a typical house is given in Figure 10.8. The contractor, an experienced house builder, has an extensive database with up-to-date information on cost and time estimates of similar houses. From the data, the contractor has calculated the volume of person-hours required for accomplishing each activity. This information is given in Table 10.3.

Figure 10.8 A construction schedule of a house

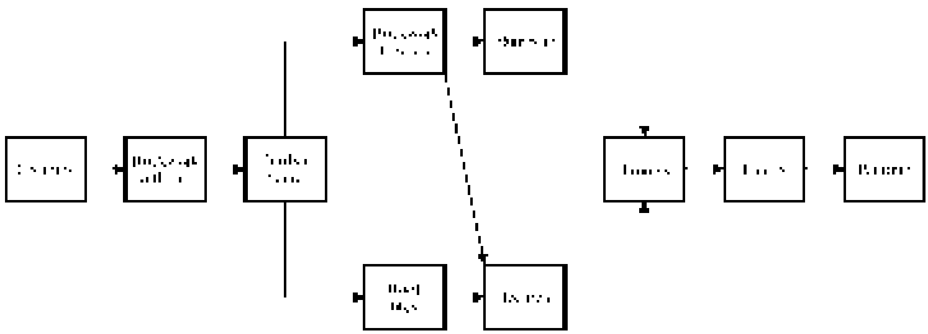


TABLE 10.3 THE VOLUME OF WORK PER ACTIVITY EXPRESSED IN PERSON-HOURS

ACTIVITIES	PERSON-HOURS PER ACTIVITY
1. Footings	48
2. Brickwork to floor	120
3. Timber frame	160
4. Brickwork to walls	420
5. Roof tiles	96
6. Electrical	96
7. Plumbing	80
8. Linings	96
9. Joinery	128
10. Paint	96

Person-hours represent productivity rates of activities. They need to be converted to activity durations, crew sizes and actual rates of output. First, the contractor needs to estimate ideal sizes of crews necessary to perform the project activities. These are given in Table 10.4 in column 3. Next, a theoretical crew size necessary to perform the volume of work is calculated using the following formula:

$$\text{Theoretical crew size} = \frac{\text{Handover rate} \times \text{Person-hours per activity}}{\text{Number of working hours per week}}$$

For the purpose of this example, let's assume that the project works six days per week, eight hours per day. The theoretical size of the 'Footings crew is then (3 × 48) / (8 × 6) = 3.0. The theoretical crew sizes for the other activities are calculated in the same manner and are given in Table 10.4 in column 4.

TABLE 10.4 CREW SIZES AND THE RATE OF OUTPUT

ACTIVITIES	PERSON-HOURS HOURS PER ACTIVITY	ESTIMATES IDEAL CREW SIZE	THEORETICAL CREW SIZE	ACTUAL CREW SIZE	ACTUAL RATE OF PROGRESS
Footings	48	2	3.0	4	4.0
Brickwork to floor	120	5	7.5	10	4.0
Timber frame	160	4	10.0	12	3.6
Brickwork to walls	420	5	26.3	30	3.4
Roof tiles	96	4	6.0	8	4.0
Electrical	96	2	6.0	6	3.0
Plumbing	80	2	5.0	6	3.6
Linings	96	4	6.0	8	4.0
Joinery	128	2	8.0	8	3.0
Paint	96	2	6.0	6	3.0

Actual crew sizes are determined next by rounding the theoretical crew size to a number that is a multiple of the estimated ideal crew size. For example, the theoretical crew size of 'Footings', calculated as 3, is be rounded to 4, which is the multiple of the estimated crew size.

The next factor to determine is the actual rate of progress per week. It is calculated using the following formula:

$$\text{Actual rate of progress} = \frac{\text{Actual crew size} \times \text{Required handover rate}}{\text{Theoretical crew size}}$$

The actual rate of progress of the activity 'Roof tiles' is: (8 × 3) / 6 = 4.0. The actual rates of progress of the other activities have been calculated and are given in Table 10.4 in column 5.

The number of crews that need to be allocated to each activity can now be calculated from the following formula:

$$\text{Number of crews} = \frac{\text{Actual crew size}}{\text{Ideal crew size}}$$

For example, the number of crews to perform the activity 'Joinery' is 8 / 2 = 4. The calculated numbers of crews are given in Table 10.5 in column 2.

The next factor to be determined is duration per crew per activity (in days). It is calculated using the following formula:

$$\text{Duration per activity} = \frac{\text{Person-hours per activity}}{\text{Estimated crew size} \times \text{Number of working hours per working day}}$$

For example, duration of the activity 'Electrical' is: 96 / (2 × 8) = 6 days. The remaining durations have been calculated and are given in Table 10.5 in column 3.

TABLE 10.5 NUMBER OF CREWS, DURATION OF ACTIVITIES, TOTAL DURATION, AND START AND FINISH DATES

ACTIVITIES	NUMBER OF CREWS	DURATION PER CREW IN DAYS	TOTAL DURATION IN DAYS	START OF ACTIVITY	FINISH OF ACTIVITY
Footings	2	3	150	0	150
Brickwork to floor	2	3	150	3	153
Timber frame	3	5	167	6	173
Brickwork to walls	6	10.5	177	11	188
Roof tiles	2	3	150	26	176
Electrical	3	6	200	29	229
Plumbing	3	5	167	26	193
Linings	2	3	150	82	232
Joinery	4	8	200	85	285
Paint	3	6	200	91	281

Finally, the total time required to complete a sequence of repetitive activities for the whole project is calculated from the following formula:

$$\text{Total activity duration} = \frac{\text{Number of houses} \times \text{Number of working days per week}}{\text{Actual rate of progress}}$$

The total duration of the activity 'Brickwork to floor' is: (100 × 6) / 4.0 = 150 days. The remaining total activity durations have been calculated and are given in Table 10.5 in column 4.

It is now possible to determine start and finish dates of the house activities from the information in Table 10.5, using the same approach as that defined in section 10.4 above. The total project duration is 291 days or 49 weeks and the first house will be completed in 96 days or just over 16 weeks. The LOB tabular schedule in Table 10.5 shows that the calculated number of crews is about right to meet the contract delivery requirements.

However, before proceeding any further, it is important to examine the impact on the schedule by the uneven number of multiple crews that have been allocated to the activities. The activity 'Timber frame' will be performed by three crews of workers, while the preceding activity, 'Brickwork to floor', will be performed by two crews only. It means that on day 6, when 'Timber frame' crews are to begin work, only two 'Brickwork to floor' activities will be completed. In order to start all three 'Timber frame' crews, it is necessary to delay the start of this activity until day 11 when enough 'Brickwork to floor' activities has been completed. The finish date of the activity 'Timber frame' will now be day 178.

Similarly, 'Brickwork to walls' employs six crews of workers while the preceding activity, 'Timber frame', employs only three. Three 'Timber to walls' activities will be completed on day 16 and six on day 21. This means that the activity 'Brickwork to walls' will now start on day 21 with all six crews and will be completed on day 198.

Table 10.6 Start and finish dates adjusted for multiple crews

Activities	Number of crews	Duration per crew in days	Total duration in days	Start of activity	Finish of activity
Footings	2	3	150	0	150
Brickwork to floor	2	3	150	3	153
Timber frame	3	5	167	11	178
Brickwork to walls	6	10.5	177	21	198
Roof tiles	2	3	150	31	181
Electrical	3	6	200	37	237
Plumbing	3	5	167	36	203
Linings	2	3	150	90	240
Joinery	4	8	200	96	296
Paint	3	6	200	102	302

The start dates of the activities ‘Electrical’ and ‘Joinery’ will also need to be adjusted to match the rate of progress of their preceding activities. The adjusted start and finish dates of the activities are given in Table 10.6.

The project will now be completed in 302 days or 51 weeks, with the first house delivered on day 108 or week 18.

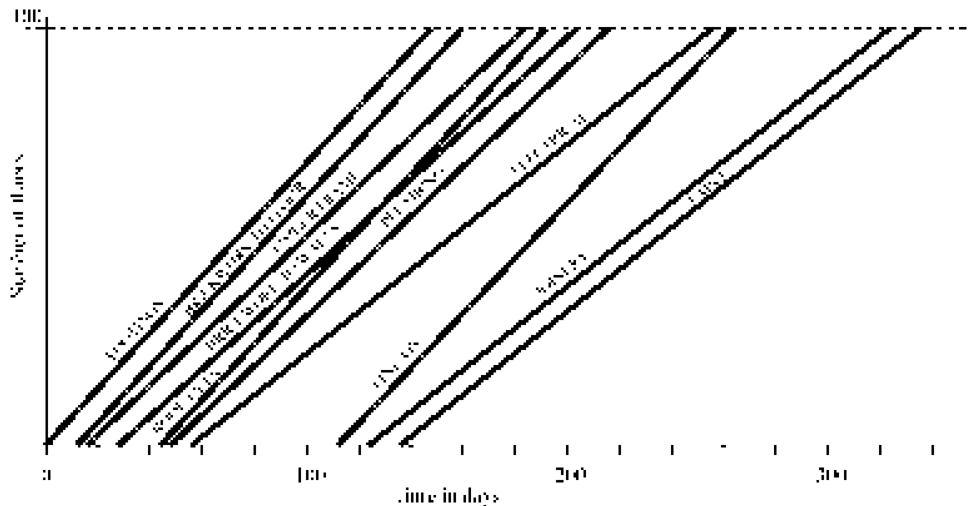
Finally, let’s add six-day buffer zones to the schedule for unforseen delays, and recalculate start and finish dates of the activities. The result in given in Table 10.7.

TABLE 10.7 THE FINAL START AND FINISH DATES WITH BUFFER ZONES

ACTIVITIES	TOTAL DURATION IN DAYS	START OF ACTIVITY	FINISH OF ACTIVITY
Footings	150	0	150
Brickwork to floor	150	9	159
Timber frame	167	17	184
Brickwork to walls	177	27	204
Roof tiles	150	43	193
Electrical	200	55	255
Plumbing	167	48	215
Linings	150	114	264
Joinery	200	126	326
Paint	200	138	338

The contractor can be reasonably confident of completing the project in 338 days or 57 weeks and delivering the first batch of houses on day 144 or week 24. The contractor’s schedule meets the contract requirements of completing 100 houses in 60 weeks with the delivery of three houses per week commencing from week 25 onwards. The LOB schedule for the project is shown graphically in Figure 10.9.

Figure 10.9 The LOB schedule for the housing project



SUMMARY

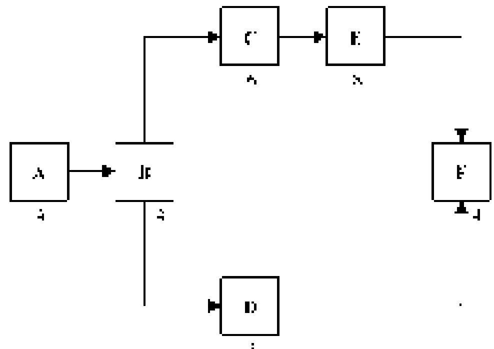
This chapter described the line of balance scheduling method. The main benefit of LOB lies in scheduling repetitive projects. It is particularly useful in determining delivery dates of repetitive activities of projects. LOB is a resource-based scheduling method that ensures that resources allocated to repetitive activities are employed continuously.

EXERCISES

Solutions to the exercises can be found on the following UNSW Press website: http://www.unswpress.com.au

EXERCISE 10.1

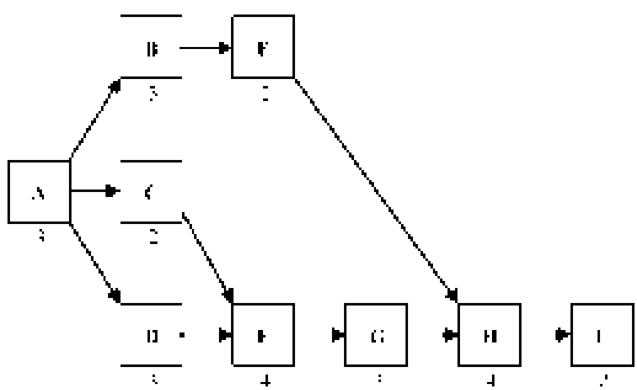
Prepare a LOB schedule (table and graph) for the construction of 40 typical floors of a high-rise commercial building. A precedence schedule showing the sequence of a typical floor construction is given below. Each activity will be performed by one crew of sub-contractors. Durations are in days. Add time buffer zones of six days between the activities.



EXERCISE 10.2

A contractor has been awarded a contract to refurbish 100 service stations and deliver them to the client at the rate of two per week after week 25. The project must be completed within 75 weeks.

Prepare a LOB schedule (table and graph) for this project. Assume a six-day working week. A precedence schedule showing the sequence of one service station construction is given below. Durations are in weeks. Add time buffer zones of one week between the activities.



CHAPTER 11

WORK STUDY

INTRODUCTION

The purpose of this chapter is to develop an understanding of the concept of work study, which is concerned with improving the productivity of production processes. Its two principal components, method study and work measurement, will be examined in detail and will be supported by practical examples.

The previous chapters of this book have examined various scheduling techniques suitable for use in the construction industry. They are generally regarded as 'operations research techniques'. 'Operations research' focuses on applying scientific methods and tools to problems involving the operation of a system and developing optimum solutions. It is a category of 'operations management', which is concerned with planning, organising and controlling business operations, systems and models.

'Work study' is a category of 'operations management' but is fundamentally different from 'operations research'. Work study aims at improving productivity by examining in detail specific parts of the system rather than a system as a whole. It increases productivity through better work methods, an improved use of resources and better management practices. Although not a scheduling technique, work study nevertheless requires the application of scheduling skills in developing more productive production processes.

In improving productivity, work study helps in identifying weaknesses in current work methods and in developing appropriate corrective strategies on which the best overall work method is then based. Work study helps the manager to examine the degree of utilisation of committed resources such as people, plant and materials. It also involves examination of management practices on which production processes depend, such as empowerment, communication, planning efforts, motivation of personnel, and incentive schemes.

'Productivity' is at the heart of work study. It is defined as the ratio between output and input.

$$\text{Productivity} = \frac{\text{Output}}{\text{Input}}$$

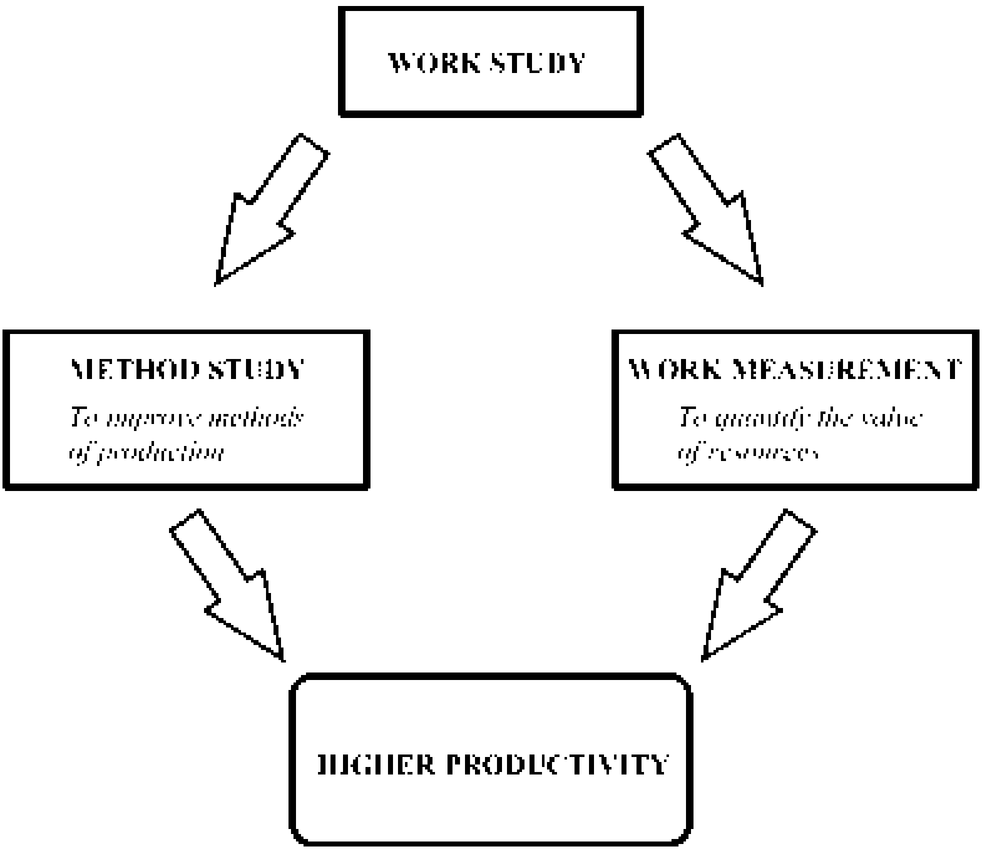
'Output' is a rate of production or the work produced, while 'input' refers to the combination of resources, work methods and management practices necessary to make the production process work. Improved productivity can be achieved either by increasing 'output' while trying to keep 'input' constant, or by reducing 'input' while trying to keep 'output' constant. The maximum improvement in productivity could ideally be achieved by increasing 'output' while at the same time reducing the volume of 'input'. In this chapter, the emphasis will be placed on achieving improvement in productivity through better utilisation of labour and plant resources, and improved work methods.

The labour resource is by far the most difficult resource to manage. People's performance rates tend to vary because no two persons are alike in motivation and skill. People may also strike, take time off, get sick or simply not be available when required. Forcing people to work harder and faster is unlikely to result in a sustained increase in the production output unless people are highly motivated, appropriately skilled and adequately rewarded, and unless most appropriate work methods have been installed.

The emphasis in managing a plant/equipment resource is on selecting the most appropriate type and maintaining its full utilisation. Because technical and performance specifications of plant/equipment are known for a wide range of tasks and applications, estimating and maintaining production rates of plant/equipment are usually not a problem.

Work study embraces the parallel techniques of 'method study' and 'work measurement' (Figure 11.1). These will now be discussed in more detail.

Figure 11.1 The definition of work study



METHOD STUDY

The aim of method study is to analyse method, systems and procedures currently in use in order to develop improvements. There is always more than one method of work that could be employed. The role of a manager is to examine as many methods as possible in order to develop an easier and more effective production process. This may require elimination of unnecessary work, more effective deployment of resources, and minimising delays and waste. The manager would need to concentrate on improving:

- the layout and the design of the workplace
- working procedures
- the utilisation of resources

- the physical work environment
- the design or specification of the end product.

The procedure for performing method study involves a number of discrete steps:

- defining the problem and selecting the work to be studied
- recording the observed facts
- examining these facts critically and seeking alternative solutions
- developing the most practical, economical and efficient method
- installing the improved method as standard practice
- maintaining the improved method.

The individual steps in the method study procedure will now be examined in more detail.

Defining the problem

Before a problem can be solved, it must first be identified. This is rarely as straightforward as it might appear. For example, a long delay in unloading trucks outside a construction site may be seen as being caused by the lack of capacity of the site crane. However, poor scheduling of the work by the project manager may be the actual main cause. Committing an additional crane would probably solve the problem in the short term, but the problem would most likely reappear in the future. The underlying cause of the problem must ultimately be fixed.

Experience will guide the manager to examine and monitor those aspects of the work that are likely to have the greatest impact on productivity. By systematically sorting through a range of technical, economic (cost and time) and human factors, the manager will gain a better understanding of the problem and its underlying causes.

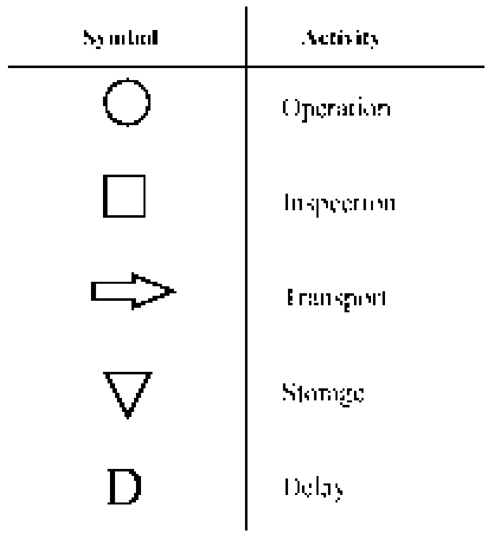
Recording the facts

A systematic examination of the problem and its underlying causes generates valuable information not just on the problem itself and its causes but also on the adopted method of work. This information assists the manager in assessing the viability of alternative solutions. It is therefore necessary to develop a system for effective recording of information. For this purpose, work study adopts a variety of charts and diagrams such as process charts, flow charts and multiple activity charts. Let's examine these charts in detail.

Process chart

A process chart is useful for representing a sequence of activities in a production process using standard symbols, see Figure 11.2.

Figure 11.2 Standard symbols used in process charts



For example, a process of placing concrete is graphically represented by the process chart symbols in Figure 11.3.

This format of data recording allows the manager to aggregate activities into their respective groups for further analysis. Productive activities are 'operations'. 'Transport' activities are generally regarded as unproductive even if they form an essential part of the production process. The activity 'Concrete kibble lifted by crane' in Figure 11.3 is a transport activity, which is unproductive. The other activities are also regarded as unproductive.

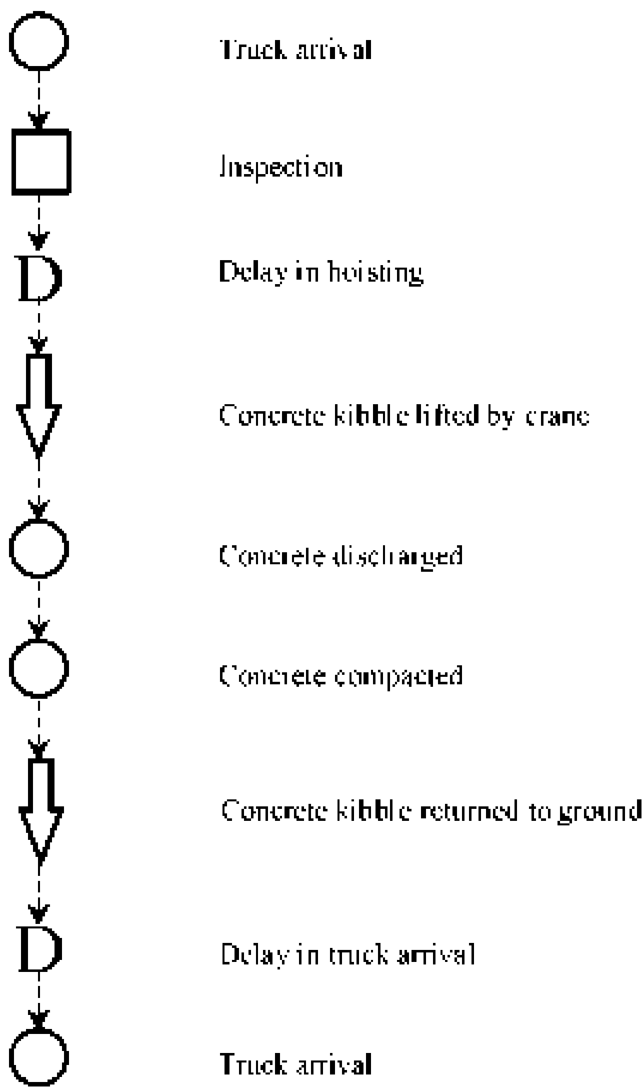
Apart from determining a ratio between productive and unproductive activities, the manager also gains better insight into the actual production process and its components which assists the manager in identifying potential weaknesses and problems. Clearly, the presence of two delay activities in Figure 11.3 highlights the specific weakness of the production process.

Flow process chart

A flow process chart records more complex information about current and alternative methods of a production process. It traces the flow of work in the process by connecting corresponding standard process chart symbols. It also:

- aggregates activities within the production process into standard symbol groups
- measures the production process in specific units such as quantity of materials, distances travelled or activity times
- summarises the present and alternative methods and their costs.

Figure 11.3 Example of a process chart



An example of a flow process chart is given in Figure 11.4. It shows a process of fabricating timber roof trusses. The chart is divided into three distinct parts:

- The top left corner defines the process, its location and the responsible party.
- The top right corner summarises information generated by the flow process chart.
- The bottom part defines the logic of the production process, measures it in appropriate units, and aggregates it according to the standard symbol groups. It also shows the flow of work.

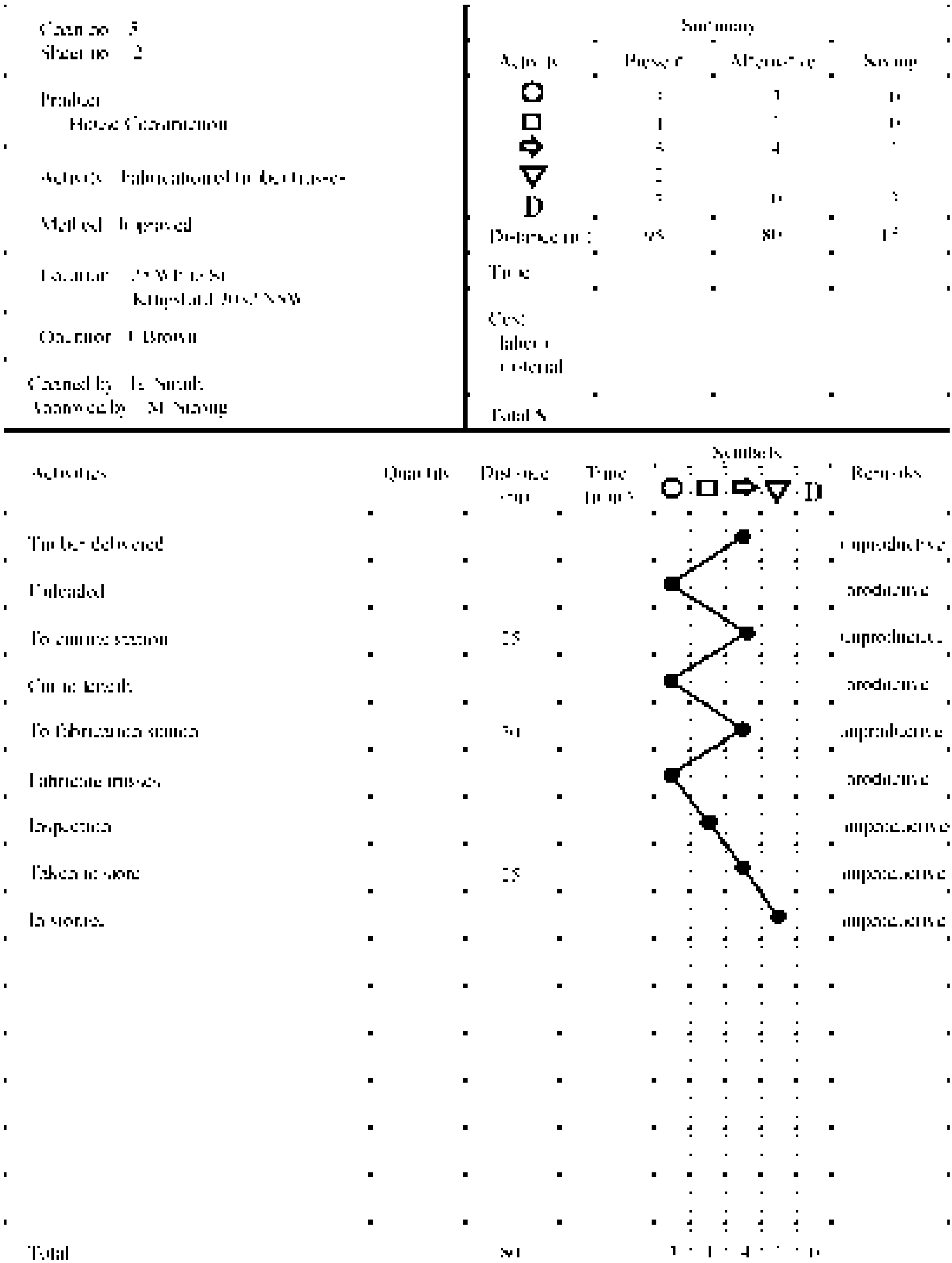
Let's look at the bottom part of the flow process chart in Figure 11.4 first. A brief glance at the total of individual aggregated activities suggests that out of 14 activities, only three are productive. Clearly, the present production method seems inefficient, suffering from discontinuity of work, delays, and frequent movement of materials. It also shows that the total length of the production process is 95 metres. An improved production method is given in Figure 11.5. The delays have been eliminated and the number of transportations and storage activities reduced. The overall length of the production process has also been reduced by 15 metres. The top right corner of the chart provides a summary of the analysis.

Figure 11.4 Example of a flow process chart – the current method of work

	Summary			
Chart no. 5 Sheet no. 1	Activity	Present	Alternative	Saving
Product House Construction	○ □ ⇨ ▽ D			
Activity Fabrication of timber trusses Method Present				
	Distance (m)			
Location 25 White St. Kingsford 2032 NSW	Time			
Operator J. Brown	Cost of labour material			
Charted by H. Smith Approved by M. Strong	Total $			

Activities	Quantity	Distance (m)	Time (min)	○	□	⇨	▽	D	Remarks
Timber delivered						●			unproductive
Unloaded				●					productive
Taken to store		30				●			unproductive
In storage							●		unproductive
To cutting station		10				●			unproductive
Awaiting cutting								●	unproductive
Cut to length				●					productive
To fabrication station		30				●			unproductive
Awaiting fabrication								●	unproductive
Trusses fabricated				●					productive
Awaiting inspection								●	unproductive
Inspection					●				unproductive
Taken to store		25				●			unproductive
In storage							●		unproductive
Total		95		3		4	2	3	

Figure 11.5 Example of a flow process chart – the improved method of work



Multiple activity chart

Multiple activity charts have already been described in Chapter 9. Their ability to visually assess the use of committed resources makes them highly suitable for recording and analysing method study information.

Flow chart

A flow chart is another tool that helps to visually record information pertinent to method study. It is most effective in displaying the flow of work within a workplace, such as construction sites, design offices and factory production floors. A line joining the standard process chart symbols that define the location of specific tasks within the production process represents the flow of work. The flow chart in Figure 11.6 shows the delivery, storage and distribution of bricks on a construction site. There may be valid reasons for the present location of the hoist and the storage area for the brick. But it would certainly be worth investigating whether both the hoist and the brick storage area could be relocated closer to the southern end of the site to reduce the amount of movement of bricks.

Examining facts and seeking possible alternative solutions

The examination stage is the most important part of method study and requires the manager to display a challenging attitude and an impartial judgment in order to examine systematically and objectively the recorded information concerning the work under investigation. The manager makes a detailed and critical review of each activity with the aim of developing a more efficient work method by eliminating any unnecessary tasks, preventing delays, reducing movements of resources and simplifying work tasks.

In developing a new work method, the manager is expected to:

- examine the facts
- discard preconceived ideas
- display a challenging attitude
- avoid hasty judgments
- look for details
- discard undesirable elements of the work method.

Developing the most practical, economical and efficient method

In this stage of method study, the manager selects the most appropriate work method from the information generated in the previous stages. In doing so, the manager needs to satisfy the following principles:

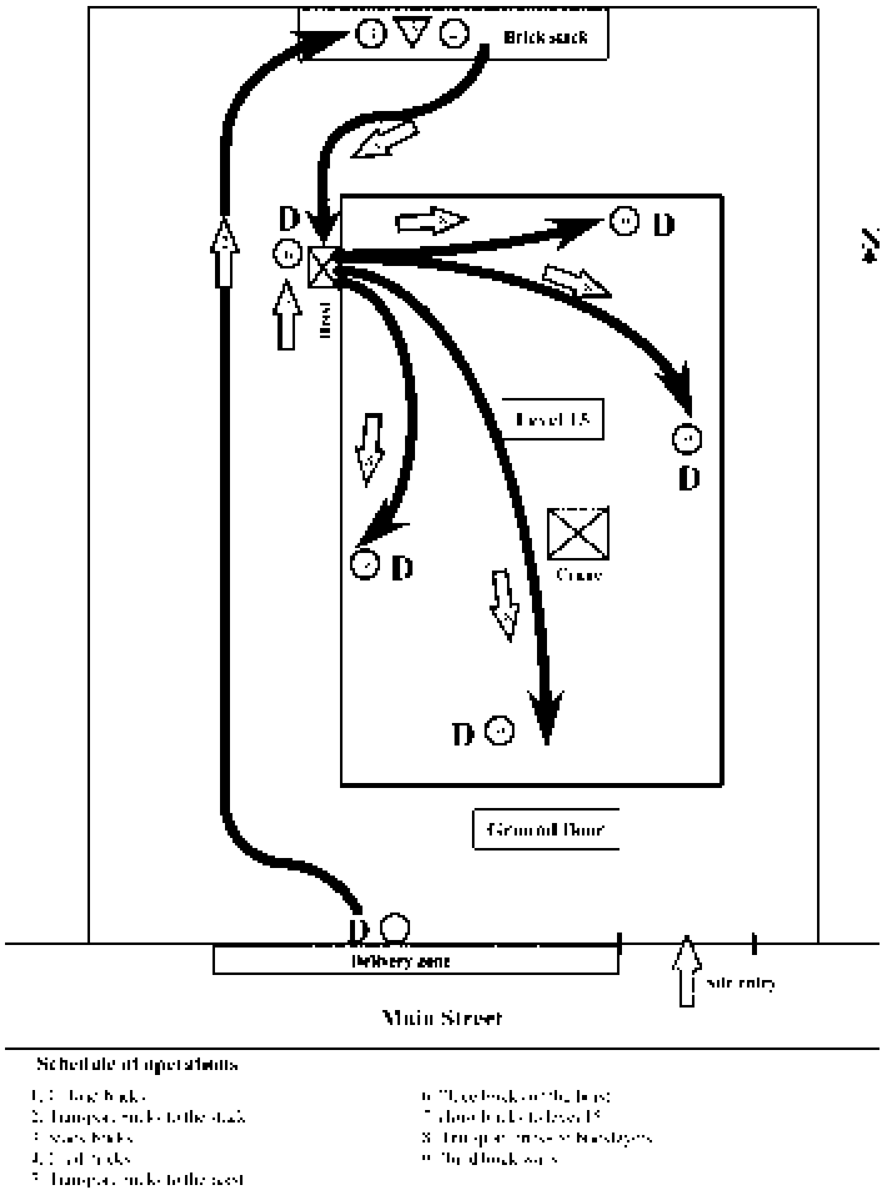


Figure 11.6 Example of a flow chart

- employing most appropriate resources, both human and physical
- maximising utilisation of committed resources
- minimising the extent of human movement
- minimising the extent of movement of materials and plant/equipment
- maintaining environmental and safety standards

- developing the most efficient, practical and safe layout of the workplace
- implementing safe working procedures.

Installing the improved method

At this stage the manager has selected a preferred alternative method and is ready to install it. A minor modification to the present method of work may often be implemented swiftly and with little or no disruption to the production process. But installation of more substantial modifications requires careful planning to ensure smooth changeover with minimum disruption to the production process. It should be carried out in two phases: preparation and installation.

Preparation

In this phase, the manager develops a plan of action for changing the current work method. It is essential that those affected by the proposed change in the work method are involved in the development of such a plan. It is also essential that the reasons for the change and the details of the proposed plan of action are communicated throughout the workplace. People are generally inclined to reject change, particularly if they don't know the reasons for it and what impact it will have on them. Enforcement of a change in the workplace by the management with little or no involvement of the workers may in extreme cases lead to industrial unrest.

In developing a plan of action, the manager would need to consider a range of issues including:

- timetable of the work
- availability of resources
- replacement of the old stock
- training of labour
- compliance with safety regulations and labour awards.

Where possible, a major change to the work method should be carried out outside normal working hours. In some cases, however, it may be necessary to close down the entire production process for a time. For example, introduction of a new car model requires a complete shutdown of the production line for a number of weeks to carry out retooling.

In situations where disruption to the production process must be kept to the absolute minimum, the manager would need to seriously consider rehearsing changeover first.

Installation

With a good plan in hand, the installation phase of a changeover should become a routine task. Monitoring the performance of a new work method is an important aspect of installation. Monitoring seeks to uncover:

- any deviations in the performance of a new method, which may require fine-tuning of the method or more significant modifications
- an unexpected depletion of the resources
- changes in workers' attitudes and motivation.

Maintaining the improved method

It is the responsibility of the manager to regularly review the performance of a new work method and attend to minor or major corrections of the method as required.

WORK MEASUREMENT

'The aim of work measurement is to determine the time it takes for a qualified worker to carry out a specific job at a defined level of performance and to eliminate ineffective elements of work' (Oxley & Poskitt 1980: 161). The principal aim is to seek the standard time of work, which can assist in (Harris & McCaffer 2001):

1. determining appropriate quantities of human and physical resources; once standard times of activities in a construction schedule are known, it is then possible to allocate appropriate resources to such activities (see Chapter 4)
2. measuring the utilisation of committed resources
3. providing the basis for sound financial incentive schemes
4. evaluating the economic viability of alternative methods of work.

The latter three issues listed above will be discussed briefly later in this chapter. Let's focus first on determining the standard time of work.

The standard time of work

There are several well-known techniques used for work measurement: time study, time and motion study, activity sampling and synthetical estimating (Currie 1959; Oxley & Poskitt 1980; Harris & McCaffer 2001). Since time study is recognised as the basic measuring technique, it will be discussed in more detail.

The technique of time study determines the standard time of work, which is the time that an average qualified worker who is sufficiently motivated, instructed and supervised would take to complete the task. The measurement of time of work is usually performed from a limited number of observations by a stopwatch.

The standard time of work can be calculated from the basic time, relaxation allowances and contingencies using the following formula:

Standard time = Basic time + Relaxation allowances + Contingency allowance

Basic time

'Basic time' is the observed time measured by a stopwatch and rated for a defined standard of performance. If the manager is able to measure the time of a specific activity performed by a large sample of workers, the manager would be able to calculate an arithmetic mean of all the measurements of the sample and use it as basic time without any adjustments. But this approach would be time-consuming and costly. A more practical approach is to measure the performance of a single worker, though in this case the worker under study may or may not represent the 'norm' or the 'standard level of performance'. The manager would need to make a subjective judgment about the observed level of performance and relate it to the manager's own perception of what constitutes a normal or standard level of performance. This process is referred to as 'rating'.

'Standard performance is the working rate of an average qualified worker who is sufficiently motivated, instructed and supervised' (Currie 1959: 38). This worker is able to maintain the speed of work day after day without undue physical or mental fatigue. A rating of 100 is commonly assigned to such standard performance (BS 1992). Ratings above 100 are associated with a worker who works faster, while ratings below 100 refer to one who works slower. For example, if 100 is the standard rating, then:

125 relates to a worker who is very quick, highly skilled and highly motivated

75 relates to a worker who is not fast, with average skill and uninterested

50 relates to a worker who is very slow, unskilled and unmotivated (Harris & McCaffer 2001: 54).

It is now possible to calculate basic time from the following formula:

$$\text{Basic time} = \text{Observed time} \times \frac{\text{Assessed rating}}{\text{Standard rating}}$$

Assume that the manager timed a specific task performed by a worker to be ten minutes. This is the observed time. The manager assessed the performance of the worker as 125. The basic time of that specific task performed by the worker is then:

$$\text{Basic time} = 10 \text{ min.} \times (125/100) = 12.5 \text{ minutes}$$

Because the manager assessed the worker's performance as better than the norm, an average worker would take more time to perform this task. Hence basic time is 12.5 minutes. If the manager's assessed rating of the worker was, say, 80, the basic time would then be:

$$\text{Basic time} = 10 \text{ min.} \times (80/100) = 8 \text{ minutes}$$

In this case, the worker under observation is slow and an average worker would therefore be expected to accomplish the task faster.

Relaxation allowances

'Relaxation allowances' provide for the time lost due to a wide range of causes such as:

- the worker attending to personal needs
- the worker relaxing, resting or recovering from the effects of fatigue
- the worker slowing down due to external influences such as weather, noise, light or other conditions.

Determination of the magnitude of relaxation allowances relevant to construction activities has not yet been adequately addressed. When used, they are expressed as a percentage of the basic time. Example of relaxation allowances can be found in Harris & McCaffer (2001: 60).

Contingency allowance

'A contingency allowance' provides for the time lost due to other factors such as maintenance of plant/equipment, waiting time, breakdowns, unexpected site conditions, variations, etc. (Harris & McCaffer 2001). The amount of contingency is expressed as a percentage of basic time.

With all the components of the standard time equation now defined, let's calculate the standard time of work from the following information:

Basic time is 20 minutes	
Relaxation allowances are 20% of basic time	$= (20 \times 20)/100$
	$= 4$ minutes
Contingency allowance is 15% of basic time	$= (15 \times 20)/100$
	$= 3$ minutes

The standard time of work is then:

Standard time = 20 min. + 4 min. + 3 min. = 27 minutes

Measuring utilisation of committed resources

With the knowledge of the standard time of work, it is possible to measure utilisation of committed resources, particularly plant/equipment and labour. The following formula defines utilisation:

$$\text{Utilisation} = \frac{\text{Total standard time of work}}{\text{Time of work available}} \times 100\%$$

Let's demonstrate the application of the above formula to a simple practical example. A project in question is a three-storey residential building. A single barrow hoist has been installed to move all the required materials to each level of the building. What is the present utilisation of the hoist based on the following information?

- **Basic time for one lifting cycle of work of the hoist is five minutes (it means that it takes five minutes to move the hoist's platform up and return it to the original location)**
- **Relaxation allowances are 25% of basic time = (25 × 5)/100 = 1.25 minutes**
- **Contingency allowance is 20% of basic time = (20 × 5)/100 = 1.0 minute**
- **At the end of day 3 the hoist made a total of 115 lifting cycles (based on an eight-hour working day).**

Standard time = 5 min. + 1.25 min. + 1.0 min. = 7.25 minutes

Utilisation = (7.25 min. × 115 lift cycles) / (3 days × 8 hours × 60 min.) × 100% = 57.9

The hoist's utilisation is presently 57.9 per cent.

Providing the basis for sound financial incentive schemes

The knowledge of the standard time of work makes it possible to determine the volume of work to be accomplished within a given period. Specific work targets may then be set that the workers would need to accomplish in that given period. To ensure that these work targets are met and that a high level of productivity is maintained, it may be appropriate to offer financial incentives to the workers. The detailed information on financial incentives can be found in Oxley & Poskitt (1980).

Evaluating the economic viability of alternative methods of work

In this section the concepts of method study and work measurement will be applied to two practical examples to determine the economic viability of alternative methods of work.

Example 1

This example assesses the present work method of lifting formwork by a tower crane on a high-rise commercial project. The crane has been assigned to this task for three hours per day. The site manager has calculated the volume of formwork required to be lifted in the allocated three-hour time-slot as 20 loads (assuming 1 load per lift). To meet the construction schedule, the work method must ensure that the crane can deliver 20 loads of formwork in three hours.

Two crews of workers have been assigned to this task. One crew is available on the level where formwork is being stripped. Its task is to attach loads of formwork to the crane. Another crew is available on the working deck with a task of unloading the crane.

A list of specific activities performed by the crews of workers, including the standard times of work, is given in Table 11.1. The cost of the committed resources is given in Table 11.2.

TABLE 11.1 ACTIVITIES AND THE STANDARD TIMES OF WORK

ACTIVITIES	STANDARD TIME (MINUTES)
Attach a set of slings to one load of formwork	2
Detach a set of slings from one load of formwork	2
Hook and unhook a set of slings to and from crane	1
Lift one load by crane	2
Return a set of slings by crane	1
Manoeuvre load (attached to crane) into position	1

TABLE 11.2 COSTS OF COMMITTED RESOURCES

RESOURCES	COST/DAY
Crane	$2000
1 crew of workers	$600
1 set of slings	$100

The present method of work is illustrated in Figure 11.7 using a multiple activity chart. It is based on using only one set of slings (one set comprises two separate slings). Is the present method sufficient to meet the project requirements?

The MAC schedule in Figure 11.7 shows that the work is performed at a regular cycle of 12 minutes. It means that the current method is able to lift one load of formwork every 12 minutes. However, in three hours the current method of work can only handle 15 loads, which is well short of the required target of 20 loads. It is also worth noting that neither the bottom nor the top crew of workers is effectively utilised. The bottom crew achieves only 40 per cent utilisation while the top crew is utilised 50 per cent of its time. Utilisation of the crane while engaged in lifting formwork is at the 80 per cent level.

The cost of the present method is calculated as follows:

crane	$\$2,000 \times 3/8$ hrs =	750.00
2 crews of workers	$2 \times \$600 \times 3/8$ hrs =	450.00
1 set of slings	$\$100 \times 3/8$ hrs =	37.50
Total cost (3 hrs)		$1237.50

The cost of handling one load of formwork is therefore $1237.50 / 15 = $82.50.

An alternative work method must be capable of moving formwork faster and better utilising the committed crews of workers. The obvious solution is to increase the number of sling sets. Let's try to employ three sets of slings. Assume that two of the sling sets are located on the level where the bottom crew is situated while the third set is on the level where the top crew is placed at the start of the work. Alternatively, it could have been assumed that all three sets of slings are locked in the storeroom on the ground floor at the start of the day. The sequence of work would be the same for the both assumptions, but the latter one would require a longer lead-time before reaching a regular cycle time of work.

The revised work method in the form of MAC is given in Figure 11.8.

Figure 11.7 The MAC schedule of the current work method

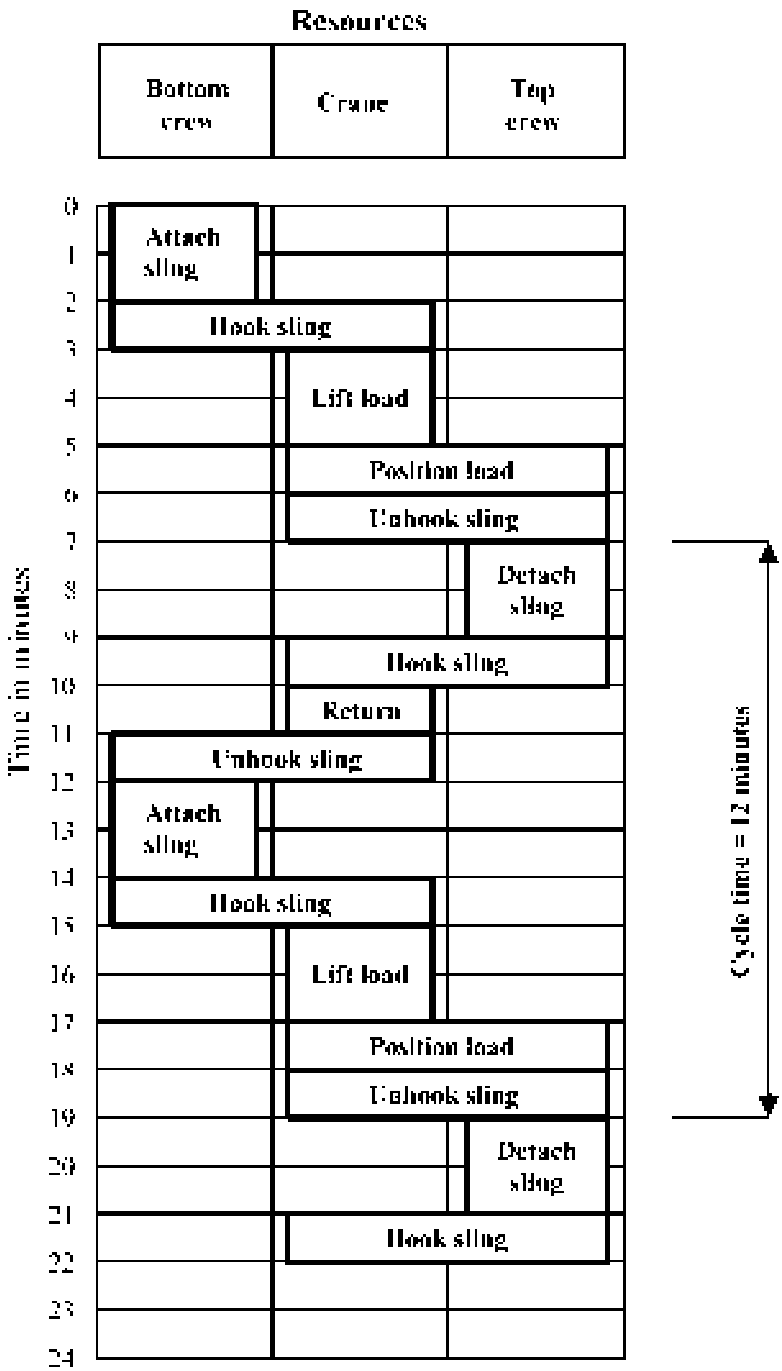
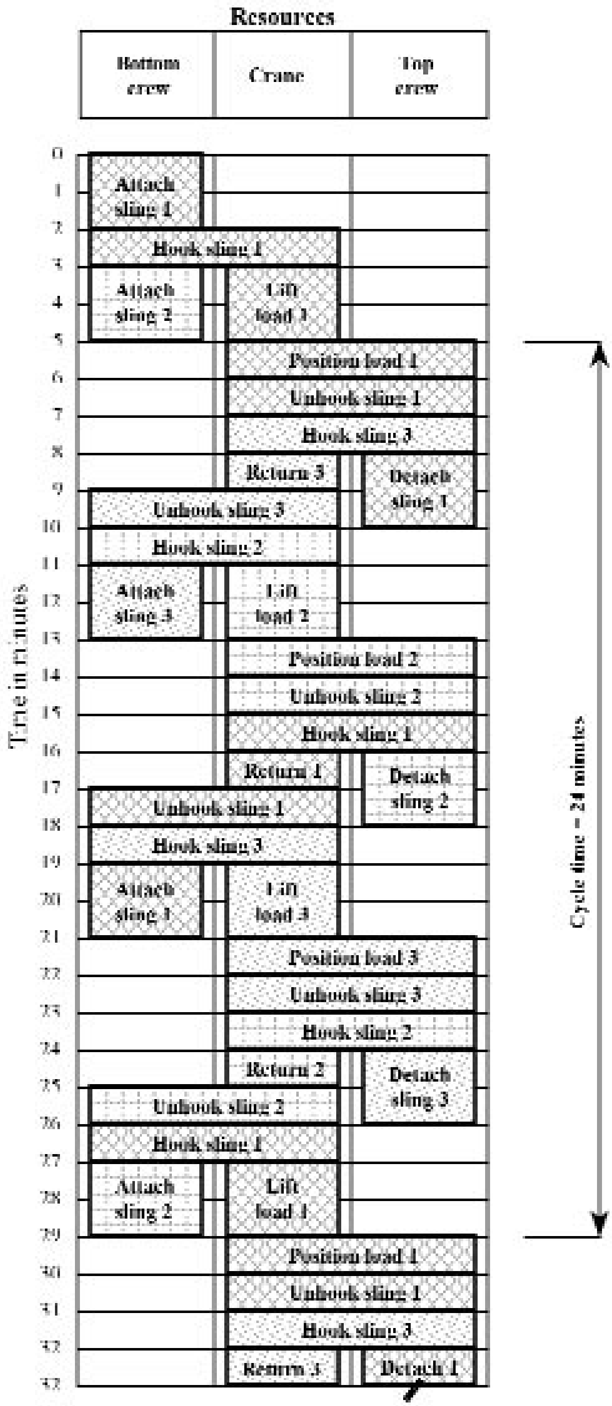


Figure 11.8 The MAC schedule of the improved method of work



The revised method of work is capable of lifting three loads of formwork in 24 minutes. It means that it meets (and exceeds) the required target of 20 loads. This method has also improved utilisation of the crews of workers from 40 to 50 per cent for the bottom crew and from 50 to 63 per cent for the top crew. The crane is now fully utilised.

The cost of the improved method is calculated as follows:

crane	$\$2000 \times 3/8$ hrs =	750.00
2 labour crews	$2 \times \$600 \times 3/8$ hrs =	450.00
3 sets of slings	$3 \times \$100 \times 3/8$ hrs =	112.50
Total cost (3 hrs.)		$1312.50

The cost of handling one load of formwork is then $1312.50 / 20 = $65.62.

Apart from delivering the required quantity of formwork material, the improved method offers better utilisation of the committed resources and a lower cost of handling.

Example 2

This example examines the current work method of delivering bricks and mortar by a single barrow hoist to typical floors of a high-rise building. The construction schedule requires at least 2500 bricks to be laid each day. The ready-mix mortar is brought to the site in trucks and stored in suitable containers near the hoist on the ground floor. Bricks are also stacked on the ground floor near the hoist.

Two crews of workers have been assigned to this task. One crew comprising labourers is available on the ground floor with the task of loading wheelbarrows with bricks and mortar. Another crew is available on the working deck. It comprises bricklayers and labourers with the task of unloading wheelbarrows and building brick walls.

Bricks and mortar are transported using wheelbarrows. A wheelbarrow can be loaded with either bricks or mortar. The capacity of one wheelbarrow is 40 bricks. One cubic metre of mortar is required for every 80 bricks laid (or two wheelbarrows of bricks). It means that wheelbarrows of bricks and mortar are delivered in the ratio of 2:1.

A list of specific activities performed by the crews of workers including the standard times of work are given in Table 11.3. The cost of the committed resources is given in Table 11.4.

TABLE 11.3 EXAMPLE 2 ACTIVITIES AND THEIR STANDARD TIMES OF WORK

ACTIVITIES	STANDARD TIME (MINUTES)
Fill barrow with mortar	1
Wheel and place mortar barrow on hoist	1
Take mortar barrow off hoist, wheel, empty and return to hoist	4
Fill barrow with bricks	2
Wheel and place brick barrow on hoist	1
Take brick barrow off hoist, wheel, empty and return to hoist	5
Hoist up	1
Hoist down	1
Change over barrows	1
Take empty barrow off hoist for refilling	1
Labourer to walk from stack of bricks to mortar storage	1

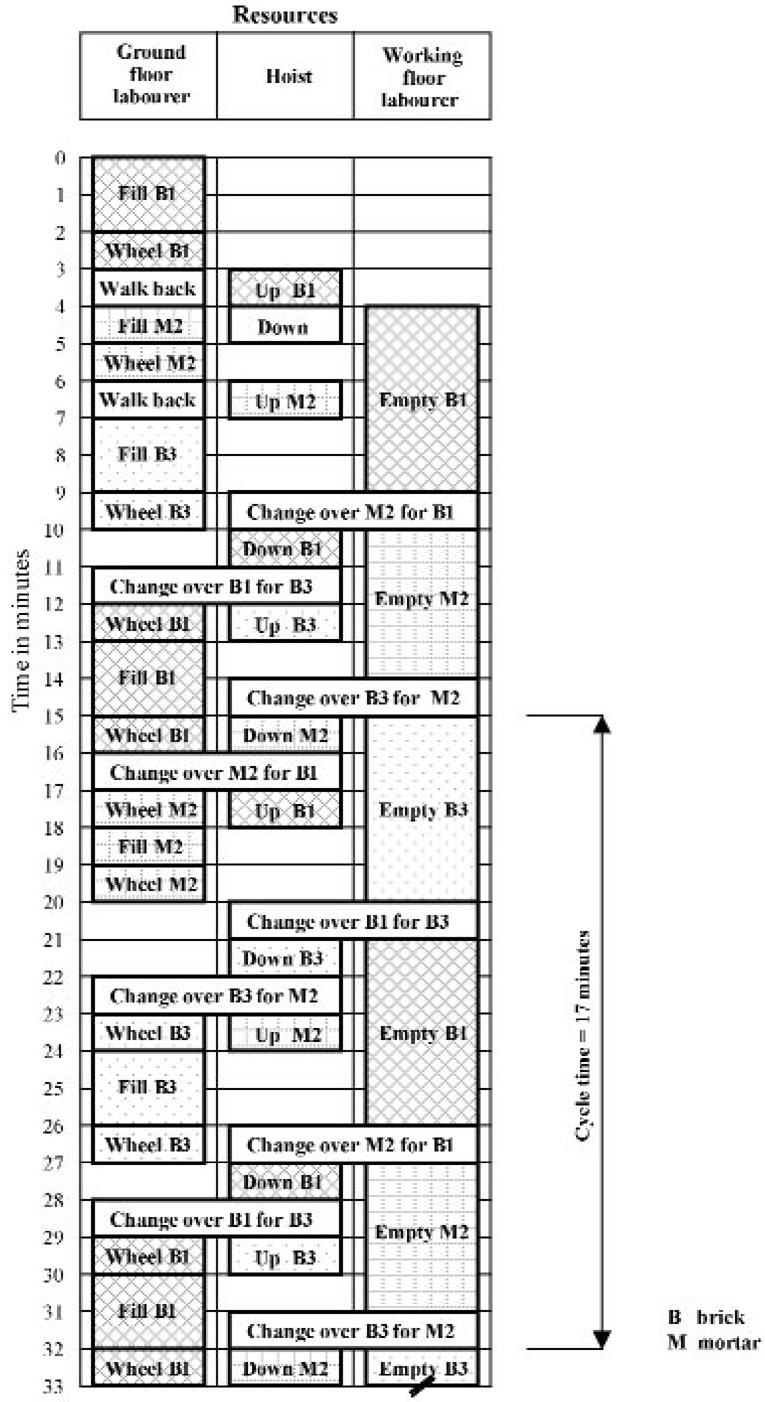
TABLE 11.4 COSTS OF COMMITTED RESOURCES

RESOURCES	COST
Bricklayer	$40/hr
Labourer	$30/hr
Hoist	$500/day
Wheelbarrow	$20/day

The present method of work is illustrated in MAC in Figure 11.9. It is based on the following decisions:

- One bricklayer lays approximately 500 bricks per day, consequently five bricklayers were employed to meet the daily production target of 2500 bricks.
- One labourer is assigned to the ground floor to load wheelbarrows with bricks and mortar and wheel them onto the hoist.
- One labourer is assigned to the working floor to take wheelbarrows off the hoist and unload them near the bricklayers.
- Only three wheelbarrows are available for moving bricks and mortar. They can be used interchangeably to move either bricks or mortar.
- Wheelbarrows are identified by numbers 1, 2 and 3. If a barrow carries bricks, its number is prefixed with 'B' and if it carries mortar, with 'M'.
- At the start of the working day all three wheelbarrows are located on the ground floor.

Figure 11.9 The MAC schedule of the present work method



The present method of work delivers two wheelbarrows of bricks and one of mortar every 17 minutes. It means that 2258 bricks are delivered to the bricklayers in eight hours. Since the required production output is 2500 bricks per day, the present work method is inadequate. The cost of the current method of work is calculated as follows:

Hoist	\$500 × 1 day =	500.00
5 Bricklayers	5 × \$40/hr × 8hrs =	1600.00
3 Labourers	3 × \$30/hr × 8 hrs	720.00
3 Barrows	3 × \$20 × 1 day =	60.00
Total cost (1 day)		\$2880.00

The cost of handling 1000 bricks is (1000 / 2258 bricks) × \$2880 = \$1275.47

A closer examination of the MAC schedule in Figure 11.9 clearly shows that the labourer working on the working floor is already fully utilised, while the other resources have some spare capacity. By placing an additional labourer on the working floor, the rate of progress is likely to increase. Let's see if it works. The revised MAC schedule based on two labourers placed on the working floor is given in Figure 11.10.

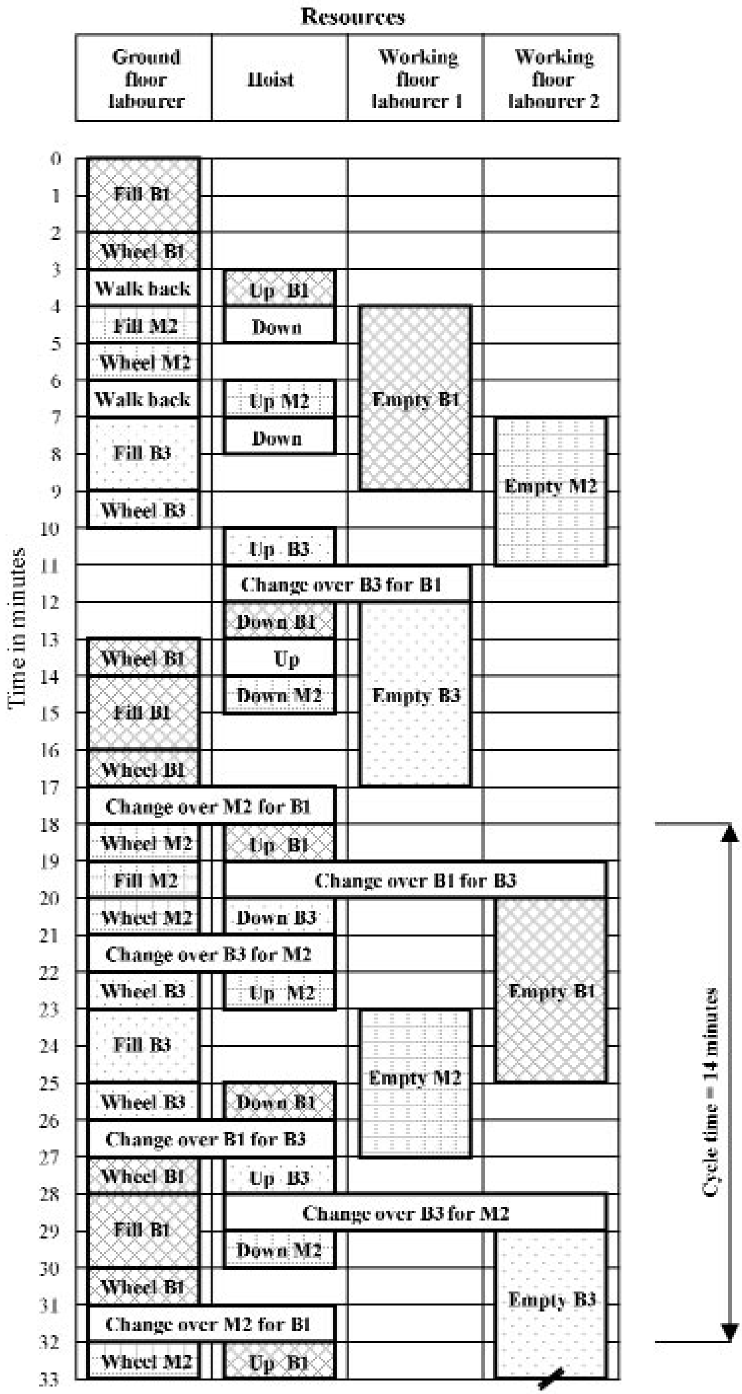
The improved method of work delivers two wheelbarrows of bricks and one of mortar every 14 minutes and thus 2742 bricks per day, which is more than the scheduled production target of 2500 bricks per day. The cost of the improved method is calculated as follows:

Hoist	\$500 × 1 day =	500.00
5 Bricklayers	5 × \$40/hr × 8hrs =	1600.00
3 Labourers	3 × \$30/hr × 8 hrs	720.00
3 Barrows	3 × \$20 × 1 day =	60.00
Total cost (1 day)		\$2880.00

Although the method is capable of supplying 2742 bricks per day, the employed bricklayers are able to lay only 2500 bricks. Consequently, the cost of handling 1000 bricks is (1000 / 2500 bricks) × \$2880 = \$1152.00.

The improved work method delivers sufficient quantity of bricks and mortar to meet the required daily output rate of 2500 bricks. It also marginally improves the cost of handling bricks and mortar. But it does not effectively utilise two labourers employed on the working floor. The reader may consider developing other alternative solutions such as replacing wheelbarrows with a larger capacity plant.

Figure 11.10 The MAC schedule of the improved work method



SUMMARY

This chapter examined the concept of work study, which is primarily a technique that aims at improving productivity of the production processes. It helps the manager to analyse work processes with a view to developing improved production methods. Through work measurement the manager is able to determine appropriate quantities of human and physical resources, measure their utilisation, and evaluate the economic viability of alternative methods of work.

EXERCISES

Solutions to the following exercises can be found on the following UNSW Press website: http://unswpress.com.au

EXERCISE 11.1

Calculate the level of utilisation of a window cleaner from the following information:

Observed time for cleaning one window = 6 minutes
Relaxation allowance + Contingency = 50% of Basic time
Expected rating of the cleaner = 100
Assessed rating of the cleaner = 120
At the end of day 4, the cleaner cleaned a total of 160 windows.
Assume that 1 working day is equal to 8 hours.

EXERCISE 11.2

Construction of a reinforced concrete high-rise building requires approximately 130 m^3 of concrete to be placed per floor. Concrete is delivered to the site in ready-mix trucks. The contractor has decided to discharge concrete from trucks to a kibble for lifting by a tower crane to the working floor. The contractor has one 1 m^3 capacity kibble on site but is able to obtain an additional kibble of 1.5 m^3 capacity on short notice, if needed.

The contractor has assigned one crew of labourers to load the kibble with concrete and the other crew to discharge concrete to the formwork. These crews of labourers are also responsible for hooking and unhooking the kibble to and from the crane as required. Following is a list of activities and their standard times expressed in minutes.

Activities	Standard time (min) 1 m^3 kibble	Standard time (min) 1.5 m^3 kibble
Load kibble with concrete	0.5	1.0
Lift kibble	1.0	1.0
Manoeuvre kibble to work area	0.5	0.5
Unload concrete from kibble	1	1.5
Lower empty kibble to ground for refilling	1	1
Manoeuvre kibble to truck	0.5	0.5
Hook kibble to crane	0.5	0.5
Unhook kibble from crane	0.5	0.5
Lift crane hook (without kibble)	1	1
Lower crane hook (without kibble)	1	1

The delivery of materials to the site is restricted to between 8.30 am to 5 pm.

Using MAC, illustrate the present method of work using a 1 m^3 capacity kibble. Will the contractor be able to place 130 m^3 in one working day? If not, try to improve the work method by using a 1.5 m^3 kibble.

CHAPTER 12

RISK AND SCHEDULING

INTRODUCTION

The common feature of scheduling techniques described in previous chapters was the reliance on the deterministic expression of time. Deterministic scheduling is based on the use of average time estimates in determining duration of activities. The planner who is responsible for the development of a schedule commonly adds allowances for uncertainty into average estimates of time. Top management then assesses the degree of 'uncertainty' that surrounds the entire project and formulates a project contingency. This contingency too is added to the schedule. Thus a contingency for uncertainty is often added to a schedule twice, first by the planner and second by top management. A rather risky estimate of duration of activities expressed as an average is thus transformed into a less risky estimate. In most cases contingencies are determined arbitrarily, largely based on past experiences of managers. Formulating activity durations in this manner makes it impossible to determine the degree of exposure of a construction schedule to risk.

The deterministic approach to scheduling is clearly unscientific and incapable of realistically modelling the duration of construction projects. A better approach is to adopt the concept of probability scheduling.

Probability scheduling incorporates uncertainty into estimates of activity duration. This offers two specific benefits: it requires the planner and the planning team to study the project in detail in order to estimate the likely impact of identified risks on duration of individual activities; and it makes the use of contingencies largely redundant.

The purpose of this chapter is first to develop understanding of the concept of risk and how it can effectively be managed using the process of risk management, and second to relate it to probability scheduling.

RISK AND UNCERTAINTY

Practically all non-trivial decisions and events in life have a wide range of possible outcomes, some expected, some hoped for, and a few unforeseen. The possibility of unsatisfactory or undesirable outcomes occurring can never be ruled out. However, if the presence of uncertainty is predicted and its likely impact estimated with a reasonable degree of confidence, an appropriate management action may be taken to mitigate its likely impact. If for example the project manager anticipates the likely delays in the supply of concrete to a project because of its location, the project manager may mitigate the impact of this uncertain event by mixing concrete on site.

From the business point of view, the presence of risk is desirable since a natural balance exists between risk and opportunity. High-risk investments tend to pay proportionately larger premiums and conversely, smaller returns are associated with low-risk investments. Risk and uncertainty are present in all aspects of construction work irrespective of size, complexity, location, resources, or speed of building.

Uncertainty exists where there is an absence of information about future events, conditions or values. As Porter (1981: 29) puts it, uncertainty commonly gives rise to risk, which could be defined as an exposure to economic loss or gain, which has a known probability of occurrence. Uncertainty has an unknown probability of occurrence.

Most commercial decisions are made under conditions of uncertainty or risk. The presence of risk may not necessarily be a problem, particularly where its impact is low. And even if its impact is high, the manager may be able to develop a strategy for mitigating its impact or where possible using a greater level of risk to generate a higher level of income.

It is the goal of every project manager to be able to perceive the presence of risk, and accurately predict its magnitude and likely impact on projects. This goal can only be satisfied through a systematic and disciplined approach to identification, assessment and response to risk. Such an approach is commonly known as 'risk management'. Detailed information on risk management and its application to the construction industry can be found in Raftery (1994), Flanagan & Norman (1993), RAMP (1998), Edwards (1995), Royal Society (1992), Cooper & Chapman (1987) and Byrne & Cadman (1984).

PRINCIPLES OF RISK MANAGEMENT

Risk management may be defined as 'the identification, measurement and economic control of risks that threaten the assets and earnings of a business or other enterprise' (Spence 1980: 22). It is a systematic way of looking at areas of risk and consciously determining how each should be treated. It is a management tool that aims at identifying sources of risk and uncertainty, determining their impact, and developing appropriate management responses.

The risk management process is defined by Australian/New Zealand Risk Management Standard AS/NZS 4360:1999 in terms of:

- establishing the context
- risk identification
- risk analysis
- risk response
- monitoring and review.

Each component of the risk management process will now be examined in more detail.

Establishing the context

Establishing the context refers to examination of the organisation, its strengths and weakness, and the environment in which it operates. Other issues considered are identification of the stakeholders and interpretation of the organisation's business plan, including its goals and objectives. The process of establishing the context sets the scope and boundaries for an application of risk management and establishes the criteria against which risk is to be assessed. The purpose is to provide a logical framework for identifying, assessing and responding to risk.

Risk identification

The principal benefits of risk management are usually derived from the process of identifying risk. This is because identifying risk involves detailed examination of the project, its components and its strategy, which helps the project manager and the project team to understand better the complexity of the project, its design, the site on which it will be erected, and the likely influence of a range of external environmental factors. The project manager thus becomes aware of potential weaknesses for which treatment responses must be developed. The project manager may also become aware of opportunities that may present themselves. But because the process of risk identification is usually a subjective one relying on the manager's ability to recognise potential risks, it may over- or under-emphasise or even overlook the importance of some risks.

Several methods of identifying risk are available. They fall into two distinct approaches: bottom-up and top-down.

Bottom-up approach to risk identification

Bottom-up risk identification works with the pieces and tries to link them together in a meaningful, logical manner. Examples of this approach are given below.

(a) A checklist approach

A checklist is a database of risks to which a firm has been exposed in the past. Depending on the volume of past data, it may be aggregated according to the type or size of project, the industry sector, the procurement type and the like. According to Mason (1973), this method offers the most useable risk identification method for construction contracting by allowing the construction firm to identify risks to which it is exposed in a rational manner.

Reliance on historical data in a checklist may be both the strength and the weakness of this approach. As long as it is used only as a guide that helps the manager to identify risks in a thorough and systematic manner, a checklist approach may be highly effective. However, a fundamental limitation is that the manager's look into the past may leave the manager open to the bias of hindsight. The manager may place too much emphasis on risks, which are either irrelevant as far as a new project is concerned, or whose real impact is just too small to warrant any form of assessment and response.

(b) A financial statement method

This method of risk identification is based on the premise that financial statement account entries serve as reminders of exposure to economic loss. Analysis of such statements would reveal the degree of exposure of resources. The weakness of the method is that it provides little help in identifying construction-related risk.

(c) A flow chart approach

This approach attempts to construct a visual chart of the actual production process showing important components of the process and the flow of work. The manager has an opportunity to focus on each element of the chart at a time and simultaneously consider the possibility of something going wrong with such an element. This approach may lead to identifying a series of risk events that may have significant impact on the project.

(d) A brainstorming approach

Brainstorming is probably the most popular approach to risk identification. It involves project participants taking part in a structured workshop where they systematically examine every part of the project under the guidance of the workshop facilitator with a view to identifying likely risk events.

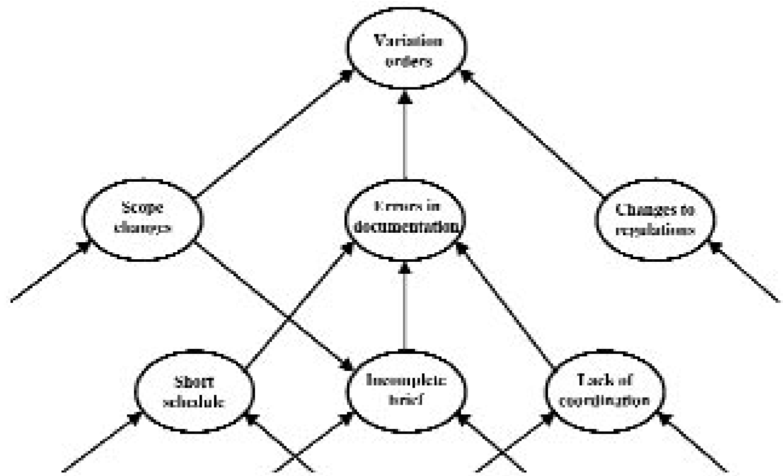
(e) A scenario-building approach

This approach relies on the development of two scenarios: the most optimistic scenario where everything occurs as expected, and the most pessimistic scenario where everything goes wrong. The aim of this approach is to assess the two opposed scenarios in order to identify the factors or risks that might influence project performance.

(f) Influence diagram approach

An influence diagram presents a more comprehensive view of the likely project risks. It helps to identify risk by a detailed assessment of cause–effect relationships among project variables. The manager would first examine a particular variable outcome (effect) and by working backwards attempt to define the causes of variation. Once identified, these causes then become effects for which causes are sought in turn, and so on. For example, the cost escalation arising from variation orders may be caused by errors in design documentation, the client's changes to the scope, or new regulations imposed by the local authority. The errors in design documentation may be caused by an incomplete brief, a lack of coordination or insufficient time set aside for design and documentation. The causes of the incomplete brief will be examined further, and so on. Graphically, the above simple example is illustrated in Figure 12.1, where circles or nodes represent high-risk events in the production process and arcs or lines illustrate cause–effect links between these events.

Figure 12.1 Example of an influence diagram



When all possible cause–effect relationships have been identified, the manager is presented with a highly detailed graphic map of possible risk events.

Top-down approach to risk identification

A top-down approach generates a holistic view of a project from which risk variables that are likely to have an impact on the project are deduced. There are two commonly used approaches:

(a) A case-based approach

A case-based approach provides an opportunity to examine a specific case in its entirety. Most commonly, a past project for which a wealth of information is available would be selected as a case study. This examination of a case serves as an excellent training ground for new managers, who gain a holistic perspective of a typical project situation and its associated risks.

(b) An aggregate or bottom-line approach

A better-known term for an aggregate or bottom-line approach is a contingency allowance. It is a global perception of the volume of risk and its impact on the project. It is expressed as a percentage of a certain performance measure, such as contract period or project cost. Contingency is commonly formulated by top management and reflects subjective perception of the likely impact of risk on the project. While attractive for its simplicity, it lacks the ability to explain in any meaningful way the basis for developing a risk management response to anticipated problems.

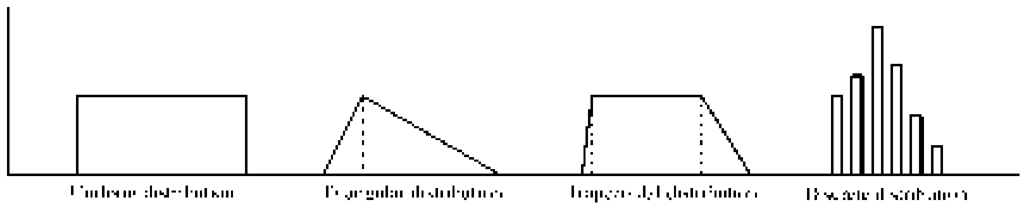
Before identified risks can be analysed, their likely magnitudes need first to be determined. This process is referred to as 'data elicitation'. Eliciting data for the identified risks is perhaps the most difficult task in risk management. Data is usually derived from databases, random experiments or the knowledge of experts.

Information extracted from a database or a random experiment provides 'objective data' that can be expressed in the form of a probability distribution. In this form, data is highly suitable for the quantitative risk assessment. Betts (1991), Ivkovic (1991) and Townley (1991) believe that objective data is preferred because of its consistency and perceived accuracy. But the use of databases in the construction industry is rare and the cost of random experiment high.

'Subjective data' is elicited by brainstorming, which accesses the knowledge and experience of the project participants. It may appear to be an arbitrary procedure or guesswork, but it is not so. If carried out by a properly structured brainstorming process, managed by an experienced facilitator, it provides collective expert knowledge of high quality. The best-known brainstorming technique is the Delphi method, which seeks information from a group of experts by means of an iterative questionnaire technique (though while highly effective, the Delphi method can be rather time-consuming).

Subjective data may be expressed as likelihood and consequence of risks in 'high' or 'low' terms (see Qualitative risk analysis on pages 255–56), or as estimates of specific values of risk variables that fit simple probability distributions, such as uniform, triangular, trapezoidal and discrete (see Figure 12.2). The simplest way of transforming subjective data into probability distributions is to arbitrarily determine a two-point estimate of the highest and lowest value of the random variable. These two points describe the uniform probability distribution, which is the simplest probability distribution. A three-point estimate of the highest, most likely and the lowest values describes the triangular probability distribution. An extension of the triangular distribution is the trapezoidal distribution, which is characterised by two estimates of the most likely values together with the highest and the lowest estimates. Shapes of simple probability distributions are given in Figure 12.2.

Figure 12.2 Examples of simple probability distributions



Uniform distribution assumes that a range of possible values for a given risk variable can only be expressed between its minimum and maximum limits. While the use of this distribution may be acceptable in some applications, for example in predicting the exchange rate of the currency, it is doubtful that it would accurately model construction cost and time.

Triangular distribution is viewed as being adequate for most applications, particularly in estimating cost and time (Wilson 1984; Raftery 1990). It is characterised, in addition to its minimum and maximum limits of values, by the most likely value.

Trapezoidal distribution is described by the minimum and maximum limits, and by two estimates of the most likely values.

Discrete distribution shows frequency of occurrence of various outcomes of a given risk variable. Such frequencies are in fact probabilities of occurrences that describe the range of possible outcomes.

When using simple probability distributions, care is required in determining the lower and upper limits of the distributions. There are no precise rules governing the determination of these limits; however, they should be set on the assumption that there is only a small chance, for example 1–2 per cent, that their values would be exceeded (Hertz & Thomas 1983; Wilson 1984).

Risk analysis

The purpose of risk analysis is to measure the impact of the identified risks on a project. Depending on the available data, risk analysis can be performed qualitatively or quantitatively.

Qualitative risk analysis

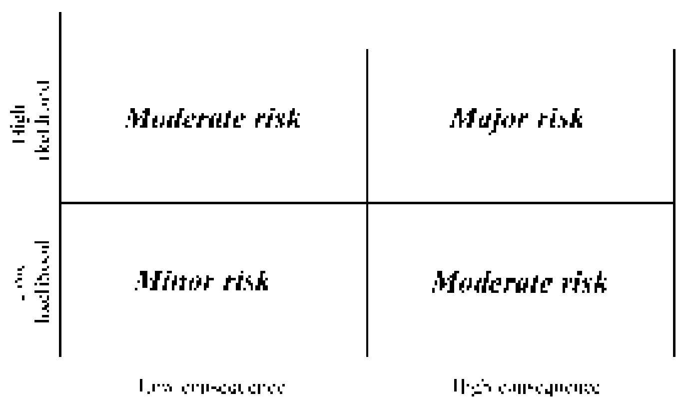
Qualitative assessment of risk is popular for its simpler and more participative approach. It involves subjective assessment of the derived data in terms of risk likelihood and consequence. When appropriately structured and systematically applied, qualitative risk analysis serves as a powerful decision-making tool.

The Risk Management Guidelines of the NSW Government (1993) and the Australian and New Zealand Risk Management Standard (AS/NZS 1999) describe a qualitative risk assessment process in which risk events are expressed in terms of likelihood and consequence. The aim of this form of risk assessment is to isolate the major risks and exclude those that are regarded as minor or have low impact.

An estimate of the likelihood of each risk may be expressed on a simple scale from low to high, or on a more detailed scale from rare, unlikely, moderate, likely, to almost certain (AS/NZS 1999).

An estimate of the consequences of each risk may also be expressed as either low or high, or as suggested in AS/NZS (1999) in terms of being insignificant, minor, moderate, major or catastrophic. A risk management matrix can then be formed using estimates of likelihood and consequence. An example of such a matrix is given in Figure 12.3.

Figure 12.3 A simple risk management matrix (adapted from NSW Government 1993)



In Figure 12.3 minor risks will commonly be ignored. Moderate risk will be carefully analysed and appropriate management responses formulated, while major risk will be given the utmost attention.

Quantitative risk analysis

Quantitative risk analysis techniques are stochastic or random in nature. The most important feature of a stochastic process is that the outcome cannot be predicted with certainty. The application of any such technique requires that risk data be expressed as a probability distribution.

The choice of technique usually depends on the type of problem, the available experience and expertise, and the capability of the computer software and hardware. A wide range of techniques is available including sensitivity analysis, probability analysis using Monte Carlo simulation, decision trees, utility functions, and full control interval and memory (CIM) analysis (Cooper & Chapman 1987). A brief review of sensitivity and probability analyses will be presented.

(a) Sensitivity analysis

Sensitivity analysis seeks to place a value on the effect of change of a single risk variable within a particular risk assessment model by analysing that effect on the model output. A likely range of variations is defined for selected components of the risk assessment model, and the effect of change of each of these risk variables on the model outcome is then assessed in turn across the assumed ranges of values. Each risk is considered individually and independently, with no attempt to quantify probability of occurrence.

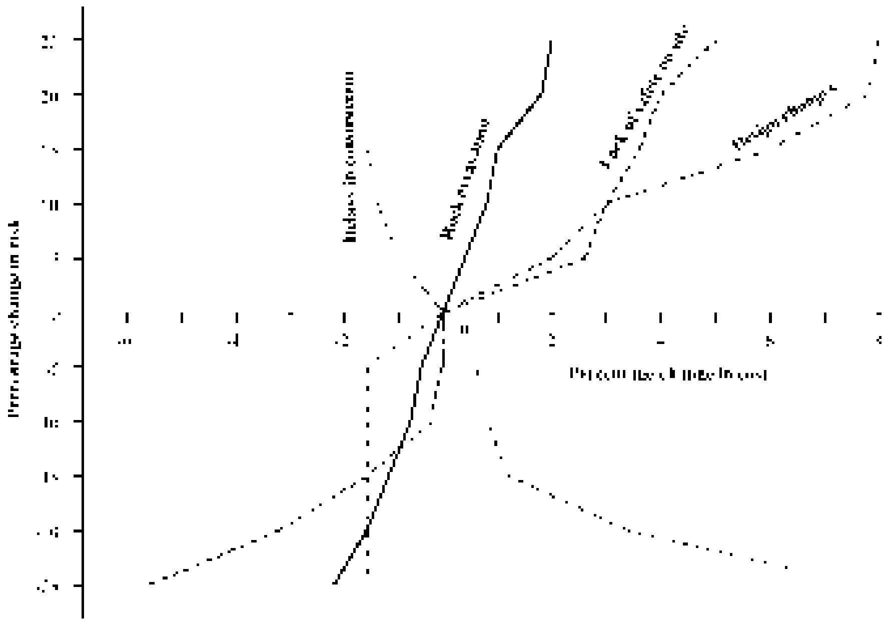
The importance of sensitivity analysis is that often the effect of a single change in one variable can produce a marked difference in the model outcome. Sometimes the size of this effect may be very significant indeed.

In practice, a sensitivity analysis will be performed for a large number of risks and uncertainties in order to identify those that have a high impact on the project outcome and to which the project will be most sensitive. If the manager is interested in reducing uncertainty or risk exposure, then sensitivity analysis will identify those areas on which the effort should be concentrated.

The outcome of sensitivity analysis is a list of selected variables ranked in terms of their impact. This is best presented graphically, with a spider diagram being the most preferred form of representation. A spider diagram is an X–Y graph with the horizontal and vertical axes showing a percentage change in the outcome variable and the percentage of change in the level of risk respectively. A spider diagram in Figure 12.4 illustrates assessment of the impact of four risk variables:

- problems associated with rock excavation
- design changes
- lack of safety on site
- delays in construction.

Figure 12.4 A spider diagram of the four risk variables



For each risk variable, the diagram graphs the impact on the cost of a defined proportionate variation in a single risk variable that has been identified as having some risk associated with its cost estimate.

Assume that the risk in the first three defined variables is related to cost overruns while the risk in the fourth variable affects the rate of production. Assume further that the risk could increase or decrease by 5, 10, 15 or 20 per cent. Each risk variable is analysed separately for different increments of risk. The resulting effects on the total project cost is determined and plotted as a series of lines.

It is clear that the flatter the line, the more sensitive the cost variation in that variable. 'Design changes' is the most sensitive variable closely followed by 'Lack of safety on site'. The impact of 'Delays in construction' becomes severe when the percentage variation in the variable is more than –20 per cent.

The major weakness of sensitivity analysis is that selected risk variables are treated individually as independent variables, and interdependence is not considered. The outcomes of sensitivity analysis thus need to be treated with caution where the effects of combinations of variables are being assessed.

(b) Probability analysis

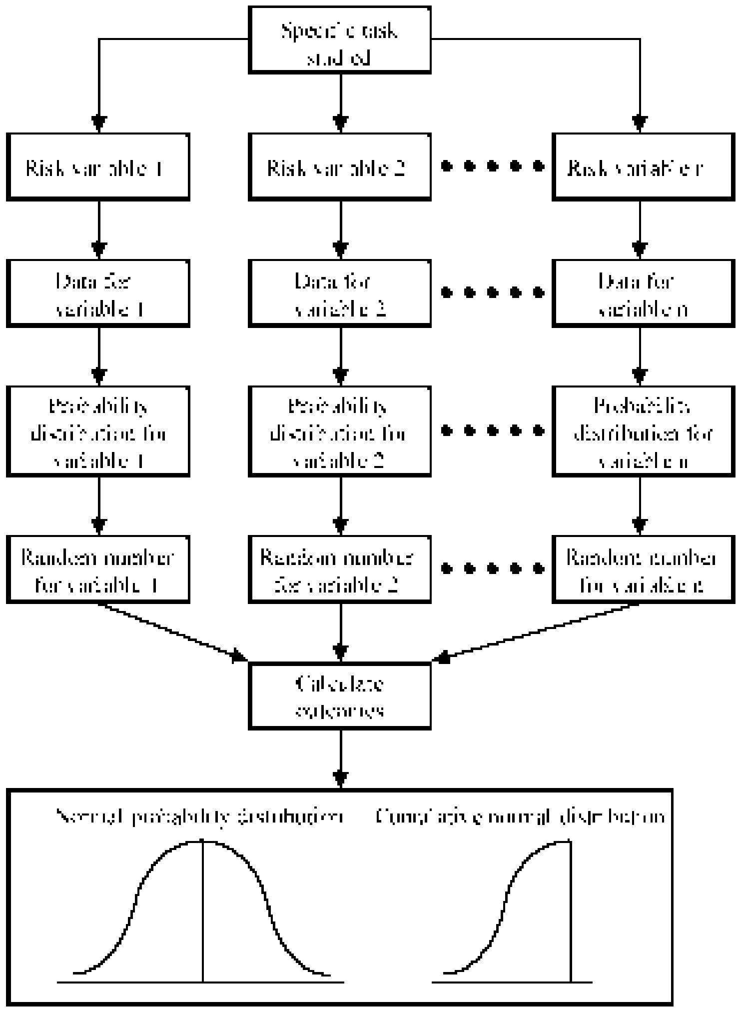
The weakness of sensitivity analysis is that it looks at risks in isolation. Probability analysis overcomes this problem. Probability analysis is a statistical method that assesses a multitude of risks that may vary simultaneously. In combination with Monte Carlo simulation, it provides a powerful means of assessing project uncertainty.

The key to probability analysis is the development of a risk analysis model. The model should include variables affecting the outcome, taking into account the interrelationships and interdependence between the variables. Each risk variable in the model is expressed as a probability distribution. The model must permit assessment of risks at the desired level of detail and accuracy. This may require breaking down risk variables into their subcomponents in order to accurately assess the impact of risk on such subcomponents.

Probability analysis is commonly performed using Monte Carlo simulation. The Monte Carlo technique generates random numbers that are related to probability distributions of individual risk variables in the model. After each iteration, the model calculates one specific outcome from the generated risk values from individual probability distributions. After a large number (at least 100) of iterations have been performed, the Central Limit Theorem, an important concept in statistics, ensures that the outcomes fall on a normal curve, which is fully described by its mean and standard deviation. Monte Carlo simulation will be examined in more detail later in this chapter while the Central Limit Theorem will be discussed in Chapter 13. A typical probability analysis process using Monte Carlo simulation is illustrated in Figure 12.5.

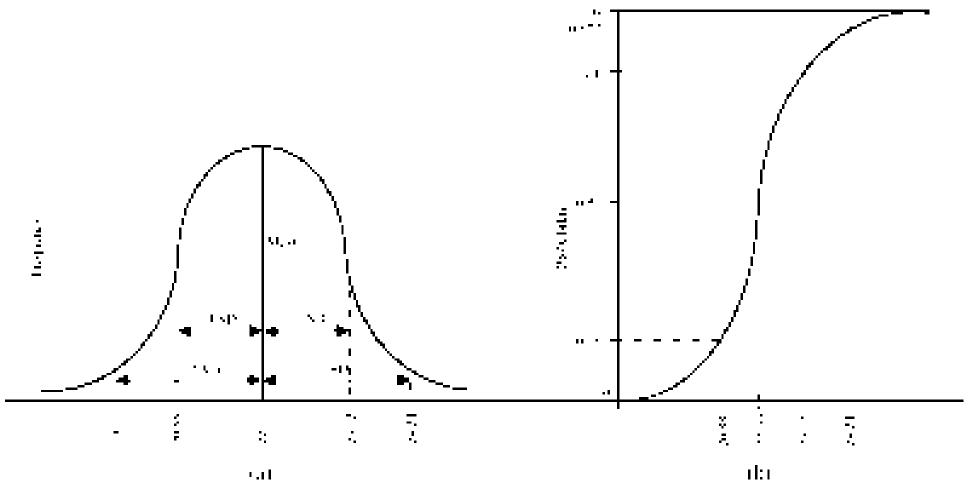
The outcome of probability analysis is a normal distribution expressed by its mean and standard deviation. For example, assume that the result of probability analysis is the mean of the cost estimate of \$22 000 and the standard deviation of the cost estimate of \$1120.

Figure 12.5 A probability analysis model



Given the properties of the normal distribution, there is a 68 per cent probability (the area between +1 SD to –1 SD from the mean) that the project cost lies in the range between $20 880 and $23 120, and a 95 per cent probability that it lies in the range between $19 760 and $24 240 (refer to Figure 12.6(a)). In cumulative terms, approximately 16 per cent of the area under the normal curve lies to the left of –1SD and 84 per cent to the left of +1SD. The similar values for –2SD to +2SD are 2.5 per cent and 97.5 per cent respectively. The likely cost outcomes for various probabilities can easily be read off a cumulative normal distribution curve given in Figure 12.6(b). For example, there is 84 per cent probability that the cost will be less than $23 120 and 97.5 per cent probability that it will be less than $24 240.

Figure 12.6 The normal distribution and the cumulative normal distribution functions



Risk response

Risk response is an action or a series of actions designed to deal with the presence of risk. This involves developing mitigation and treatment strategies, and implementing them.

The manager may adopt one of two possible response strategies: transfer the risk and/or control it.

Risk transfer

Risk transfer involves shifting the risk burden from one party to another. This may be accomplished either contractually by allocating risk through contract conditions or by insurance. Contractual transfer is a popular form of risk transfer. It is used extensively in construction contracts, where one party with power transfers the responsibility for specific risks to another party. The most commonly occurring risk transfers involve:

- clients transferring risk to contractors and designers
- contractors transferring risk to subcontractors.

Risk transfer by insurance is highly desirable in those situations where insurance policies exist. The purpose of insurance is to convert the risk into a fixed cost. This approach assigns a dollar value to the risk.

Risk control

When risk can neither be transferred nor insured, management action is required to manage it. This is commonly achieved through processes of risk avoidance and risk retention.

A simple approach to managing risk is to avoid it in the first place. For example, a risk of unreliable concrete supply from a single supplier can be avoided by engaging two suppliers. Similarly, if the contractor believes that the client imposes an excessive burden of risk through contract conditions, the contractors may avoid the risk altogether by not bidding for the job.

Not all risks can be avoided. However, their impact may potentially be reduced, for example by developing alternative solutions or even redesigning sections of the project. In collaboration with the project stakeholders, the manager needs to develop appropriate treatment strategies and to assign responsibility for their implementation.

While risk avoidance and risk minimisation can help reduce the overall level of risk, some residual risk will always remain. It is this risk that requires close attention. The most common approach to controlling residual risk is to convert it into a contingency allowance. Contingency may be expressed as a single-value estimate of a particular measure of performance such as time, cost, hours of work, etc., or as a probability distribution of a particular measure of performance.

Perhaps the most serious weakness of a single-value contingency approach is its inflationary impact on the base estimate. When a percentage contingency is added to the base estimate, every item in that estimate will be inflated by the percentage figure of the contingency, irrespective of whether such items represent 'risk' or not. For example, a 10 per cent contingency added to the cost estimate inflates the cost of each item in the estimate by 10 per cent. If the Pareto Principle holds, then only about 20 per cent of such cost items in the cost estimate represent the real risk. They should then account for approximately 80 per cent of the uncertainty.

When a risk contingency is expressed in the form of a probability distribution, it is possible to determine its value at a specific level of probability. For example, a prudent manager may prefer to accept certain level of risk but at the probability level of 85 per cent or higher. It is then a simple task to determine the actual value of the risk at that level of probability.

Monitoring and review

Although listed last, monitoring and review is not the end step of the risk management process. In fact monitoring and review start almost from the beginning and are maintained throughout the entire risk management process. Since no risk is static, monitoring and review ensure that changing circumstances are identified and reassessed. This is necessary to ensure relevance of the entire risk management process.

RISK MANAGEMENT PLAN

A risk management plan is a written statement describing the entire risk management process. It specifies the processes employed and summarises the results obtained in each stage of risk assessment. It aggregates identified risks into low–high impact and likelihood types. It lists elicited values of risk variables and assigned probability distributions, where appropriate. It defines treatment strategies particularly for high impact or likelihood risks and assigns responsibilities. It lists discarded risks. It also reports on resource requirements, timing of actions, and monitoring and reporting mechanisms.

PROBABILITY SCHEDULING

The traditional deterministic process of scheduling, which includes the formulation of time contingencies, has already been discussed in this book. Attention was drawn to the practice of adding two layers of contingencies to average estimates of activity durations in a highly subjective manner. Clearly, the deterministic approach with arbitrarily added contingencies is deficient.

An alternative approach is to apply the process of risk management to the entire scheduling process. This requires identification of risk that is likely to impact on individual activities in a schedule, its assessment and the development of treatment strategies for minimising its intensity. With this information in hand, the planner, together with other project 'experts', ascertains the extent of variability of activity duration and expresses it as a probability distribution. The combined impact of risk on the schedule is then assessed using probability analysis. The planner is able to predict, with a high degree of confidence, that a project will be completed by a certain date. This approach is much more robust, and in comparison with single-value or deterministic scheduling, it should produce more accurate schedules.

Some people argue that since probability scheduling depends largely on subjective assessment of risk variables and subjective expression of their values, this approach is inaccurate and in no way superior to single-value scheduling. Keeping in mind the probability scheduling approach and its features described above, let's compare it to the traditional, single-value scheduling. Single-value scheduling is mainly a mechanical process of establishing durations of activities within the logic of a construction schedule. For a preferred construction strategy, the planner assigns activity durations based on the planner's personal experience or industry standards in the form of mean values. Mean values of activity durations may or may not be representative of actual durations. If a schedule is developed and the level of contingency determined without first applying a rigorous process of risk management, it must be asked whether the planner and the firm's top management really have detailed knowledge of the project, understand its main features and complexities, and are aware of the extent of exposure to risk. It follows that probability scheduling is a more robust approach that should make the planner feel more confident about formulating the best possible scheduling strategy.

Probability scheduling is commonly performed either by Monte Carlo simulation or by a PERT technique. The former approach will now be briefly discussed. PERT will be examined in detail in Chapter 13.

Monte Carlo simulation

Simulation attempts to predict in advance the outcome of a certain decision. It implies 'having a look before a leap'. Monte Carlo simulation is a method of using random numbers to sample from a probability distribution where random numbers are related to the relative probabilities (frequencies) of the factor being simulated so that the more probable values of the factor are picked appropriately more often. Through sampling and with a sufficient number of iterations, the Monte Carlo method will recreate the input distributions. It is recommended that at least 100 iterations are performed in order to minimise a sampling error.

The following simple example demonstrates the working of Monte Carlo simulation. Let's assume that the frequency of sales of computers achieved by the computer manufacturing company over the past 100 days is given in the first two columns of Table 12.1. The third column contains frequencies of sales expressed as probabilities.

TABLE 12.1 THE FREQUENCY OF SALES OF COMPUTERS

COMPUTERS SOLD PER DAY	FREQUENCY OF SALES	PROBABILITY PER CENT	RANDOM NUMBERS
20	2	1	0
21	7	4	1–4
22	26	16	5–20
23	40	24	21–44
24	22	13	45–57
25	19	12	58–69
26	26	16	70–85
27	10	6	86–91
28	8	5	92–96
29	4	2	97–98
30	2	1	99
Total	166	100	

The frequency of sales of computers in the past 100 days is expressed as a discrete probability distribution. To ensure that simulation accurately represents the frequencies of sales, consecutive random numbers that are equal to the value of the probabilities will be assigned to each frequency group. Since total probability is equal to 1 or 100 per cent, in total 100 random numbers from 0 to 99 are used.

The probability of selling 20 computers is 1 per cent, which is equivalent to one random number. Let's assign the first random number in the series '0' to represent this probability.

The probability of selling 21 computers is 4 per cent. Therefore four random numbers 1–4 are assigned to this probability. The next probability value of 16 per cent, which reflects the sale of 22 computers. It is assigned the next sixteen consecutive numbers 5–20, and so on until all 100 random numbers have been assigned. Since any random number is equally likely to occur, the more probable frequency groups will occur more often in the simulation process provided it has been iterated a large number of times.

A discrete probability distribution of the sales of computers can easily be constructed and simulated in a spreadsheet enhanced with an add-in risk analysis software such as @Risk. After 100 or so iterations, the simulated frequencies of sales begin to stabilise to closely match those of the input distribution.

Monte Carlo scheduling

The technique of Monte Carlo simulation is commonly used in probability scheduling. The heart of probability scheduling is a computer-generated critical path schedule, which either has simulation capabilities or could be enhanced with such simulation capabilities through add-in simulation software. The 'I Think' software is an example of the former case and the 'Monte Carlo for Primavera' of the latter.

The development of a probability CPM schedule requires the activity's duration to be expressed as a distribution of possible durations. Triangular distribution is the one most commonly adopted. It expresses values of durations as:

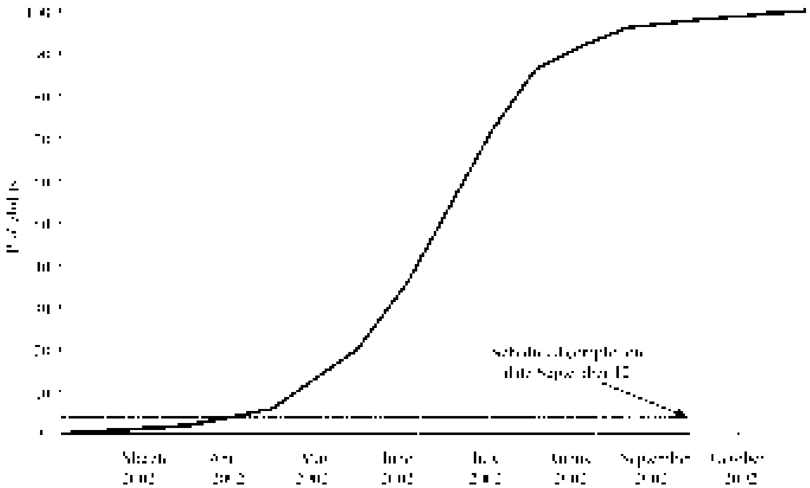
- most optimistic
- most pessimistic
- most likely.

After all activities in a schedule have been expressed as probability distributions, activity-to-activity, resource-to-resource and activity-to-resource correlations will be set by the planner to create a highly realistic scheduling model.

A risk analysis is then performed on a schedule. In individual iterations, the input duration distribution of each activity is sampled and ESD, EFD, LSD and LFD, total duration and float values are calculated. These values will vary from iteration to iteration. When the value of total float is zero or even negative, the activity is critical. Because durations of activities vary for each iteration, the position of a critical path is not constant. The computer software will calculate in percentage terms the criticality of each activity. For example, it may show that the activity 'formwork to walls' is on the critical path 67 out of 100 iterations.

The output distribution of a simulated schedule is, according to the Central Limit Theorem, a normal distribution. When expressed as a cumulative density function, the planner is able to determine the probability of completing the project by the contract date. This is illustrated in Figure 12.7. The probability of completing the project by the contract date of 12 September 2002 is about 98 per cent. Similarly, there is about 90 per cent probability that the project could be completed by 1 August 2002.

Figure 12.7 The cumulative density function of the project duration



Some simulation software is also able to express activity costs as probability distributions from which the software generates a cumulative cost-density function. The planner is then able to determine the probability of completing the project within the contract cost. By comparing both the cumulative time and the cumulative cost-density functions, the planner gains better understanding of the likely project performance and is able to formulate a much more representative level of contingency.

SUMMARY

This chapter introduced the concept of risk and uncertainty into scheduling. First it defined risk and uncertainty, then the process of risk management. In the later part of the chapter, probability scheduling using Monte Carlo simulation was briefly described. The second method of probability scheduling known as PERT will be examined in the next chapter.

CHAPTER 13

THE PROGRAM EVALUATION AND REVIEW TECHNIQUE (PERT)

INTRODUCTION

The purpose of this chapter is to examine the concept of PERT or the *Program Evaluation and Review Technique* in theoretical and practical terms.

PERT is a technique that can be used to plan and control projects surrounded by uncertainty. The fundamental aim of PERT is to track the progress of a project and show, at different time intervals, the probability of completing that project on time. Unlike Monte Carlo–based CPM scheduling, which relies on sampling, PERT relies on statistics, particularly the Central Limit Theorem, in calculating the probability of project outcomes.

PERT was developed in 1958, in parallel to the critical path method, by Malcomb et al. (1959) to assist the US Navy in the development of the Polaris submarine/ballistic missile system. It was primarily conceived as a project control technique to ensure that the highly complex and strategically important Polaris project would be delivered on time. The fact that the project was completed and commissioned well ahead of its schedule is largely attributed to PERT.

Throughout the 1960s PERT remained the principal planning and control technique in the United States, particularly on large military and aerospace projects such as Atlas, Titan I, Titan II, the Minuteman rocket systems and the Apollo space program. However, by the late 1960s the critical path method gained in popularity and has since become the most widely used planning and control technique.

The lack of software support is probably the main reason why PERT is rarely used in the construction industry. Nevertheless, the concept of PERT is fundamentally sound and suitable for planning and control of construction projects. It provides a plausible alternative to a Monte Carlo–based scheduling approach.

This chapter will first examine the original event-oriented modelling in PERT, which is based on the arrow network. For this approach, the probability concept in PERT will be defined and the computation method developed. Later, the PERT approach will be replicated using the precedence method of scheduling.

NETWORK CONSTRUCTION

In its traditional format, PERT is concerned with specific events or milestones, which are important to accomplish and against which progress is measured. When these events or milestones have been defined, they are linked together by arrows to form a PERT network, which in fact is identical to the arrow network (for detailed information on arrow networks, see Chapter 3).

While PERT and the arrow method of CPM share the same network, information they generate is interpreted differently. CPM focuses on activities that are to be accomplished while PERT is concerned with events. For example, events 1–2 in Figure 13.1 define the activity 'Excavate site' in CPM, while in PERT event 1 may relate to 'Contract awarded' or 'Start excavation' and event 2 to 'Site excavated'. The difference in interpreting PERT and CPM is illustrated in Table 13.1.

Figure 13.1 A PERT network

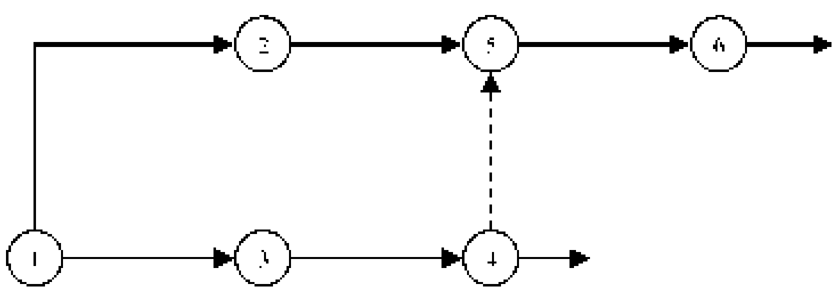


TABLE 13.1 A COMPARISON OF INTERPRETATION OF CPM AND PERT NETWORKS

CPM ACTIVITY	CPM ACTIVITY DESCRIPTION
1–2	Excavate site
1–3	Excavate for sewerage and drainage services
3–4	Install sewerage and drainage services
2–5	Form slab-edge beams
5–6	Concrete to ground floor slab

PERT EVENT	PERT EVENT DESCRIPTION
1	Contract awarded, start excavation
2	Site excavated, formwork started
3	Services excavated, installation started
4	Services installed
5	Slab-edge beams formed, services installed, concrete to slab started
6	Ground floor slab concreted

THE PROBABILITY CONCEPT IN PERT

The fundamental modelling and computational difference between PERT and CPM is related to the expression of duration of activities (it should be remembered that in PERT, an activity is treated as a pair of events). CPM defines duration of activities deterministically as a single-value estimate, while PERT, being probabilistic in nature, assumes that activity duration is a random variable with relatively large variances. In PERT, distribution of activity duration is assumed to fall on a beta probability distribution curve. Sasieni (1986) and others have questioned the validity of this assumption, but no firm consensus has yet emerged on the choice of a more appropriate distribution for modelling durations of activities in PERT.

Beta distribution is described by its mean and standard deviation. These two parameters are calculated from three estimates of activity duration, where:

- m is the most likely time interval between two events but not necessarily the mean
- a is the most optimistic time. This is the shortest time interval and is equivalent to a chance of 1 in 100 that the time estimate will be achieved

b is the most pessimistic time estimate. This is the longest time interval representing the worst scenario and is equivalent to a chance of 1 in 100 that the estimate will be this bad.

These three time estimates may be derived from a database or, as is commonly the case, subjectively by 'experts'. The mean 't_e' of beta distribution is expressed in the following formula:

$$t_e = \frac{a + 4m + b}{6}$$

The standard deviation 's' of beta distribution is expressed as follows:

$$s = \frac{b - a}{6}$$

In finding the expected duration of the project, PERT relies on a widely used statistical concept known as the Central Limit Theorem. Harris (1978: 326) describes the theorem in the following terms: 'If independent probability distributions are to be summed, then the mean of the sum is the sum of the individual means, the variance of the sum is the sum of the individual variances, and the distribution of the sum tends to the shape of the normal curve regardless of the shape of the individual input distributions'. According to this theorem, the expected project duration 'T_e' is a sum of mean 't_e' durations of critical activities in a schedule, provided the number of critical activities is reasonably large.

$$T_e = \Sigma(t_e) \text{ for critical activities}$$

Similarly, the standard deviation 'S' of the distribution of the expected project duration is according to the theorem derived as a sum of a square root of squared standard deviations (variances) of individual critical activities.

$$S = \sqrt{\Sigma s^2} \text{ for critical activities}$$

The values 'T_e' and 'S' are the mean and the standard deviation of the normal distribution by which the normal distribution is fully defined. It means that for a different set of mean and standard deviation values there is a unique normal curve. Another interesting characteristic of the normal distribution is its bell-like shape, which is smooth and symmetrical around its mean. Although the curve extends indefinitely in either direction from the mean, 99.7 per cent of the area under the curve lies between minus three to plus three standard deviations from the mean. Within two standard deviations either way from the mean lies 95.5 per cent of the area, and 68 per cent of the area lies within one standard deviation either way from the mean. The steeper the curve, the smaller the dispersion and conversely, the flatter the curve, the greater the dispersion of values from the mean. These areas under a normal curve represent the probability of possible outcomes. The interpretation is that, for example, the project duration that falls within one standard deviation either way from the mean has a 68 per cent probability of being achieved.

The characteristics of a normal curve permit calculation of probabilities of values that are not exactly one, two or three standard deviations from the mean. The first step is to establish a 'z' score, which is the distance of a particular value from the mean. It is calculated as follows from the following formula:

$$z = \frac{x - \mu}{\sigma}$$

where

z = the distance from the mean (in standard deviations)
x = a particular value in question
μ = the mean of a normal distribution
σ = the standard deviation of a normal distribution.

A 'z' value is then converted to a probability value using a probability table, given in Table 13.2. For example, a 'z' score of +1.36 is the distance 1.36 standard deviations to the right of the mean.

TABLE 13.2 THE PROBABILITY TABLE FOR A NORMAL DISTRIBUTION

Z	0	1	2	3	4	5	6	7	8	9
0.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
0.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5754
0.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
0.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
0.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
0.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
0.6	.7258	.7291	.7324	.7356	.7389	.7422	.7457	.7486	.7518	.7549
0.7	.7580	.7612	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
0.8	.7881	.7910	.7939	.7967	.7996	.8023	.8051	.8078	.8106	.8133
0.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8906	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9430	.9441
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9824	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998	.9998
3.5	.9998	.9998	.9998	.9998	.9998	.9998	.9998	.9998	.9998	.9998
3.6	.9998	.9998	.9999	.9999	.9999	.9999	.9999	.9999	.9999	.9999

Apart from the criticism that a beta distribution may not accurately model a distribution of values of activity durations, others, notably Keefer & Bodily (1983) and Sasieni (1986), questioned the correctness of the PERT method, particularly with regard to the application of the Central Limit Theorem and the assumption of independence. Another problem alluded to by Sculli (1983), Kuklan et al. (1993) Gong & Hugsted (1993) and Ranasinghe (1994) concerns an optimistically biased estimation of project time. This is because PERT assumes that the critical path cannot change for as long as other non-critical paths have float. However, it may well be that risk associated with non-critical events/activities is greater than that of critical activities. Should this risk eventuate, the available float may be insufficient to absorb any ensuing delays. In PERT, the more float there is on parallel non-critical paths, the better the probability of accomplishing the schedule on time.

THE COMPUTATIONAL PROCESS IN PERT

PERT adopts the computational process defined in Chapter 2 for the arrow CPM method. After a PERT schedule is created, the planner determines activity durations. These are assigned to activities as mean t_e values. The planner then performs the forward and backward pass calculations, which determine position of a critical path.

In the next step, the planner calculates float. In PERT, float is referred to as 'slack'. There are two types of slack in PERT: activity slack and event slack. 'Activity slack ' (AS) is the same as total float in CPM. It is calculated from the following expression:

$$\text{Activity slack AS} = LSD_J - EFD_I$$

'Event slack' (ES) is unique to PERT. It expresses the difference between the scheduled T_s and expected T_e event times, and is calculated from the following expression:

$$\text{Event slack ES} = T_s - T_e$$

The calculation process of ES starts at the last project event and from there it progresses to the beginning of the schedule.

Finally, the planner determines the probability of meeting the scheduled completion date of the project. Initially, the planner calculates a 'z' score, for which the planner then finds the actual probability value in the probability table.

EXAMPLE OF A PERT SCHEDULE

The following example demonstrates the computational process used in PERT. An office refurbishment schedule is illustrated in Figure 13.2. Durations of activities are expressed as three time estimates and are given in Table 13.3 together with calculations of values of mean t_e, standard deviation s and variances s_2 for each activity.

The contractor is required by the contract to complete refurbishment of the project in 22 weeks (T_s = 22 weeks). The client wants to know the probability that the project will be completed on time.

Figure 13.2 A PERT schedule of the refurbishment project

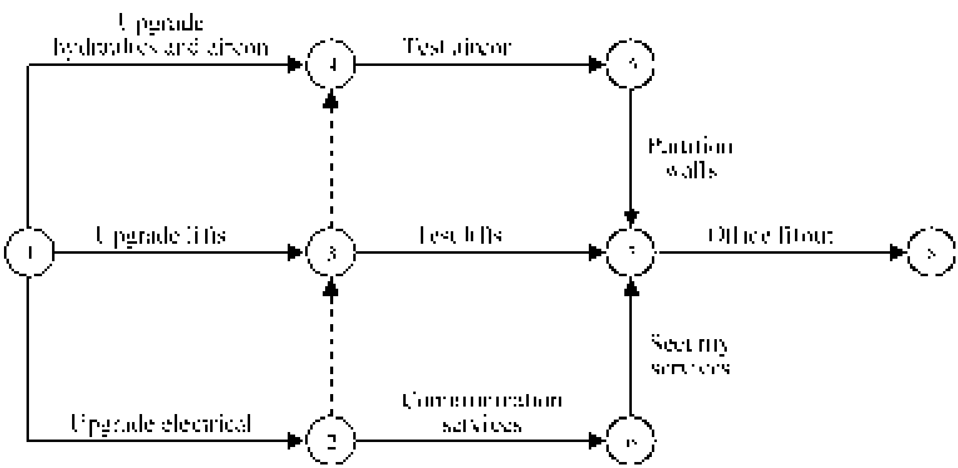


TABLE 13.3 THREE TIME ESTIMATES, a, m AND b, OF ACTIVITY DURATIONS AND t_e, s AND s^2 VALUES

ACTIVITY	a	m	b	t_e	s	s^2
1–2	5	6	9	6.33	0.67	0.44
1–3	8	9	12	9.33	0.67	0.44
1–4	4	5	7	5.17	0.50	0.25
2–3	0	0	0	0.00	0.00	0.00
3–4	0	0	0	0.00	0.00	0.00
2–6	4	5	8	5.33	0.67	0.44
3–7	2.5	3	4	3.08	0.25	0.06
4–5	1.5	2	5	2.42	0.58	0.34
5–7	3	4	6	4.17	0.50	0.25
6–7	2.5	3	4	3.08	0.25	0.06
7–8	2	3	5	3.17	0.50	0.25

Step 1

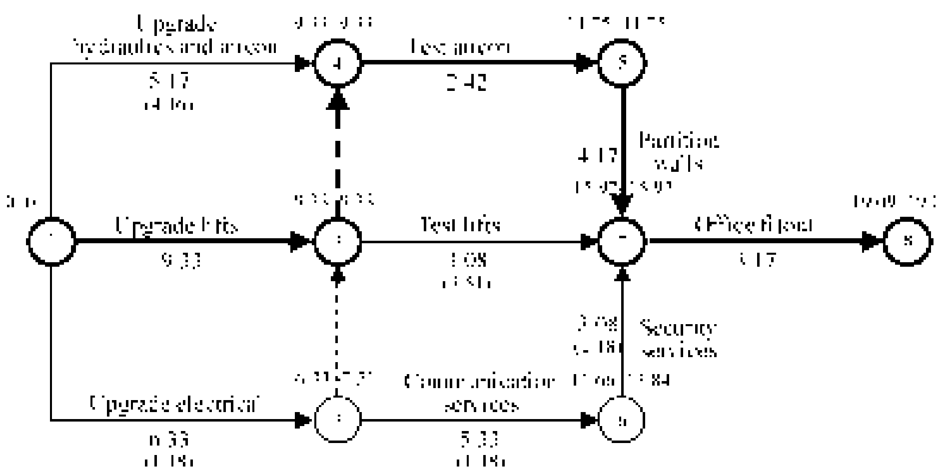
From the three time estimates of activity durations, the planner calculates the mean, standard deviation and variance values of time distributions of each activity in the schedule. These values are given in Table 13.3. In PERT, the mean values t_e represent durations of activities.

Step 2

The planner performs the forward and the backward pass calculations of the schedule, determines the critical path, and calculates values of activity and event slack. The overall project duration T_e becomes the mean value of the output normal distribution.

The calculated schedule is illustrated in Figure 13.3. The expected completion time of the project T_e = 19.09 weeks. Slack values of non-critical activities are calculated as total float and are given in brackets below the names of activities.

Figure 13.3 The calculated PERT schedule



Event slack values are calculated as = $T_s - T_e$.

For the event 8, T_s = 22 and T_e = 19.09. Therefore, ES8 = +2.91

By working from the last to the first event in the schedule, the remaining ES value are calculated. They are given in Table 13.4. For example, for event 7:

T_s = 22 (T_s at event 8) – duration (3.17 weeks) = 22 – 3.17 = 18.83
T_e = the earliest finish of the activity 5–7 = 15.92
ES_7 = 18.83 – 15.92 = +2.91

TABLE 13.4 CALCULATIONS OF EVENT SLACKS

EVENT	T_e	T_s	EVENT SLACK
8	19.09	22	+2.91
7	12.5	18.83	+2.91
6	24.2	15.75	+4.09
5	24.8	14.66	+2.91
4	15.0	12.24	+2.91
3	15.0	12.24	+2.91
2	7.2	10.42	+4.09
1	0	2.91	+2.91

Step 4

According to the Central Limit Theorem, the completion time of the project is normally distributed with the mean T_e and the standard deviation S. These two values are now calculated as follows:

T_e = 19.09 weeks

$S = \sqrt{\Sigma s^2}$ for the critical activities
$S = \sqrt{(0.44 + 0 + 0.34 + 0.25 + 0.25)}$
$S = \sqrt{1.28}$
$S = 1.13$

The probability z of completing the project in 22 weeks is calculated from the following formula:

$$z = \frac{x - \mu}{\sigma}$$

where

$x = T_s$
$\mu = T_e$
$\sigma = S$

$z = (22 - 19.09) / 1.13 = 2.58$

In the probability table, a z score of 2.58 is read off as 99.5 per cent probability. Therefore, there is an almost 100 per cent probability that the project will be completed in 22 weeks.

If, for example, the scheduled completion date of the project is only 20 weeks, a z score is:

$$z = (20 - 19.09) / 1.13 = 0.81$$

The project would then have just under 80 per cent probability of being completed in 20 weeks.

AN ALTERNATIVE APPROACH TO PERT

The original concept of PERT, based on the arrow CPM method, is event-oriented. Its main aim is to ensure completion of events or milestones on time. The dependence of PERT on the arrow method may be the main reason for its loss of popularity. In CPM scheduling, the arrow method has almost entirely been superseded by the precedence method, which is not only easier to work with but it is also better supported by quality computer software.

Whether or not PERT will re-emerge as a popular planning and control technique is not clear. Perhaps its appeal could be rejuvenated by applying it on a precedence network. Let's examine this possibility.

The most obvious difference between the arrow and precedence methods of CPM scheduling is the lack of events in the precedence method. It means that rather than being concerned with events, a precedence-based PERT would focus on activities. This is probably of little relevance to the final outcome provided that the planner is able to adapt to the change.

The original concept of PERT expresses two different types of slack: activity slack and event slack. In a precedence-based PERT it would be possible to express free slack (the same as free float) and total slack (the same as activity slack or total float), but event slack would not be applicable. The process of forward and backward pass calculations, and the probability concept of PERT, would remain the same.

Let's test the validity of this on the same refurbishment project illustrated on page 275.

Figure 13.4 illustrates a schedule of the refurbishment project in a precedence format. Estimates of durations of activities together with the values of mean t_e, standard deviation s, and variance s^2 for each activity are given in Table 13.5, which is basically identical to Table 13.3.

Figure 13.4 A precedence-based PERT schedule of the refurbishment project

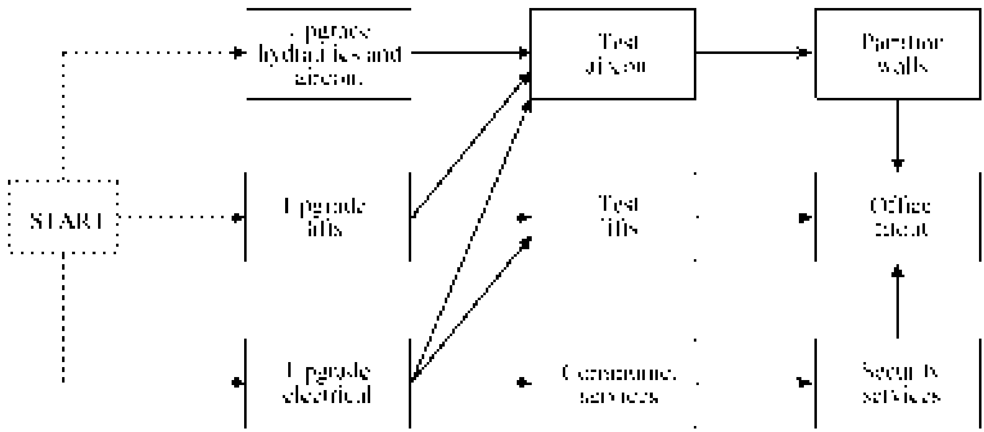
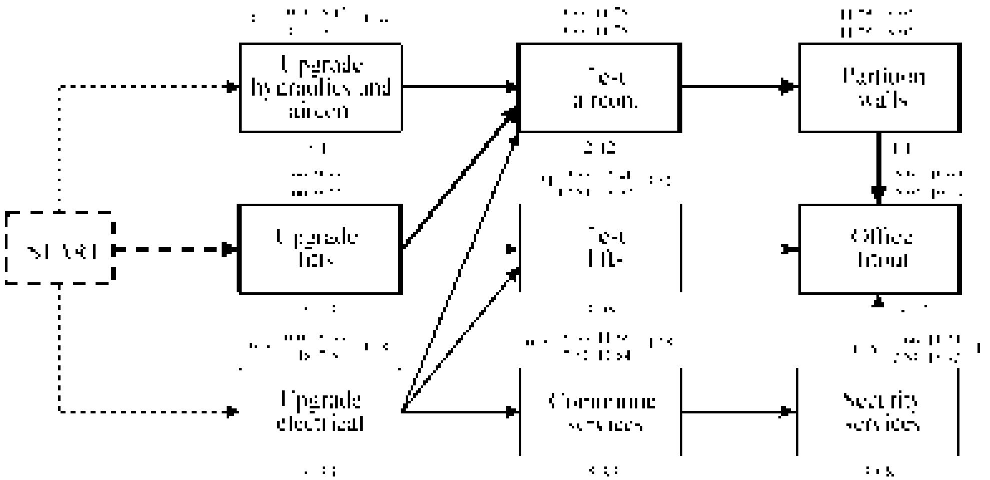


TABLE 13.5 A PRECEDENCE-BASED PERT SCHEDULE OF THE REFURBISHMENT PROJECT

ACTIVITY	a	m	b	t_e	s	s^2
Upgrade electrical	5	6	9	6.33	0.67	0.44
Upgrade lifts	8	9	12	9.33	0.67	0.44
Upgrade hydraulics and aircon.	4	5	7	5.17	0.50	0.25
Communication services	4	5	8	5.33	0.67	0.44
Test lifts	2.5	3	4	3.08	0.25	0.06
Test aircon.	1.5	2	5	2.42	0.58	0.34
Partition walls	3	4	6	4.17	0.50	0.25
Security services	2.5	3	4	3.08	0.25	0.06
Office fitout	2	3	5	3.17	0.50	0.25

The mean, standard deviation and variance values of time distributions of each activity in the schedule have been calculated in Table 13.5 above. The forward and the backward pass calculations, the critical path, and free and total slack values are given in Figure 13.5. The overall project duration and the position of the critical path are, as expected, identical to the arrow-based schedule in Figure 13.3.

Figure 13.5 The calculated PERT schedule



Since calculations of durations are the same, the values of the mean and standard deviation of the output normal curve are also the same, as is a z score and the probability of completing the project within 22 weeks.

SUMMARY

This chapter has introduced the concept of probability scheduling and control using PERT. Although the original concept of PERT was developed around the arrow method of CPM to track progress of events or milestones, the PERT method works equally well when based on the precedence method of CPM.

The PERT method, particularly the use of beta distribution and the assumption of independence among activities in a schedule, has frequently been criticised. Nevertheless, PERT's value in planning and evaluating large, particularly military, projects has successfully been demonstrated in the past.

EXERCISES

Solutions to the exercises can be found on the following UNSW Press website: http://unswpress.com.au

EXERCISE 13.1

Standard deviations and variances of activities in a project are given in the following table. What is the probability (z) that the project will be completed within 25 weeks? The project duration T_e has been calculated as 23.5 weeks.

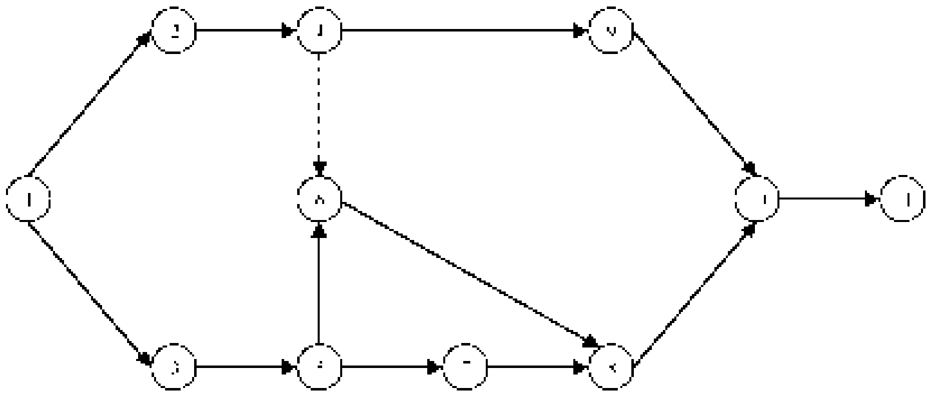
ACTIVITY	s	s^2
A	1.00	1.00
B	**1.33**	**1.77**
C	0.67	0.45
D	**0.83**	**0.69**
E	**0.50**	**0.25**
F	0.50	0.25
G	**0.83**	**0.69**
H	1.50	2.25

Activities B, D, E and G are critical.

EXERCISE 13.2

An arrow-based PERT schedule shows a sequence of activities related to the construction of a small building project. Information on durations of activities and values of means, standard deviations and variances are given in the following table. What is the probability that this project will be completed in 31 weeks?

Convert the arrow-based PERT schedule to a precedence-based PERT schedule and repeat the exercise.

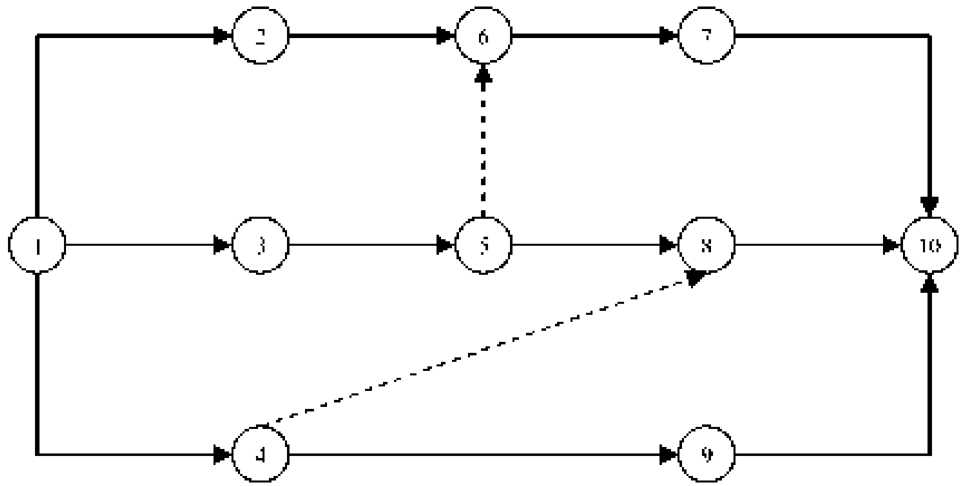


ACTIVITY	A	M	B	T_E	S	S^2
1–2	6	9	15	9.5	1.50	2.25
1–3	2	4	8	4.3	1.00	1.00
2–4	6	8	10	8.0	0.67	0.45
3–5	4	7	12	7.3	1.33	1.77
4–6	–	–	–	–	–	–
4–9	2	3	6	3.3	0.67	0.45
5–6	4	7	9	6.8	0.83	0.69
5–7	5	9	11	8.7	1.00	1.00
6–8	1	2	4	2.2	0.50	0.25
7–8	2	3	5	3.2	0.50	0.25
8–10	2	4	5	3.8	0.50	0.25
9–10	1	4	6	3.8	0.83	0.69
10–11	2	3	5	3.2	0.50	0.25

EXERCISE 13.3

Information on durations of activities in an arrow-based PERT schedule, and values of means, standard deviations and variances are given in the following table. What is the probability that this project will be completed in 32 weeks?

Convert the arrow-based PERT schedule to a precedence-based PERT schedule and repeat the exercise.



Activity	A	M	B	T_E	S	S^2
1–2	2	3	5	3.2	0.50	0.25
1–3	6	8	14	8.7	1.33	1.78
1–4	4	7	11	7.2	1.17	1.36
2–6	5	7	8	6.8	0.50	0.25
3–5	4	6	10	6.3	1.00	1.00
4–8				0.0	0.00	0.00
4–9	3	5	9	5.3	1.00	1.00
5–6				0.0	0.00	0.00
5–8	6	9	13	9.2	1.17	1.36
6–7	7	10	12	9.8	0.83	0.69
7–10	2	5	7	4.8	0.83	0.69
8–10	3	5	8	5.2	0.83	0.69
9–10	8	12	17	12.2	1.50	2.25

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