APPLICATION OF OPTIMISATION TECHNIQUES TO PLANNING AND ESTIMATING DECISIONS IN THE BUILDING PROCESS

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ABSTRACT

An integrated computer model for time and cost optimisation has been developed for multi-storey reinforced concrete office buildings.

The development of the model has been based on interviews completed with Planners, Estimators and Researchers within 2 of the top 20 (in terms of turnover) UK main contractors, and on published literature, bar charts and bills of quantities of concrete framed commercial buildings.

The duration and cost of construction of a typical multi-storey reinforced concrete office building is calculated through the first part of the integrated model, i.e. the simulation model. The model provides a set of choices for the selection of materials and plant and possible methods of work. It also requires the user to input the quantities of work, gang sizes and the quantity of plant required, lag values between activities, output rates, unit costs of plant, labour costs and indirect costs. A linked bar chart is drawn automatically by using the data available from the simulation model.

The second part of the model, (optimisation) uses the data provided by the simulation part and provides sets of solutions of time vs. cost from which the minimum project cost corresponding to the optimum project duration is calculated under the given schedule restrictions.

Linear programming is used for the optimisation problem. The objective function is set to be the minimisation of the project cost which is the total of the direct costs of all the activities creating the project and the indirect costs of the project. The constraints are formulated from the precedence relationship, lag values, and normal and crash values of time and cost for the activities supplied by the simulation model.

The simulation part has been validated by comparing and contrasting the results with those methods and practices adopted by commercial planners and estimators. The validation of the optimisation part has been undertaken by plotting time-direct cost curves from the results and checking the convexity of the curves. Additionally, the validation procedures included taking account of the opinions of practitioners in the industry on the practical and commercial viability of the model.
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LIST OF TERMS

Normal duration: The time required to complete the activity with the resources available and without any extra input.

Normal cost: The direct cost of undertaking an activity at the normal duration.

Crash duration: Time allocated to complete the activity using increased resources (Cooke (1988)).

Crash cost: The direct cost of undertaking the activity by using increased resources (Cooke (1988)).

Normal project duration: The total of the normal duration of activities required to complete the project. This is also called the least cost solution which can then be defined as the time required for completing the project at the lowest possible direct cost. (Antill, et.al (1990))

Normal direct project cost: The cost which is the total of the normal direct costs of all activities.

Normal project cost: The total cost of the project which is equal to the summation of the normal direct costs of the project and the indirect costs of the project at the normal duration.
**Crash project duration** : The duration calculated from the combination of the crash and the normal duration of activities required to complete the project.

**Crash project cost** : The summation of the direct and indirect costs of the project which are associated with the crash duration.

**The least time solution** : The shortest possible time, at the minimum cost for that completion time. (Antill, et.al (1990)) In order to reduce the time, some activities should be speeded up (crashed), but crashing all activities will cost more while giving the same duration for the completion.
CHAPTER 1
(1.1) The Problem

In arriving at any decision in the management of a project, an analysis must be undertaken of the associated problems and should take into account the management goals and objectives, and all the possible constraints and alternative solutions. Problem analysis can be achieved by utilising either qualitative methods, quantitative methods or both. While qualitative methods are based on a manager’s intuition and experience, quantitative methods are based on facts and data associated with the problem. The two methods are complementary to each other and reliable decisions can be achieved by combining the two together during the decision making.

The most important decisions in the construction industry are normally related to time and cost. Time and cost related decisions are undertaken starting from the pre-tender stage and carry right through until the end of a contract. During competitive bidding, the construction period is usually dictated by the requirements of the client and a successful tender is usually the lowest priced. However as Avery (1994) states, for the sensible contractor a successful tender is the basis from which the successfully finished project is achieved. Thus, it is vital for a contractor to arrive at a realistically achievable
minimum tender price in which the contract can be completed within the period required by the client. Thus, during the pre-tender stage the contractor has to consider a range of alternative solutions in order to satisfy the required project completion time and to arrive at realistic cost and duration estimates.

Duration and cost estimation of construction projects involve handling a number of interacting variables some of which are easily predictable and quantifiable, whereas others rely on intuition and experience. The selection of manpower, materials and plant and possible methods of work are some of the many factors which affect project duration and cost.

The complexity of the problem lies, on the one hand, in the large number of different combinations of activities required to perform a certain task and on the other hand, in the unpredictability of external influences. Furthermore, the large amount of data to be handled can render the task unmanageable.

In an industry where decisions are undertaken in very short periods of time, construction managers require decision support systems which ease the quantitative analysis during the decision making. Various computer based time and cost models which could be used in this way have been developed since the 1980s. Current
effort is directed towards integrated time and cost models where simulation, generation and optimisation methods are used.

Newton (1991) discusses the difference between these methods. 'Simulation' presents the structure of a problem where structure refers to how the problem is conceptualised in terms of its boundary, the variables considered, and the inter-relationships between variables. A set of input data is provided by the user and then the outcome is evaluated based on a range of other considerations. The 'generation method' produces a set of candidate solutions. This is a more mechanical approach where for a range of starting values, the model is capable of generating an entire collection of potential solutions. Monte Carlo Simulation is an example of simulation applied to the generation method. The 'optimisation method' evaluates a series of solutions and searches for the best solution for the given criteria. These methods will be discussed in more detail in subsequent chapters.

Each method has its limitations in providing a realistic solution to the practical problems of estimating time and cost, and future refinements are expected to reduce these limitations. One approach to improving effectiveness may be to combine two or more of the existing methods.
(1.2) Aim, Objectives and the Methodology of the Research

The aim of the project is to develop an integrated computer model which will evaluate sets of time vs. cost solutions and obtain the optimum time corresponding to the minimum cost. This involves the following objectives.

(1) To identify, in general terms, the decision making processes involved in building construction, and to determine the factors affecting the quantitative decision making in relation to time and cost estimates and to establish the relationship between project costs and duration.

(2) To review the state of art of computer based time/cost models.

(3) To develop a computer model which integrates simulation and optimisation methods. The integrated model will be utilised firstly to simulate the effects of different factors on the cost and duration of a project, and then to evaluate sets of project cost vs. duration values including optimum time corresponding to minimum cost. The first model will be combined with the latter in such a way that the input to the simulation model or the output from it will be used by the optimisation model.
It is important to consider the opinions of construction practitioners in developing such models. Thus structured interviews have been undertaken with planners, estimators and researchers from two construction companies Wimpey Construction and Kyle Stewart Ltd. (KS). Wimpey Construction have been the collaborating establishment for this research project.

(1.3) Contribution to Existing Knowledge

The main contribution of this research to existing knowledge is the combination of simulation and optimisation techniques in the evaluation of time/cost solutions.

The current development of the integrated model includes all the procedures that are required to be undertaken to determine the minimum project cost corresponding to optimum project duration. Thus, the computer model enables rapid comparison of alternative solutions that affect project costs and duration, simulates the relationships between construction activities, models the activity time/cost relationships and evaluates sets of project duration/cost solutions including minimum cost corresponding to optimum duration.

The development environment (use of an expert system shell for the simulation model) provides a good basis for future development of the model in combining the qualitative analysis,
assisted by development of the expert system, with the quantitative analysis provided by the current model.

(1.4) Main Findings of the Research

The literature review and interviews with the construction practitioners (planners, estimators, teaching company associates and plant manufacturers) produced the following findings.

(1) The cost and time significant activities for reinforced concrete multi-storey office buildings.

(2) The most appropriate estimating and planning techniques for reinforced concrete multi-storey buildings (i.e. repetitive work).

(3) The factors affecting the quantitative decision making for time and cost estimation.

(4) Interaction between estimating and planning procedures during pre-tender stage.

(5) The precedence relationships that are used while sequencing construction activities during pre-tender and pre-contract stages.
(6) Methods of accelerating a project duration, and the effect of productivity loss on activity and project costs during the acceleration of the project duration.

(7) Cost-duration relationships for the whole project and project activities.

(8) The appropriate method for optimisation of time and cost for repetitive construction during early construction planning (i.e. pre-tender and pre-contract).

(9) Formulation of the optimisation problem for multi-storey reinforced concrete office building construction to provide not only one (i.e. minimum cost vs. optimum project duration) but also sets of duration/cost solutions.

(10) The criteria that have to be considered while validating a time/cost optimisation model.

(11) The use of an expert system shell for a non expert system development and the future benefits of it.
Chapters 2, 3 and 4 comprise a review of the background literature. A general review of decision making during the construction process is discussed in Chapter 2. A state of the art review of computer based time and cost models, with emphasis on simulation and optimisation models, is presented in Chapter 3. Chapter 4 gives an overview of activity and project time/cost relationships. Chapter 5 first gives a general view of the linear programming techniques available and discusses the Simplex Algorithm that has been used for the development of the optimisation model. Chapters 6 and 7 discuss respectively the development stages and the characteristics of the simulation and the optimisation models. Validations of these models are addressed in Chapter 8. The strengths and weaknesses and future developments of the integrated model and general conclusions and recommendations for further research are outlined in Chapter 9.
CHAPTER 2
(2.1) Introduction

This chapter can be considered as an introduction to the basis of the current project.

A general overview of the decision making procedures in the building process is presented with the emphasis on the importance of decisions related to time and cost during the three stages of the construction process, i.e. pre-tender, pre-contract and contract stages. Additionally, the importance of integrated computer modelling during decision making related to project cost and duration are also emphasised.

(2.2) The Building Process

Groak (1992) describes the building process as "the organising or bringing together of a set of inputs or resource flows, and their assembly or transformation into a specified building output or product, in a given period of time, on a specified site".

The beginning of the building process involves a client/owner requiring a building. A team of designers and consultants (including architects, structural engineers and
services engineers), plan and detail the building arrangement and construction. The building contractor constructs the building from manufactured components and materials according to the specifications. The building is then occupied and used, however further building works may still be required. According to Groak (1992) and Greeno (1990) all of these activities (including manufacturing of components and materials) can be analysed in terms of the 'building process'. However, for the aim of this research the focus will be on the construction phase where it can be divided into three stages according to the decision requirements of the construction manager. These are; pre-tender, pre-contract, and contract stages. Different decisions are made by the management in each of these three stages. However, decisions made at one stage may affect the other stages of the process. For example, the tender price is decided during the pre-tender stage, and if the project is won the aim of the management team will be to finish the project within the budget limits according to the tender price and make decisions accordingly.

The decision making process during construction will be discussed later in this chapter. At this point it may be useful to look into the environment which affects these decisions.
(2.3) Construction Environment

Fellows et.al (1983) state that the construction industry has some characteristics which when taken individually are shared by some other industries. However, the combination of these characteristics creates a unique environment which requires a unique management approach during decision making. Thus, to be able to stress the importance of decision making by the contractor for the long term survival of his/her firm within the industry, it may be useful to point out the major characteristics of the industry. These can be stated as:

(1) Construction project: The construction industry is a project based industry where each project is unique and the product is sold before it is produced.

(2) Workforce: The operatives have a strong craft tradition. They have been casually employed but in recent years there have been increases in the subcontracting practice in response to fluctuating demand and employment legislation.

(3) Ease of entry to the industry: Although there is an effective form of registration and control over design consultants, there are few constraints for setting up a building contracting firm. The interim payments system during construction, extensive credit concessions for
material purchasing and highly developed plant hiring facilities mean that there is very little capital requirement. The demise of contractors is also equally easy.

(4) The nature of demand: The demand for construction is a derived demand. It is derived from the need for buildings for living, manufacturing or storing goods, or operating various services. Thus, the demand for construction is strongly related to the state of the economy, the level of interest rates and business activity. Buildings being capital items, make them targets for cuts in expenditure by both government and the private sector which leads to fluctuations in demand.

(5) Government role: The government is the biggest client of the industry. This results in government having direct control over demand for the industry. This causes demand fluctuations as governments use the construction industry as a regulator of the economy. Additionally there have been continual increases in regulations relating to building standards and land use, through building regulations and planning legislation.
Anderson (1979) states that after a management problem arises, the first step by the management will be to make an analysis of the problem which includes:

(a) a statement of the specific goals or objectives,
(b) an identification of all constraints,
(c) an evaluation of alternative decisions, and
(d) a selection of the apparent 'best' decision, or solution to the problem.

The analysis process may take two basic forms; i.e. qualitative and quantitative (see Figure 2.1).

![Figure 2.1 The Decision Making Process (Ref.: Anderson (1979))](image-url)
The qualitative analysis is based upon the manager's judgement and experience. In the quantitative analysis, the focus is on the quantitative facts or data associated with the problem and the development of mathematical expressions that describe objectives, constraints and relationships that exist within the problem.

Both of these analyses provide important information to the manager. The final decision is made depending on the comparison and evaluation of this information. While the skills of qualitative analysis usually increase with the manager's experience, the skills of quantitative analysis are normally learned by studying quantitative methods. The manager who is able to apply quantitative procedures should be in a better position in comparing and evaluating the qualitative and quantitative sources of decision information and in combining these two sources to achieve the best possible decision.

(2.5) Management Decisions During the Construction Stage

(2.5.1) Types of Management Decisions

Ansoff (1968) identifies three major categories of decision which are; operating, strategic and administrative decisions. These are defined as follows:
(1) Strategic decisions "...primarily concerned with external, rather than internal problems of the firm, and specifically with selection of the product mix which the firm will produce and the markets to which it will sell."

(2) Administrative decisions "concerned with structuring the firms resources in a way which creates a maximum potential."

(3) Operating decisions ".....usually absorb the bulk of the firms energy and attention. The object is to maximise the efficiency of the resource conversion process"

From the construction management point of view strategic decisions involve decisions such as those on markets, clients, a firm's long range survival and its policy about sub-contracting work and employing direct labour. On the other hand, administrative decisions involve how to structure responsibility, work flow, information flow, location of facilities, and obtaining and developing resources. Finally operating decisions involve allocating resources, planning and monitoring projects, and scheduling and co-ordinating sub-contractors. Although the three categories of decisions are interdependent, the following discussion will be on operational decisions undertaken during the construction phase.
(2.5.2) Decision Analysis During the Major Stages of the
Construction Phase

Decisions taken by the building contractor are normally subjected to four constraints: time, cost, the quantity and the quality of the work required. The quantity and quality of the work are defined in the project drawings and specifications. The contractor has more control over the time and cost concerned whilst performing the project activities than on the quantity and quality of work required. Bennett & Ferry (1987) stress that research has shown that decision making during the construction phase can have a significant effect on the time and cost of construction of the building.

The operational decisions are developed around three main stages of the construction phase. These are:

- Pre-tender,
- Pre-contract, and
- Contract stages.

The discussion in this section will be based on the procedures taken by large construction companies and for traditional procurement methods.
Pre-Tender Stage

Pre-tender stage can be divided into three decision making phases. These are:

(1) bidding or not bidding for a project,
(2) determining the cost and duration of a project, and
(3) determining the bid price of the project.

The first decision at this stage is on whether to bid or not on the particular project. This decision is important because of its financial consequences. The decision implies the incurring of substantial costs which may not be recovered immediately. This decision is affected by various factors like current workload of the company, workload of estimating and surveying departments, availability of the capital and resources, type, location, size and value of the project, value of own work in relation to that of nominated subcontractors and suppliers, degree of complexity of the project, time availability to prepare the tender, previous knowledge of client, architect, subcontractors, and market conditions at that time (Cooke (1984)). However, Odusote and Fellows (1992) and Shash (1993) found four factors that were considered as the most important ones by the main contractors. These are need for work, number of competitors, experience in such projects, and client related factors like ability of client to pay, good relationship with the client and ability to provide
client satisfaction. Shash (1993) also states that while considering these factors during their decisions, most of the top contractors depend on subjective assessment in making bid/no bid decisions.

After the decision to tender, the degree of commitment by the company on that particular project is decided by a group consisting of the general manager/director, the chief estimator, the contracts manager, the planning engineer, the buyer, the office manager and the job estimator.

At this stage, the principal role of the management team is estimating and planning. Harris and McCaffer (1995) state that while estimating evaluates the use of resources in terms of cost, planning evaluates the use of resources in terms of time and putting both together is necessary to obtain cash flow. Additionally, the estimates and pre-tender programmes are used for production planning, cost control and valuations if the contract is won.

The last decision at the pre-tender stage is in determining on the bid price or in other words in the adjudication of an estimate. Adjudication is "the action taken by the management to convert an estimate into a tender" (Code of Estimating Practice, CIOB (1983)). Under a traditional cost plus mark-up pricing model, the mark-up is a certain percentage to cover the office
overheads, contingencies and profit. Shash (1993) states that subjective assessment is undertaken by most of the top contractors for this decision and the most important factors affecting the decision on the mark-up size are complexity of the project, the risk involved due to the nature of the work, and the current workload.

(2.5.2.2) Pre-Contract Stage

If the contract is won, pre-tender planning is repeated in a more detailed form. The sequence of activities, and the duration of each activity for the whole project is determined again. The resources (man power, plant and material) are scheduled in order not to have them too early or too late on site, which may affect cost for the former and duration for the latter.

(2.5.2.3) Contract Stage

During the contract period decisions are made on a relatively reduced time scale. Each section of the pre-contract plan stage is examined in relation to immediate needs and a detailed plan is produced. Although greater accuracy is possible for the decisions taken during the contract stage there is still need for subjective decision making. This is due to the complexity and variability of the available alternatives and the
need to analyse them and select the most appropriate ones as quickly as possible. Qualitative analysis is also required when interruptions occur because of reasons like strikes, equipment breakdown or inclement weather. The analysis may include re-determining activity sequences, re-estimating duration, arranging new delivery programmes for materials and plant, re-arranging subcontractors and relating the revised time scales to the cost and financial plans.

(2.6) Importance of Integrated Time/Cost Models During the Decision Making Process at the Major Stages of the Construction Phase

While pre-tender and pre-contract stages mainly consist of planning and estimating, monitoring and control are involved during the construction stage. Due to their dependence on planning, monitoring and control are the most important management roles.

Harris and McCaffer (1995) describe monitoring as the act of checking the actual progress and actual resource usage against planned progress and planned resource usage. On the other hand, control is the act of taking decisions to alter the likely future outcome and bring the project back on the planned schedule, i.e. decisions relating to the rescheduling of activities, the
reordering of activities, and the altering of resources to change the duration of activities.

As stated by Cusack (1981), the uncertain nature of the construction process makes it impossible to treat planning and control as separate functions. Oxley and Poskitt (1986) state that "it is possible to have a plan without control but in this case it will lose most of its value. On the other hand it is impossible to have control without a plan."

Longmuir (1993) emphasises the fact that when the project time and cost information are maintained independently, they are controlled independently too. This not only creates unnecessary work for project management personnel but it also slows down the decision making process and makes decisions less reliable due especially to the need to analyse information from two sources. At this point the benefits of utilising integrated computer time and cost models become apparent due to the fact that firstly computer models would provide the facility for rapid analysis of quantitative data and secondly integration of time and cost would overcome the difficulties that arise in merging separately assembled data from different sources.

The integration of time and cost estimation is of great importance during decision making at the pre-tender stage. As Farrow (1985) and Avery (1994) stress, for the sensible
contractor a sensible tender is the basis from which the successfully finished project will be achieved, providing a satisfactory level of return on the way. Farrow (1985) then goes on to say that when the period of execution of the contract is stated in the tender documents, the tendency may be to base the estimate on it without much question. However, it is for the benefit of the contractor to check if the given time is sufficient or too little or too much, within the context of ordinary working conditions and the resources available. If the time is too little, the extra cost of achieving completion in the required time by way of overtime or shift working or other means must be calculated, if indeed the required completion date is realistic. In the case of more time for completion being allowed than required, an offer to complete before the given date may influence the placing of a contract and should certainly produce a competitive tender by reducing supervisory, overhead and other time based contract costs. Thus, Zakieh (1991) states that the main aim in the cost estimates and pre-tender planning should be to establish the optimum way of sequencing the job in order to arrive at a minimum price. This can be achieved by utilising integrated computer models which estimate cost and duration values, analyse their relationships and optimise them. More detailed discussion is undertaken later in this thesis where in Chapter 3, the current developments in computer time-cost models based on simulation and optimisation methods, in Chapter 4, the relationship between cost and duration and also in Chapter 6 the
procedures undertaken for determination of cost and duration values are discussed. In addition the development of the integrated model for time and cost estimation and their optimisation are discussed in Chapters 6, 7 and 8.

(2.7) Summary

Reliable decisions can only be achieved by exercising quantitative and qualitative analysis together during the decision making process. However, in an industry where most management decisions have to be taken in a short period of time and with many uncertainties, employing qualitative analysis alone may be found to be much quicker and simpler even though employing quantitative analysis in addition may prove to be more effective. Therefore the facility for rapid analysis of the quantitative data is essential as this would enable immediate comparison of alternative solutions using time and cost criteria. At this point the use of computer modelling arises as it is not practical and usually impossible to analyse the relevant data manually. However, it should be stressed that use of computer models only provides the information on which managers can base their decisions and arrive at expected outcomes. Thus, they are an aid, and not a replacement to the manager's decision making role.

Decisions during the construction phase are generally related to time and cost and decisions related to the one also
affect the other. Thus, it is beneficial for the contractor to utilise time and cost computer models which integrate the estimates of cost and duration values, analyse their relationship and even optimise them in order to arrive at more reliable decisions in shorter periods of time.

The following chapters describe the development of a computer model which will, enable rapid comparison of alternative solutions using time and cost criteria, simulate the relationships between construction activities, and determine optimum time and cost solutions.
CHAPTER 3
(3.1) Introduction

The literature review showed that various computer based time and cost models have been developed since the 1980s (Cusack (1984), Bennett and Ferry (1987), Newton (1991)). Current effort is directed towards integrated time and cost models where simulation, generation and optimisation methods are used together.

Newton (1991) discusses the difference between these models. 'Simulation' represents the structure of a problem where structure refers to how the problem is conceptualised in terms of its boundary, the variables considered and the inter-relationships between variables. A set of input data is provided by the user and then the outcome is evaluated based on a range of other considerations. The 'generation method' produces a set of candidate solutions. This is a more mechanical approach where for a range of starting values, the model is capable of generating an entire collection of potential solutions. Monte Carlo Simulation is an example of simulation applied to the generation method. The 'optimisation method' evaluates a series of solutions and searches for the best solution for the given criteria.
Each method has its limitations in providing a realistic solution to the practical problems of estimating time and cost, and future refinements are expected to reduce these limitations. One approach to improving effectiveness would be to combine two or more existing methods which is the principal feature of this research. Thus, in this chapter the discussion will focus on the current developments in computer time-cost models based on simulation and optimisation methods. The combination of these two methods are used in the development of the computer based time and cost model developed during this research.

(3.2) Simulation Models

According to Shannon (1975) simulation is the most powerful tool to model the operation of complex processes or systems. The same author defines simulation as "the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system".

So et.al (1994) state that simulation "is a method of sampling from the possible outcomes in such a way that the sample represents the whole".
According to Pritsker (1986) and Lutz and Hijazi (1993) simulation is the process of designing a mathematical and logical model on a computer to permit inferences to be drawn about the system.

Lewis (1987) sums up the above definitions as follows: "The technique of simulation involves building a computer model of the real system to be investigated. The model uses data structures and algorithms to represent those features of the system which are relevant to the problem in hand. The simulator is able to manipulate the model, changing system parameters and observing the influence of these changes on other aspects of the model. The observations will allow predictions to be made about the effects of making similar changes in the real system".

Lewis (1987) then continues by saying that the simulation model of a project (or part of a project) may be used like conventional planning tools such as CPM and PERT to predict the overall duration of the work and the timing of various events during the course of the work. It may also be used to forecast the variation in the level of required resources during the course of the work. Additionally it is stated that simulation is useful for answering 'what if' questions. Finally Lewis (1987) points out that by using simulation modelling, it is possible to build features which influence the progress of work but whose
influence is difficult to quantify like the effects of weather, or variations in labour productivity.

Benefits of modelling with simulation can be generalised in the following statements:

(1) By simulation, a range of probabilities can be obtained rather than a single answer based on different input data.

(2) Simulation can support both deterministic and stochastic (i.e. probabilistic) input elements.

(3.3) Simulation of the Construction Process

According to Bowen et.al (1987) and Beeston (1987) time-cost models are 'realistic cost models' and they must consider the cost implications of the way in which the buildings are physically constructed, and that different construction methods significantly affect cost. Such models must simulate the construction process. According to Beeston (1987) there are three main approaches to be considered when building the time/cost models. These are:

(1) Representation of the decision making process of the planners when calculating the plant/labour requirements of a design.
(2) Attachment of costs to activity networks.
(3) Detailed simulation of the construction process.

According to Beeston (1987) both representation of the decision making process of the planners and attachment of costs to activity networks, gradually approach the ideal detail of simulation of the total construction process.

Ndekugri and Lansley (1992) group simulation studies of the construction process under four main headings.

(1) Gaming simulation at the project level.
(2) Simulation at the corporate level.
(3) Simulation at the level of site operations.
(4) Non gaming simulation at the project level.

Gaming simulation at the project level covers the simulation models that are designed for teaching and training purposes. Simulation at the corporate level includes the simulation issues relating to strategy, organisation structure, various functional areas of management, and interaction of a head office with its various sites. Both gaming simulation and simulation at the corporate level are not relevant to this research so they will not be covered in detail.
(3.3.1) Simulation at the Level of Site Operations

Under this heading is included the simulation of construction operations like concreting, bricklaying and earthworks. Although this area of simulation modelling is not directly related to the level with which this research is concerned, it may still be useful to discuss it, as it is concerned with time and cost of construction activities.

The basic approach to this type of simulation involves the application of Monte Carlo simulation both to the estimated duration of the individual tasks in the operations and to the duration of delays. Baxendale (1984) defines Monte Carlo simulation as "a method of obtaining an approximate solution to a numerical problem by the use of random variables". The aim in using Monte Carlo simulation has been to incorporate the effects of uncertainty and variability on time and cost.

For the development of models to simulate site operations, CYCLONE, which is a system of notation for modelling (see Halpin and Woodhead (1976)) and communicating information regarding various processes, has been frequently used. CYCLONE provides the basis for dynamic modelling of construction operations in terms of flow networks.
Riggs (1980) used CYCLONE to simulate the construction operations for a pavement construction. Different time and cost values are determined by employing an automatic sensitivity analysis which allows the user to vary the resources. For the output rates of the resources the BETA distribution is used.

Ndekugri and Lansley (1992) states that CYCLONE has also been used to develop an interactive simulation system called INSIGHT. To use INSIGHT the required operations should first be recorded on videotape. This is then played back and using CYCLONE notation and computer graphics a flow chart of the operations are drawn. The means and distribution of the duration of each task or delay is then determined by the use of the flow chart. This data is then used to determine outputs and costs.

Dabbas and Halpin (1982) integrated a CPM network software system, PROJECT I, with the CYCLONE simulation methodology which provided improved estimates for activity duration for multi-storey office buildings. This approach consists of taking a construction operation or process and breaking it down into a series of repetitive activities that involve the cyclic movement of or sharing of resources and thus determining activity duration by using CYCLONE. The activity duration can also be input into the PROJECT I system directly by the user without employing the CYCLONE part. Additionally the direct and indirect costs for resources are required to be input. The whole system
calculates different time and cost values for varying numbers of vertical material transportation systems of concrete hoists, hoppers, trucks and buggies.

(3.3.2) Non Gaming Simulation at the Project Level

The simulation models that can be categorised under this area are the most relevant developments to this research. The common objective of the simulation studies under this heading is to determine the duration of the construction projects. The costs are also included within some of these models.

The first formal model of the construction process was the Gantt chart. After that, the Critical Path Method (CPM) and the Programme Evaluation and Review Technique (PERT) were developed (Neale and Neale (1989)).

(3.3.2.1) CPM and PERT

Carr and Meyer (1974) state that modelling with CPM means that the activities are represented graphically in a network indicating the dependencies among them. The completion time required for the project, the critical path of activities which determine the project completion time and the float in the schedule are calculated using the network dependencies and estimated activity duration.
Although PERT is based on the same logic as CPM it includes (during the calculation) the additional component of variability of activity duration that form the network.

Atkin (1987) states that the attractions of PERT and CPM are firstly the ease with which the technique can be applied, and secondly the ability to accelerate activities through trade-offs of time and cost (see Chapter 4).


(1) A large number of activities have to be presented in a CPM network which makes it very difficult to visualise the project. This also requires large computing facilities.

(2) The continuity of work cannot be guaranteed by employing CPM techniques. This is due to the fact that a gang with a fast production rate has to be idle while waiting for the slower gangs.

(3) While employing CPM techniques, only critical activities are shortened to minimise the project cost. Shortening only the critical activities would increase their production rate and
similar activities at different stages would then have different production rates.

(4) The use of the CPM and PERT network methods involves the emphasis being placed on finding an optimal solution based on the shortest project duration. The optimal solution in construction usually involves the minimisation of resource utilisation and cost which does not necessarily coincide with the shortest duration.

(5) While emphasis is put upon minimising the total duration of a project, unrealistic assumptions are made that resources are unlimited.

(6) The models represent only one plan of how the project can be performed.

(7) PERT requires three activity duration estimates instead of one and this makes it less preferable to the user.

Carr and Meyer (1974) point out the disadvantages of using CPM and PERT for modelling repetitive construction. The authors state that the CPM technique is a powerful tool for projects with two criteria, which repetitive construction often lacks. These two criteria are:
(1) The number of activities must be commensurate with the complexity of the project.

(2) The activities must have clear dependencies which define the required progress through to project completion.

O'Brien et al. (1985) also state that while modelling multi-storey building construction with CPM, the scheduler can easily develop an anticipation of the result before the diagram is completed. This is due to the fact that once the 'typical floor' is reached in a multi-storey project, construction becomes a series of production cycles. Resources required for an activity move from one cycle to another. Additionally, Suhail and Neale (1994) emphasise that the application of CPM failed to respond to the frequent changes in the sequential operations between the repetitive units and to maintain work continuity for the gangs.

By contrast Jaafari (1984) does not agree with the above authors. He states that despite numerous criticisms, project and construction planning should be done using CPM scheduling. He argues that the main factors affecting successful planning are a realistic estimation of the productivity of crews, the inclusion of sufficient time buffers between dissimilar trades, and that CPM is found to be equally useful as a planning tool for linear or repetitive projects. Jaafari (1984) then points out that the
actual productivity in construction varies considerably and in a random manner, even in repetitive work.

(3.3.2.2) Line of Balance (LOB)

Carr and Meyer (1974) state that there are many characteristics of LOB that make it a practical modelling tool for the construction of repetitive work. It is easy to calculate and to understand and can therefore be useful for decisions by field personnel. The technique is compatible with the other modules of an information system and increases the efficiency of their use. The LOB can be adapted to the characteristics of different project types and is a valuable addition to the methods available to the construction manager in directing his projects.

Like Carr and Meyer (1974), Kavanagh (1984) agrees that LOB is a superior model to CPM for repetitive construction. However, Kavanagh (1984) states that LOB was designed to model simple repetitive production processes and, therefore, does not fit into a complex construction environment. Additionally, Reda (1990) and Lutz and Hijazi (1993) point out another limitation of LOB. This is that project duration is reduced with little regard for project cost which means that the LOB is not a preferable model to simulate the construction process. Finally, Al Sarraj (1990) showed that the use of the LOB method had been very limited in
construction management as the method was not in an acceptable form for general applications in construction.

(3.3.2.3) Integration of CPM and LOB (CPM/LOB)

Suhail and Neale (1994) present a new methodology CPM/LOB that integrates the advantages of CPM and LOB by the float times calculated by CPM in the LOB. It is stated that the model is based on rates of completion relating to the units of resource, and it can produce enhanced LOB information incorporating float times by utilising the resource managing capacity of CPM. The authors say that "the virtue of the method lies in its invulnerability to changes in the sequence of work and to its ability to maintain work continuity for the working squads involved in the repetitive activities. Although the method is stated to be used by the first author in various projects, no record has been found of further research in this area or of its acceptance within the industry.

(3.3.2.4) Bar Charts

Kavanagh (1985) states that there is an inverse relationship between the complexity of a model and the extent to which the model is used. This can be easily seen with CPM and PERT which are not preferred by the end user. In fact bar charts
are the most widely used method of representing a project's plan and progress.

Carr and Meyer (1974) also point out that bar charts are preferred more by the construction practitioners than any other method. The authors state that the construction practitioners like bar charts because they are easy to read and to keep up to date. However it is also stated that the bar chart will indicate those activities which are behind schedule but it will not indicate the effect of such delays upon the completion of the project or the units within the project. It can be concluded from Carr and Meyer's comments that the bar chart is a much better tool for planning than for controlling.

During the interviews conducted by the present author it was observed that linked bar charts are still the most preferable tool to use for planning.

(3.3.3) The Current State of the Art in Computer Based Models For Non Gaming Simulation at the Project Level

The recent computer developments in the area of simulation modelling are outlined below.

Bowen et.al (1987) proposed a computer model based on PERT-like networks representing the cost as it occurs on the network.
The model was to be developed by using artificial intelligence to link sub networks representing different designs. Although the model is aimed to be used mainly in the early design stage, it is stated by the authors that there is no reason why it cannot in addition be used for planning and controlling of construction. However, there has been no further literature to suggest that this model was actually developed by the authors.

COCO (Costs Of Contractors Operation) is a model which has been developed by Beeston (1987) which simulates the logical decision process used by several construction planners when allocating resources to a project. It is stated by the author that although this model does not simulate the construction process, it provides a further step towards this by simulating the construction plan.

Bindslev (1987) discusses a computer cost model called PROXIMA. The cost values for different activities can be stored in data files and these can be called back or updated. Additionally one module of the system provides activity bar charts from the input of activity descriptions and also planned and actual start and finish times. In addition network analysis is provided. However there is no connection between the modules of time calculations and cost storage.
Lewis (1987) states that to be accepted by the industry, a simulation system should meet the following requirements.

(1) It should require only elementary computing skills from the user.

(2) It should be capable of modelling a wide range of construction situations, using concepts familiar to a construction practitioner.

(3) Its use should be both rapid and simple to learn.

(4) The computer hardware required should be readily accessible to the practitioners.

Lewis states that ICONS (Interactive CONStruction Simulation) meets the first two requirements. ICONS is built in two parts. ICONS BUILD and ICONS RUN. ICONS BUILD operates from user input by building a diagram representing the real system. The real system is presented from inputs of labour, plant and material requirements, and the direction of flow of materials and activities under that system, or the sub activities under an activity. After the data entry ICONS BUILD checks the consistency of the data and if no errors are found, the file is compiled and executed by ICONS RUN. Finally the total cost and duration is determined. After the end of a run, a variable can be changed and
the same procedure can be applied to obtain a new time and cost value. Lewis states that by comparing the results obtained from the different simulations, the optimum time and cost can be determined. However, it is stated that in most real life cases optimisation is a complex problem involving many combinations of variables. Thus, use of practical experience during the input of different variables can reduce the number of combinations which need to be examined. However, this is an empirical method but not a systematic optimisation approach to achieve an optimum value.

Ahuja and Nandakumar (1985,1986) discuss a computer model PRODUF (project duration forecast) that is used to simulate the expected occurrence of the uncertainty variables. The model requires the input of a strategic and a tactical plan and historical data on the significant uncertainty variables like weather, crew absenteeism, and the learning curve. The activity duration are then revised and the probability of completing the project by a particular schedule date is provided. The limitations of the model resides in the dependency of the output on the reliability of the historical data available on uncertainty variables.

Carr (1979) also developed a stochastic computer simulation model called MUD. The model provides estimates of activity duration, activity criticality, project duration, and estimates of the uncertainty for each of these time estimates. The
simulation occurs in two steps. The first step is the simulation of the effect of uncertainties which are not dependent on the time of the year. Monte Carlo simulation is used at this stage. The second step is the simulation of the effect of the weather which is dependent on the calendar date. This is achieved by simulating the daily progress of the project according to the dependencies of a CPM network. Sensitivity correlation values which relate the effects of weather parameter occurrences to the daily progress of the activities are estimated by the user. Then, by correlating the sensitivity corrections with actual weather data samples, the progress of the project is simulated. These applications provide statistical summaries of multiple iterations which give estimates of the mean and standard deviation of the activity and project times.

Bennett and Ormerod (1984), and Bennett and Ferry (1987) also discuss a computer simulation model which considers the effect of variability and interferences on the project duration. The data required by the model are an activities network, the work content of each activity in resource and monetary terms, and a management plan. It is stated that at the early planning stages, all the information may not be available, however the model can draw results from the available information. The total time and cost of the project is then determined from the simulation by considering time and cost of each activity which is either input by the user or implemented by the resources
allocated to it. The uncertainty is taken into account by quantifying variability and interference. After a number of simulations, CPS produces the output in the form of minimum, maximum and mean duration and costs. However, one disadvantage of the model is that it does not produce a bar chart for the user to see the most likely outcome.

Computer simulation has also been used with the line of balance technique for the planning of linear construction projects. A system called SIREN (simulation of repetitive networks) was developed by Kavanagh (1985). The user inputs a precedence diagram for the repetitive unit (e.g. one floor of a high rise building) and additional 'sub-networks' that are not part of the repetitive sequence. From this information the whole network is produced automatically. The various crews are simulated as queuing to carry out the activities. Additionally Monte Carlo simulation is used to model the effects of crew and equipment availability, the learning curve and the weather, on the project duration. This characteristic of the model is stated to be in a way creating a disadvantage as it hinders the attainment of the objective that the system be user friendly. However, there are some important limitations to this model. These are principally that: no information is provided about activity criticality; during resource allocation priority is not given to the critical activities; the programme does not delay activities that are floating. However it is stated that most
paths in the repetitive work will be close to critical. Only one crew of labourers are assumed to be working in an activity. Finally, the model presumes that the repetitive units are independent. However, it is stated that eliminating this restriction would make the model intolerably complicated.

(3.4) Optimisation Models

Atkin (1987b) states that the next step after modelling time and cost relationships is to seek the least-time or least-cost solution, or some combination of the two, such that it represents a compromise. The author then states that this is a matter of seeking an optimum which could be regarded as the 'best' solution, although in practice the client may make a different selection which is closer to satisfying his/her needs. Thus, the author argues that in this case in order to satisfy the client's needs one cannot optimise. The concept of satisfying is stated to be the 'good enough' solution by both Atkin (1987b) and Simon (1969). However, the case for producing a mathematical optimum is not undermined, as Simon (1969) and Atkin (1987b) admitted that "no one should satisfy if they could just as easily optimise."
(3.4.1) Dynamic Programming

Atkin (1987a, 1987b) then discusses a time/cost model which was at its experimental stage. The model reflects a design and production approach in which large numbers of possible design options are evaluated to produce the feasible sub-set. It is stated that from the computational point of view it is significantly difficult to handle the large number of possibilities. This is handled by division of the single problem into a series of sub problems.

It is stated that the model overcomes the incompatibility of the different formats used by architects and quantity surveyors for design elements and contractors' work packages, by modelling both of these within a network representation. The network contains only mutually exclusive activities in their simplest form. For most practical applications concurrence of activities must be accommodated and this is modelled by the .AND. condition.

The activity on node is combined with activity on arrow representations. This allows interactions between successor and predecessor activities. The author states that this characteristic of the model overcomes the weaknesses of elemental cost planning where construction implications are not taken into account.
It is stated by Atkin (1987a) that dynamic programming is employed, which reduces the amount of computational effort that would be needed if the network was to be evaluated by CPM or PERT algorithms. It is also pointed out that an advantage of dynamic programming is that the activities with the least cost and least time paths are adopted, whereas with CPM or PERT all activities must be performed. The least time and least cost paths required to complete the network are identified by a backward process of computation. The process starts with the finish of the project and progresses stage by stage until the start is encountered. The optimum solution is achieved by calculating and comparing the times and costs of all possible policies at each stage, to achieve the combination of the activities with the lowest overall cost. However Atkin points out that during the optimisation process individual dates are not calculated until the main work has been completed. This means the exact optimum value is not known until the start is encountered.

Robin (1975) and Butcher (1967) also developed time/cost models by using dynamic programming. However, the model developed by Butcher (1967) can only deal with combinations of sequential and parallel links which makes it unsuitable for construction projects where there are complex interrelationships and interdependencies between activities. On the other hand the model developed by Robinson (1975) deals with non increasing activity
functions where the complexity of the model makes it impossible to manage even for small projects.

Moselhi and El-Rayes (1993) discuss an optimisation model which determines the optimum crew formation for each repetitive activity that minimises the project cost of repetitive construction projects. This is achieved by evaluating the impact of different project duration acceleration strategies on the overall cost. These strategies include increasing the crew size, overtime work or additional shifts. Dynamic programming is used for the model development. The solution from the model is achieved in two stages. Firstly local minimum conditions for different resource allocations are identified by a forward process. After that, a backward process is undertaken to find out the overall minimum cost situation and optimum crew formation for each repetitive activity that provide the overall minimum cost situation.

(3.4.2) Integer Linear Programming

Cusack (1985) states that many attempts have been made to model the relationship between project cost and duration by using integer linear programming. It is stated that from these models the most mathematically precise ones were those developed by Meyer and Shaffer (1965). This model has been refined by Cusack (1984). According to Cusack (1985) the major problems
faced with these models are the large number of constraints and variables that are generated. However, these numbers are reduced by the use of breakthrough points on the cost curve. Thus although this model is improved than the earlier models, particularly in relation to the number of variables, it still maintains the following disadvantages.

(1) The analysis required to derive the constraints from the network is too complex for an average user.

(2) Large computing facilities are required due to the large number of constraints and variables.

(3) The potential practitioners "will reject out of hand any sophisticated mathematical model" (Cusack (1985)).

It is stated that to increase the acceptance by the practitioners it seems logical to look for less complex solutions. "The assumption being that it is justifiable to sacrifice ultimate mathematical rigour in favour of operational acceptability." Thus, Cusack (1985) developed a heuristic approach which was achieved by modifying the computational procedures and simplifying the output information of the model suggested by Fondahl in 1961. It is stated that the model by Fondahl was of limited application as it was manually based and also it could not deal with non-linear cost curves. Cusack's
model not only eliminates these disadvantages it also overcomes the disadvantage that once an activity is speeded up during one stage of the crashing it remains speeded up although that may not be necessary. Cusack's algorithm allows an activity to be relaxed after it becomes non critical. Thus, unnecessary expenditures are eliminated.

Additionally, Karshenas and Haber (1990) propose a linear integer model for the optimisation of project schedules. It is stated that by the use of this model the least cost schedule with the optimum duration will be obtained. This is achieved by minimising the total project cost which is the objective function. The constraints show firstly that each activity exists, secondly the project's logic is maintained, and finally (at any point in time) more resource units are idle than the number that are mobilised. However, it is stated by the authors that for application of the model to real life it must be computerised.

(3.4.3) Heuristic Modelling

It is stated by Cusack (1985) that the principal challenge is to schedule the activities in such a way that the cost is minimal and the project finishes before a given time T. By using the heuristic approach the project is firstly scheduled for a minimum cost and the project is speeded up by one time unit. Most of the activity curves are assumed to be piecewise linear (see...
Section 4.5.3) with no more than three pieces. Ten precedents for each activity are allowed. The piecewise time-cost functions, precedence relationships, average costs and activity descriptions are required to be input by the user. The output from the model can be obtained in three different formats. Firstly there is a full data listing. Secondly there is an abbreviated output which consists of the first and last project durations only, plus the activity number, the duration, the cost, the activity description, the critical path, the project duration and the project costs. Thirdly, there is a detailed output which provides the output data as listed, as abbreviated output for every project duration. The advantage of this approach is stated to be that it is only necessary to have an algorithm that accelerates the project one unit of time, and thus time-cost relationships are identified over a whole range of unit time values and not just at one point. It is also pointed out by Cusack (1984) that a heuristic approach is not only simpler computationally, it also produces results that are directly comparable with the integer linear programming models at the minimum cost duration. It is concluded by the author that the goal in achieving optimum solutions should be in producing schedules that are valuable to practising managers as a basis for decision making.

Sunde and Lichtenberg (1995) discuss a present value cost-time model to obtain optimal activity duration corresponding to minimum project cost. The model is based on determination of
activities to be crashed in order to increase the benefit of the project by considering the resource limitations on the project. The model requires firstly the resources to be levelled by the user. Then, the time intervals are checked one by one from start to finish of the project, to identify under-use of the resources and to improve the resource use. The activities, in the intervals with under use of resources, are crashed one time unit at a time. Then, the change in the net benefit of the project is determined and the most economical solution is chosen. The iteration continues in each time interval until the resource capacity is reached or net benefit is not increased. The effects of uncertainty and correlation between activities are also considered in the model by representing these by fictitious activities at the end of the project. The authors compare this model with the CPM time/cost trade off method. It is stated that the new model shows a considerable increase in benefit for the projects tested when compared with the CPM method. However, it is also stated that although the new model is practical, it may overlook the optimal solutions.

(3.4.4) Linear Programming

Sebestyen (1993) states that, in most cases, for practical reasons, techniques could be based on linear models.
Skibiniewski and Armijos (1990) and Haidar et al. (1994) compare the accuracy of optimum solutions by using both linear and non-linear programming and find linear programming satisfactory for the early phases of large construction project planning processes. Two models have been developed by Skibiniewski and Armijos (1990) to compare these two programming approaches. The objective of the two models was to determine the optimum construction costs when there is the possibility of employing various resources for the construction project. The first approach employs multi-linear functional relationships between costs and time for performing specific activities. The variables employed are the different number of hours for each activity and the quantity of work. Piecewise linear approximations are used in this approach. On the other hand, the second approach uses non-linear functions between cost and duration of an activity and uses historical data concerning such functions. Although the relative accuracy of the minimum cost solutions have been found to be similar in both models, it is stated that the differences in absolute accuracy between the results from both models may arise due to estimation error in piecewise linear procedures and due to the varying quality of historic data regarding duration and cost of activities.

Perera (1980) also discusses the application of linear programming. The linear programming model, formulated from a linked bar chart is used to compress networks to achieve
reduction of project duration while keeping the total cost increase to a minimum. The main advantage of the computer model is stated to be its ability to solve time-cost trade off problems for overlapping precedence networks.

(3.5) Summary

The current developments in time and cost modelling have been discussed in this chapter. Particular emphasis has been given to the simulation models developed for the construction process and the optimisation models which aim to minimise the total project cost.

Non-gaming simulation at the project level includes the most relevant applications to this research. CPM, PERT, LOB, bar charts and integration of CPM and LOB have also been discussed. The advantages and disadvantages of these models was considered by emphasising their application to planning multi-storey buildings (CPM/PERT are not suitable), their adaptability with cost modelling (LOB is not suitable) and their acceptance by the industry (use of bar charts is the most widely adopted technique).

The review of state of art computer simulation in this area showed that four simulation models combine both time and cost parameters at the project level (COCO, PROXIMA, ICONS and CPS).
Although the strengths and weaknesses of each model differ the weaknesses can be generalised as not combining the time and cost calculation modules, not presenting the duration output in the form of a bar chart or network diagram and finally disregarding the user friendliness due to the complicated structure of the model.

The discussion of optimisation models also showed that each of these models has strengths and weaknesses which are generally due to the strengths and weaknesses of the programming technique used. However, the choice of the programming technique depends on the expected characteristics of the model which includes the assumption related with time-cost relationships. Thus, the choice of the optimisation technique to satisfy the aim of this research will be discussed in Chapter 5 following the discussion in Chapter 4 related with the time-cost relationships for the construction of a project.
CHAPTER 4
(4.1) Introduction

It has been discussed in Chapter 2 that the most important parameters that have to be considered by a contractor at the construction stage are time and cost. Generally, the contractor has to prepare the estimates in such a way that the required quality of work is achieved under circumstances where the project cost is as low as possible and the project duration is as short as possible. To be able to determine the 'best' combination of time and cost for the completion of a project, one should be aware of the relationship between the two.

The total cost of completing a project consists of both direct and indirect cost elements. Direct and indirect costs of a project change if project completion time is shortened or extended, resulting in different total cost values for different project completion times. The time/cost trade-off for the construction of a project will be discussed in this chapter with reference to time/cost curves.
(4.2) Direct Costs

Direct costs are related to the material, labour and plant required to carry out the activities. Direct costs are directly related to the individual activity and the shorter the activity duration, the greater in general is the total direct cost of finishing that activity. The activity duration can be shortened by;

(1) increasing or changing resources to provide a greater output of work,
(2) employing overtime and shift work, or
(3) using a different method of construction.

Cusack (1981) states that using a different method of construction does not necessarily mean an increase in cost. The author gives pre-cast as opposed to in-situ wall/floor construction as an example.

Direct costs of plant and labour are calculated in the same manner. They depend on the hourly use, and the total direct cost is calculated by the hourly labour/plant cost (referred to as unit cost in this research) multiplied by the total number of hours the plant/labour is required (see Section 6.7). On the other hand the direct cost of a particular type of material is calculated by multiplying the unit cost of that material with the
quantity required (which includes purchasing, handling and transportation costs). These can be expressed as:

\[ C_1 = U_1 \times D_1 \times N_1 \]
\[ C_p = U_p \times D_p \times N_p \]
\[ C_m = U_m \times Q_m \]
\[ DC_i = (C_1)_i + (C_p)_i + (C_m)_i \]

where:
- \( C_1, C_p, C_m \) = Costs of labour, plant and material respectively.
- \( U_1, U_p, U_m \) = Unit costs of labour, plant and material respectively.
- \( D_1, D_p \) = Duration required, respectively, for labour and plant to work on the particular activity.
- \( N_1, N_p \) = Number of, respectively, labour and plant required to work on the particular activity.
- \( Q_m \) = Quantity of material required for an activity.
- \( DC_i \) = Direct cost of the activity \( i \).

As it has been previously stated direct cost of a project \( DC_p \) is the total of the direct costs of all activities and can be expressed as the summation:

\[ DC_p = \sum_{i=1}^{N} DC_i \]

where:

\( N \) = Number of activities in a project
(4.3) Indirect Costs

It is stated in the Code of Estimating Practice (1983) that the indirect costs of a project will increase in direct proportion to the increase in the project duration. The indirect costs depend on the length of time that staff, plant and equipment are required on site. The project indirect costs consist of those costs which depend on the duration of each activity, and also on the duration of the project as a whole.

There have been different approaches to what is included within the estimation of project indirect costs. Scott and Kagiri (1992) state that labour indirect costs, overheads and profits are included. Tah et.al (1994) state that the indirect costs consist of site overheads, general overheads, profits and allowances for risks. The authors also emphasise that the general approach adopted by main contractors is to prepare their estimates according to the Code of Estimating Practice. While estimating the project tender price under the Code of Estimating Practice there are three main areas which are considered in addition to the direct cost calculations. These are project overheads, head office overheads and profit. It is stated in the Code of Estimating Practice (1983) that the sum of head office overheads and profit are included in the mark-up for the tender price, which leaves the project overheads under Preliminaries as indirect costs. It has been observed that this is the approach
taken by the interviewed companies in the current research. During the interviews, the planners stated that the items under 'Preliminaries' in the Bill of Quantities are considered as indirect costs. The indirect costs are determined after the calculation of the project duration and the direct costs. The main headings for the items included under indirect costs by the main contractors interviewed for the majority of the projects are listed below.

(a) Cost of supervision.
(b) Hutting on site.
(c) Erect and dismantle the huts.
(d) Compound areas for huts to stand on.
(e) Security.
(f) Hoarding and temporary fencing.
(g) Notice board.
(h) Telephone instalment and rental.
(i) Office furniture and equipment.
(j) Plant used (Plant schedule).
(k) Erect and dismantle plant
(l) Scaffolding
(m) Transport of offices/plant
(n) Sundries: includes samples, testing, protection, survey equipment, printing drawings, cleaning the building, drying out the building, attendance on nominated sub-contractor.
(o) Temporary facilities: includes water, electricity, drainage, access road, temporary works.

It should be noted here that groupings of items relating to project overheads differ from one company to another, therefore for this research indirect costs are taken as the items stated under 'Project Overheads' in Code of Estimating Practice (1983) which is applicable to a wide range of companies. The following main groups of items are given under the major headings as follows:

1. Employers requirements: This includes all accommodation and other specific requirements by consultants and clerk of works.

2. Management and staff: This includes all costs of employing personnel that have not been included in unit rates of head office overheads.

3. Site accommodation: The cost of hiring or purchasing the accommodation is calculated in this section where the layout of the site and time period of various elements of accommodation are important factors to be considered.

4. Attendant labour and miscellaneous items: It is sometimes easier for the contractor to group various miscellaneous
labour matters under project overheads rather than pricing them in unit rates. This usually happens when a number of trades require attendance from the main contractor or when dealing with unloading and distribution of materials. Additionally, cleaning during and at the end of the construction, attendant labour of the subcontractor and the drivers of plant can also be included here.

(5) Miscellaneous labour costs: These include the allowances made for travel, fares, subsistence, attraction money depending on the availability of the labour, additional bonus payments and exceptional inclement weather.

(6) Facilities and services: The installation and removal of services together with consumable items and time related costs, and also services and facilities such as cleaning, security and testing may be included here.

(7) Temporary works: The costs of temporary access and hoarding which include recurring costs to maintain access and the costs of final removal. Thus, the duration of the project and the characteristics of the area are very important in estimating these.
(8) Mechanical plant: The cost of mechanical plant is generally taken as a direct cost. However any mechanical plant missing in direct cost calculations can be included here.

(9) Non-mechanical plant: The cost of the non-mechanical plant is included under direct costs. However, some may be regarded as consumable items and charged fully against the contract.

(10) Sundries: This includes any unusual features related to the project that do not fall within any of the other categories.

(11) Contract conditions: There may be allowances that need to be included to account for fixed price or fluctuating prices. These are included in the indirect costs under this heading.

The indirect costs are calculated on both a fixed-charge basis and time-related basis. It is stated by Pilcher (1992) that most of the companies utilise their own methods to calculate the indirect costs.

It was established by the author during interviews with the construction companies that the indirect costs of a project are usually between 8 and 15% (in extreme cases up to 20%) of the direct costs. Scott and Kagiri (1992) and Tah et.al (1994) also
emphasise the importance of taking indirect costs as a percentage of direct costs.

(4.4) Total Project Cost

The total project cost includes both direct and indirect costs of the project, and is given by the simple summation:

\[ C_p = DC_p + IC_p \]

where;

\( C_p \) = Total project cost
\( DC_p \) = Direct cost of the project
\( IC_p \) = Indirect cost of the project

(4.5) Activity Direct Cost Curves

To be able to draw any time/cost curve one should know the different cost values corresponding to different possible durations. For activity direct cost curves these values are generally determined by assigning different quantities of plant and labour to the activity or by employing overtime or shift work as discussed in Section 4.2, i.e. starting from normal duration and then crashing the activity until crash duration is reached. In this way, points corresponding to different time/cost values can be located on a time/cost graph and can then be connected to form a time/direct cost curve.
(4.5.1) The Theoretical Direct Cost Curve

It is stated by Antill and Woodhead (1990) that "if there are a great many possible ways to crash an activity, the time/cost curve will approach the continuous ideal theoretical curve" (See Figure 4.1). However, in practice it is not possible to obtain such a curve as a sufficient number of points cannot be obtained to produce a continuous curve.

(4.5.2) The Multi-linear Direct Cost Curve and the Assumption of Convexity

The practical representation of the theoretical curve is therefore in a multi-linear form. The additional cost per day of time saved, i.e. the slope of the curve, is not uniform over the duration of the activity. The slope of the lines get steeper as the activity duration is crashed more, i.e. activity is crashed firstly by considering the cheapest way to crash and moving to the next cheapest and so on. Antill and Woodhead (1990) state that the multi-linear relationship between duration and direct cost of an activity is the most frequent condition in practical circumstances (see Figure 4.2). On the other hand, Cusack (1981) suggests that a high 90% of the activities in a construction project have multi-linear time/cost curves with no more than three sections.
As is seen from Figure 4.1 and 4.2 the time and cost curve is automatically assumed to be convex. The assumption for this is
explained below. The application of the procedure can be found in Section 4.6. Figure 4.3 shows the section of the curve in Figure 4.2 between all normal and lowest crash cost which can be applied for both activity and project cost curves.

![Figure 4.3 Convex Time/Cost Curve](image)

<table>
<thead>
<tr>
<th>Time - Cost Slope</th>
<th>Pseudo Activity</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta c_3/\Delta t_3 )</td>
<td>( A_1 )</td>
<td>( A_1 )</td>
</tr>
<tr>
<td>( \Delta c_2/\Delta t_2 )</td>
<td>( A_2 )</td>
<td>( A_2 )</td>
</tr>
<tr>
<td>( \Delta c_1/\Delta t_1 )</td>
<td>( A_3 )</td>
<td>( A_3 )</td>
</tr>
<tr>
<td>( (\Delta c_1+\Delta c_2+\Delta c_3)/(\Delta t_1+\Delta t_2+\Delta t_3) )</td>
<td>Total A</td>
<td>Total Project</td>
</tr>
</tbody>
</table>

Such an approximation causes a multi-linear relationship associated with different intervals.

Physically, (pseudo) activity \( A_1 \), as seen in Figure 4.3 above must be crashed first, then \( A_2 \) and finally \( A_3 \). Since the CPM computational procedure effectively searches the critical
activity to find the one that can be crashed the cheapest, it will naturally choose the (pseudo) activities in the proper order $A_3, A_2, A_1$ since the cost slope increases as in going from $A_3$ to $A_2$ to $A_1$ for any convex curve. (It does not have to be 3 (pseudo) activities, the curve can be divided into any appropriate number of activities.) However, if the time/cost curve was not convex, then the cost slopes may be lowest for $A_1$ and highest for $A_3$ as shown in Figure 4.4 below. In these cases, the CPM computational procedure would crash the activities in a sequence that would not be physically meaningful, i.e. in the order of $A_1, A_2, A_3$.

![Cost vs. Duration Graph](image.png)

**Figure 4.4 Concave Time/Cost Curve**

(4.5.3) **Linear Direct Cost Curve**

Although a multi-linear relationship between duration and direct cost of an activity has been stated to be the most frequent situation in practice, the different slope values can be approximated for simplicity to provide a linear relationship (see Figure 4.5 (a)). Additionally in some cases such as overtime
work which results in an increase in direct costs (Ahuja (1984)), a linear relationship exists without any approximations (see Figure 4.5 (b)).

(a) Approximation of (b) Linear Time/Direct Cost Multi-linear Relationship Relationship

Figure 4.5 Activity Time/Direct Cost Relationship

(4.5.4) The Discrete Direct Cost Curve

A discrete relationship between duration and direct cost of an activity occurs when there are a limited number of ways of achieving the completion of the activity. As demonstrated in Figure 4.6 there is no relationship between the normal and crash costs. Thus the direct cost curve becomes discontinuous. Ahuja (1984) states that this may be the case in a tunnelling project where by using an extra piece of plant the cost can jump up; or a pile driving job where additional cost would represent the mobilisation or demobilisation of an additional pile driving rig.
The direct cost and duration of a project depends on the cost and duration of each activity. Thus, it can be stated that the relationship between project duration and direct cost is dependent on each activity duration-direct cost relationship, and on the manner in which the project direct cost curve is affected by the activity direct cost curves. Therefore, the project direct cost curves should be produced by taking account of the following situations.

1. Activity curves which are linear.
2. Activity curves which are multistage linear.
3. Activity curves which are discrete.

Like activity curves, project curves are also obtained by crashing the activities and finding different project time/cost values. However, it should be noted here that while producing
project direct cost curves, it is not acceptable to calculate the normal project duration and cost and then crash all the activities or any activity desired. This would result in an increase in the project direct cost but not necessarily in the decrease of the project duration. Thus, before starting to crash activities, the first step should be to determine the activity to be crashed first. The procedure for crashing activities and plotting the project direct cost-duration curve is as follows (Ahuja (1984)).

(1) Determine the normal and crash duration and cost for all activities, and determine normal project duration and cost.

(2) Identify the critical path for the normal duration.

(3) Compute the cost slope of each activity using the following expression;

\[ CS = \frac{CC - NC}{ND - CD} \]

where:

- \( CS \) = Cost slope
- \( CC \) = Crash cost
- \( NC \) = Normal cost
- \( ND \) = Normal duration
- \( CD \) = Crash duration

(5) Shorten the critical activity with the lowest cost slope and plot the values of duration and direct cost on the curve.
Crash each activity until either its crash duration is reached or a new critical path is formed.

(6) When a new critical path is formed, shorten the combination of activities with the lowest combined cost slope. If several parallel paths exist, shorten each of them simultaneously to reduce the overall project duration.

(7) At each step check if there is float time for any of the activities. These activities can then be expanded which would reduce the direct cost.

(8) Compute the new project duration and cost for each step. Plot these points on the project time/cost curve.

(9) Continue crashing until it is not possible to shorten the duration.

(4.6.1) When The Activity Curve is Linear

Figures 4.7 to 4.9 demonstrate the development of the project time/direct cost curve when the activity curves are linear. Figure 4.7 shows the activity duration to direct cost relationships for the three activities of the project. In Figure 4.8(a), the network diagram is drawn for the project when all activities are in their normal duration mode. In Figure 4.8(b) the network diagram shows that Activity 1-2, which has the lowest
cost slope on the critical path, is crashed from its normal duration of 20 units of time to 10 units. After Activity 1-2, Activity 2-3 has the lowest cost slope. Normally this activity has to be crashed on its own. However, crashing Activity 2-3 itself would not decrease the project duration. Thus, Activity 1-3 is crashed at the same time (Figure 4.8(c)). It should be noted here that the network principles outlined all through this thesis are based on the format shown in Figure 4.8 (a).
Figure 4.7 Linear Activity Direct Cost Curves
Earliest finish of Activity 1-2
Duration of Activity 1-2
Latest finish (LF) of Activity 1-2
Float = (LF-ES)-duration

Begining event of Activity 1-2
Latest start (LS) of Activity 1-2

Activity 1-2 is crashed Cost=2550 All critical

Activities 2-3 & 1-3 are crashed Cost=4570 All critical

Figure 4.8 Network Diagrams While Crashing the Activities with Linear Direct Cost Curves
Figure 4.9 Project Direct Curve When Activity Direct Cost Curves are Linear

Figure 4.9 shows the direct cost curve for the example in Figure 4.7. The curve is convex and the slopes of the lines get steeper as the project duration is reduced. It is stated by Antill and Woodhead (1990) that "this is a characteristic of parametric linear programming problems". The assumption of convexity is explained by the fact that any concave portion in the curve may be due to an arithmetic error or a logically incorrect order during the crashing procedure (The assumption of convexity is discussed in Section 4.5.2 ). It is also stated by the authors that there may be cases where artificial cost slopes are assigned to activities which result in non-convex sections and where non-optimal curves are obtained. However, non-convexity and non-optimality are beyond the scope of this research and will not be discussed in detail.
When there is a multi-linear relationship between duration and direct cost of an activity (see Figure 4.2), different cost slopes of the activity should be considered separately. When the crashing of the section with the lowest cost slope is completed, crashing does not necessarily continue with the other sections of the same activity (see the example in Figures 4.10, 4.11, 4.12). The sections with different slopes are considered as different activities and the procedure is exactly the same as discussed in Section 4.6.

When multi-linear activity curves are used instead of linear activity curves for the crash calculations, more accurate project direct cost results are determined as more points are taken into account. Greater values of project direct costs are produced when a multi-linear activity curve is linearized. This can be observed when the values obtained in the examples in Figures 4.7 and 4.10 are compared. The slope values for the curves in Figure 4.7(b) & 4.7(c) are the linear approximations of the multi-linear slopes in Figure 4.10(b) & (c). Thus, the final cost value in Figure 4.9 is greater than the value obtained in Figure 4.12.
Figure 4.10 Linear & Multi-Linear Activity Direct Cost Curves
All normal  Cost = 2250  All critical

Activity 1-2 is crashed  Cost=2550  All critical

Activities 2-3 and 1-3 are crashed Cost=3650  All critical

Figure 4.11  Network Diagrams While Crashing the Activities with Linear & Multi-Linear Direct Cost Curves
Activities 1-3 and 2-3 are crashed  

Cost = 3970  All critical

Activity 1-3 and 2-3 are crashed  

Cost=4510  All critical

Figure 4.11 (continued) Network Diagrams While Crashing the Activities with Linear & Multi-Linear Direct Cost Curves

Figure 4.12 Project Direct Cost Curve When the Activity Direct Cost Curves are Linear & Multi-Linear
When the project consists of activities with discrete direct cost curves the importance given to the cost slope does not apply. When the apparent cost slope of the discrete point activity curve is the lowest, and the network model does not allow a complete jump of the activity duration from normal to crash point, the activity with the second lowest cost slope has to be crashed first. The activity with the discrete time/cost curve can be crashed as soon as the network model allows a complete jump. The application of this process can be found in Figure 4.13.

Figure 4.14 shows the different stages of network diagrams while crashing the activities to achieve a decrease in the project duration. It starts with all the normal durations (Figure 4.14 (a)), then shows the situation when Activity 1-3 is crashed (Figure 4.14(b)), as crashing Activity 1-2 from 20 to 10 days would result in increased cost but not in decrease in the project duration. Then Activity 1-2 is crashed together with Activity 1-3. Finally Activity 1-3 and Activity 1-2 are crashed. The result from crashing this activity can be seen in Figure 4.15 i.e. when the full jump occurs for the crashing of the activity, it causes a discontinuity in the project direct cost curve.
Figure 4.13 Discrete & Linear Activity Direct Cost Curves
All normal Cost = 2200 1-3 is critical

Activity 1-3 is crashed Cost=2400 All critical

Activities 1-2 & 1-3 are crashed Cost=3200 All critical

Figure 4.14 Network Diagrams While Crashing the Activities with Discrete & Linear Direct Cost Curves
Activity 1-3 & 2-3 are crashed    Cost=3640    All critical

Figure 4.14 Network Diagrams While Crashing the Activities with Discrete & Linear Direct Cost Curves

Figure 4.15 Project Direct Cost Curve When the Activity Direct Cost Curves are Discrete & Linear
(4.7) Total Project Cost Curves

The discussion in the previous sections are related to direct cost curves. To obtain a total cost curve for a project, the indirect project costs are plotted on the same curve and the indirect costs for each duration are added to the direct costs of that duration and the total cost versus duration curve is obtained. In Figure 4.16 both direct and indirect costs have continuous ideal theoretical curves.

It has been established during interviews with construction organisations conducted by the author and also, by authors like Antill and Woodhead (1990) and Pilcher (1992), and Code of Estimating Practice (1983), that indirect costs are frequently taken as being directly proportional to time. Thus, Figure 4.17 (a) and (b) show more practical and realistic curves than does Figure 4.16.

Finally, Figure 4.17 (c) and (d) present the most simplistic relationship between duration and costs of a project. According to Juresca (1967) it is more practical to represent the time/cost relationships linearly. He states that this is justified due to the fact that both cost and time can only be estimated and that "greater precision in a calculation, which would go beyond the accuracy of the original estimates, simply cannot be justified". This approach is also supported by Pilcher (1992) where such a curve is stated to be preferred by most of the construction companies. The interviews conducted by the author showed that this approach had also been exercised by the two construction companies which were consulted.
Figure 4.16 Theoretical Project Cost-Duration Curve

Figure 4.17 Practically Used Project Cost-Duration Curves
Figure 4.17 (continued) Practically Used Project Cost-Duration Curves
The procedure to obtain new values of total project cost by crashing activities follows the same steps for direct project cost calculations as discussed in Section 4.6. However the change in indirect costs also has to be considered to get a total cost figure. To achieve this the following steps are undertaken.

(1) When activity is crashed for $n$ days, the indirect cost of the project is decreased by $\Delta IC$. This is determined by the following expression:

$$\Delta IC = (n \times \frac{NIC}{D})$$

where;

NIC = Project indirect cost at normal project duration.
D = Project duration

(2) The new project cost is calculated by adding the current direct costs to the current indirect costs.

Figures 4.17 (b) and (c) show different total cost points that can be obtained while crashing activities. These are:

(1) Normal project duration-cost point : Point $(d_1, c_1)$ - 4.17(a)
(2) The least time solution point : Point $(d_3, c_3)$ - 4.17(b)
(3) The all crash solution point : Point $(d_3, c'_3)$ - 4.17(b)
(4) The minimum cost point : Point $(d_2, c_2)$ - 4.17(a)
The minimum cost point can also be detected from Figure 4.17 (a), (c) and (d) where the total project curve reaches a minimum point \((d_2,c_2)\) and then starts rising again. The minimum cost point provides some indication of the optimum level of effort. The optimum time corresponding to minimum total project cost can be determined as demonstrated in the example below.

Table 4.1: Example of Normal and Crash Cost-Duration Values of Project Activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>Normal Time (day)</th>
<th>Crash Time (day)</th>
<th>Normal Cost (£)</th>
<th>Crash Cost (£)</th>
<th>Cost Slope (£/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>8</td>
<td>4</td>
<td>500</td>
<td>800</td>
<td>75</td>
</tr>
<tr>
<td>2-4</td>
<td>4</td>
<td>2</td>
<td>300</td>
<td>400</td>
<td>50</td>
</tr>
<tr>
<td>1-3</td>
<td>3</td>
<td>2</td>
<td>300</td>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td>3-4</td>
<td>6</td>
<td>3</td>
<td>800</td>
<td>1000</td>
<td>66.6</td>
</tr>
</tbody>
</table>

Indirect cost/day = £50

Table 4.2: Direct, Indirect and Total Cost Values While Crashing the Project Activities

<table>
<thead>
<tr>
<th>Duration (a)</th>
<th>Direct Cost (£)</th>
<th>Indirect Cost (£)</th>
<th>Total Cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 12</td>
<td>1900</td>
<td>600</td>
<td>2500</td>
</tr>
<tr>
<td>(b) 10</td>
<td>2000</td>
<td>500</td>
<td>2500</td>
</tr>
<tr>
<td>(c) 9</td>
<td>2075</td>
<td>450</td>
<td>2525</td>
</tr>
<tr>
<td>(d) 6</td>
<td>2500</td>
<td>300</td>
<td>2800</td>
</tr>
<tr>
<td>(e) 6</td>
<td>2700</td>
<td>300</td>
<td>3000</td>
</tr>
</tbody>
</table>
Table 4.2 shows the direct, indirect and total costs of the project for Figures 4.18 (a), (b), (c), (d) and (e). It is seen that the minimum total project cost (£2500) is reached when project duration is at 12 and 10 days. In this case 10 days would be the optimum time in the context that it is the shortest project duration corresponding to the minimum total project cost.
Figure 4.18 Total Cost Values with Network Diagrams While Crashing the Activity Durations

Figure 4.18 Total Cost Values with Network Diagrams While Crashing the Activity Durations
Activity 1-2 and 3-4 are crashed  Total Cost = 2800
All critical

Activity 1-3 is crashed    Total Cost = 3000
1-2 & 2-4 are critical

Figure 4.18 (continued) Total Cost Values with Network Diagrams
While Crashing the Activity Durations
(4.8) Summary

Time and cost are the most important parameters to be considered for a contractor during the construction of a project and these two parameters are closely interrelated.

The total project cost includes direct and indirect costs. Project direct cost is the summation of the direct costs of all activities. Direct cost of an activity consists of costs of materials, labour and plant to undertake that activity. Direct cost of an activity generally increases (mainly due to the labour productivity loss (discussed in Chapter 6)) when the activity is accelerated by employing more labour/plant or overtime/shift work. On the other hand, indirect costs, which are generally considered as 'Project Overheads' do not depend on the duration of each activity but on the duration of the whole project. As the project duration is accelerated, generally, the direct costs of the project increase and the indirect costs decrease (and visa versa).

Theoretically, activity direct cost curves are presented in a non-linear convex form. However, multi-linear or linear curves are preferred more in practical circumstances. On the other hand a linear relationship is generally exercised for the indirect cost-project duration relationship. Aggregation of direct and indirect cost values results in a total project curve in which
the cost value reaches a minimum point at a particular duration (optimum duration). However, it is time consuming to prepare time/cost curves and find optimum duration corresponding to minimum cost, manually. On the other hand by utilising computer time/cost models reliable results can be achieved in a rapid manner.
CHAPTER 5
(5.1) Introduction

The discussion in Chapters 2, 3 and 4 has provided the foundations for determining the technique that is most suitable for the development of the integrated computer model.

The discussion in Chapter 3 shows that various models have been developed for the purpose of achieving the minimum project cost and optimum project duration. Dynamic modelling, non linear programming, linear programming, and heuristic modelling are the techniques that are mainly used to develop the optimisation models. According to Lutz and Hijazi (1993) all of these techniques have two common benefits. Firstly, they can be used for modelling both before and during the project to forecast project duration and project costs. Secondly, they have the capability to investigate output variation as input elements change.

To be able to choose the most suitable programming technique for the objectives of this research, the first important criterion to consider is the relationship between activity time-cost. This can be considered to be either linear or non-linear (see Chapter 4). However, a linear relationship is normally assumed between activity time and cost for the following reasons:
(1) Non-linear cost curves are essentially 'theoretical cost curves' due to the fact that in practice it is not possible to obtain such curves. This is because there are only a limited number of ways in which time and cost relationships can be investigated and thus only a finite number of points can be defined (see Section 4.5.1).

(2) During the interviews conducted by the author, the planners confirmed that in practice a linear relationship is always assumed between project duration and costs.

(3) Skibiniewski and Armijos (1990) and Haidar et.al (1994) (see Chapter 3) have established that linear programming provides results as reliable as non-linear programming, especially for the early phases of large construction planning processes.

The assumption of linearity between project duration and costs means that non-linear programming must be rejected as a possible choice. Dynamic programming, heuristic modelling, integer linear programming and linear programming are methods that can be used when a linear relationship is assumed between project time and costs.
All of the programming techniques mentioned above have their advantages and disadvantages, some of which have been discussed in Section 3.3. All of the advantages and disadvantages have been considered in relation to the objectives of the current research and for this the linear programming technique is found to be the most suitable one. The following sections discuss the reasons for this choice.

**Dynamic programming:**

Jelen (1970) states that "dynamic programming is an optimisation technique that is especially applicable to the solution of multistage problems". Computations are carried out in stages which reduce their total amount. Taha (1989) states that as each stage of the problem is considered independently, these stages must be linked in a manner that guarantees a feasible solution both for each stage and for the entire problem.

Lutz and Hijazi (1993) emphasise that the advantages of dynamic programming are that it is not constrained by linear assumptions and it can be readily computerised. Conversely, Taha (1982) and Lutz and Hijazi (1993) stress the fact that stylised input is required for each situation and also output needs to be converted into a graphical format to be easily interpreted by the
end user. Finally Taha (1989) emphasises that dynamic programming is based on such powerful optimisation principles that it is not adequate for solving the general linear programming problem.

**Heuristic methods**: 

Heuristic methods are stated to be the alternative solution to the mathematical methods of dynamic, integer linear, linear and non-linear programming to handle large networks directly. The heuristic approach provides a less complicated mathematical procedure.

During the literature review (see Section 3.3.2.1) and the interviews, it was concluded that firstly, networks are not the best approach for planning and programming the construction of multi storey building projects (repetitive construction), and secondly bar charts are preferable to any other planning techniques used by the construction planners. Thus, it was decided that the results from the simulation part would be presented in the form of a linked bar chart. In addition, applying a heuristic approach based on a network would require additional computational effort and time, and would make the computer model more complicated for the end user. Although a heuristic approach to the current project could still be applied without the use of network presentation, application of linear programming was preferred. This is because firstly, it would
provide more mathematically accurate results when duration and cost are estimated under the same assumptions related to the approximation of piecewise direct cost curves and the linear relationship between indirect costs and project duration. Secondly and more importantly it was found to be a more straightforward procedure from the model development standpoint.

**Integer linear programming:**

Integer linear programming can deal with the problems in which some or all of the variables can have non negative integer values only. It could have been used in this research by rounding up the time, cost and lag values to the nearest integer. As the rounding of these values is a common practice by the construction planners, that would not affect the results substantially. However, it is stated by Taha (1989) that the performance of models based on integer programming has not been as successful as the linear programs, especially when the size of the problem increases. This is because although several finite algorithms have been developed for the integer linear problem, none of them are uniformly efficient from the computational standpoint especially due to the effect of round off error.

Due to the reasons discussed in this section, linear programming was chosen for the optimisation part of the integrated computer model.
(5.3) Standard Form of Linear Programming Models

The process of solving any optimisation problem can be stated by the 'input-process-output' model (see Figure 5.1).

![Figure 5.1 The Model For Optimisation Problems](image)

To use linear programming the input (i.e. the variables and constraints) and the output (i.e. the objective function (see Figure 5.2)) should satisfy three main characteristics. These are:

1. The objective function is one of either maximisation or minimisation and is a linear function of the decision variables.

2. The constraints are in the form of linear inequalities or equalities.

3. All the decision variables are non-negative.

![Figure 5.2 Linear Programming Model](image)
However not all the problems that can be solved by linear programming methods are presented in the standard form with the above mentioned three characteristics. Thus, to obtain a standard form one should:

(1) Convert an inequality equation to an equality by adding a slack variable (for inequalities of 'less than or equal to' \( \leq \)) or by subtracting a surplus variable (for inequalities of 'greater than or equal to' \( \geq \)).

For example:

\[
\begin{align*}
\text{x}_1 + 2\text{x}_2 & \leq 6 \quad \rightarrow \quad \text{x}_1 + 2\text{x}_2 + s_1 = 6, \quad s_1 \geq 0 \\
\text{x}_1 + 2\text{x}_2 & \geq 6 \quad \rightarrow \quad \text{x}_1 + 2\text{x}_2 - s_1 = 6, \quad s_1 \geq 0
\end{align*}
\]

(2) Make the right hand side of an equation positive if it is negative, by multiplying both sides by -1.

For example:

\[
\begin{align*}
2\text{x}_1 - 3\text{x}_2 = -5 & \rightarrow -2\text{x}_1 + 3\text{x}_2 = 5 \\
2\text{x}_1 - 3\text{x}_2 < -5 & \rightarrow -2\text{x}_1 + 3\text{x}_2 > 5
\end{align*}
\]

(5.4) Methods for Solving the Linear Programming Problems

Various authors like Jelen (1970), Lau (1988), Taha (1989) and Urry (1991) have discussed the methods of solving linear problems in which all use exactly the same procedures. In this
chapter, the procedures are discussed by taking Taha (1989) as a basis.

(5.4.1) The Graphical Method

The graphical method is practical only for the problems with two variables. However, it provides the basis for the more advanced methods. The following example shows the steps taken in the graphical method (Taha (1989)).

ex:

Maximise \( z = 3x_1 + 2x_2 \)

Constraints:

\[ x_1 + 2x_2 \leq 6 \] \hspace{1cm} (1)
\[ 2x_1 + x_2 \leq 8 \] \hspace{1cm} (2)
\[ -x_1 + x_2 \leq 1 \] \hspace{1cm} (3)
\[ x_2 \leq 2 \] \hspace{1cm} (4)
\[ x_1 \geq 0 \] \hspace{1cm} (5)
\[ x_2 \geq 0 \] \hspace{1cm} (6)

The procedure starts by plotting the feasible solutions (see Figure 5.3). The solution space is shown by the area ABCDEF. Each point within or on the boundary of the solution space ABCDEF satisfies all the constraints and is a feasible solution.
To find out the optimum solution, the direction in which the objective function increases for a maximisation problem (the objective function decreases for a minimisation problem) should be observed. This is done by plotting parallel lines representing the objective function, i.e. different values to \( z \) (see Figure 5.4). The parallel lines are moved upwards to the point where any further upwards movement would result in a none feasible solution. It is seen in Figure 5.4 that the optimum solution occurs at point C. C is the intersection point of lines 1 and 2. Therefore the values of \( x_1 \) and \( x_2 \) are calculated by solving the simultaneous equations:

Figure 5.3 Graph Showing the Solution Space
\[ x_1 + 2x_2 = 6 \]
\[ 2x_1 + x_2 = 8 \]

Thus, \( x_1 = \frac{10}{3} \) and \( x_2 = \frac{4}{3} \)

Therefore, \( z = \frac{38}{3} \)

![Figure 5.4 Finding the Value of the Objective Function by Using Parallel Lines](image)

(5.4.2) **Simplex Method and Simplex Algorithm**

The fundamentals of the Simplex Method are based on a graphical solution where the optimum solution is associated with a corner, i.e. the extreme point of the solution space.

The Simplex Method involves starting at a feasible corner (extreme point) which is normally the origin, and moving from one feasible corner to another, (adjacent corner point), until the optimum is reached.
In the standard model the number of equations \((m)\) is less than the number of unknowns \((n)\). The number of unknowns \((n)\) includes surplus and slack variables.

Geometrically, the corner points are created by the intersections of the boundary planes. To identify the corner points from the standard form, \((n-m)\) variables are set to be equal to 0 and the standard equations are solved for the remaining \(m\) variables. However, Taha (1989) states that a requirement for selecting \((n-m)\) variables to be set equal to zero is that the remaining \(m\) variables have a unique non-negative solution. The variables that are set to 0 are called non-basic variables. The remaining ones are called basic variables. The unique solutions resulting from setting \((n-m)\) variables to 0 are called basic solutions. A feasible solution is where a basic solution satisfies the non-negativity restrictions.

The Simplex method deals with basic and feasible solutions by moving from one basic solution to another where each basic solution is related to another by an iteration. A Simplex Algorithm with iterations is used to solve the problems and the optimum value is reached after a number of iterations.

For an easy understanding of the details of the Simplex Algorithm, it is useful to see how one can move from one basic solution to another (i.e., from one corner point to another).
This can be achieved by referring to the example below and putting the constraints into the standard form as discussed in Section (5.2).

The standard form for the constraints is:

\[
\begin{align*}
  x_1 + 2x_2 + s_1 &= 6 \quad \text{(1)} \\
  2x_1 + x_2 + s_2 &= 8 \quad \text{(2)} \\
  -x_1 + x_2 + s_3 &= 1 \quad \text{(3)} \\
  x_2 + s_4 &= 2 \quad \text{(4)} \\
  x_1, x_2, s_1, s_2, s_3, s_4 &\geq 0
\end{align*}
\]

Maximise \( z = 3x_1 + 2x_2 + 0s_1 + 0s_2 + 0s_3 + 0s_4 \)

In Figure 5.3, corner points A and B are adjacent. Table 5.1 lists the non-basic and basic variables associated with the two points.

<table>
<thead>
<tr>
<th>Extreme Point</th>
<th>Non-basic (zero) variable</th>
<th>Basic variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( x_1, x_2 )</td>
<td>( s_1, s_2, s_3, s_4 )</td>
</tr>
<tr>
<td>B</td>
<td>( s_2, x_2 )</td>
<td>( s_1, x_1, s_3, s_4 )</td>
</tr>
</tbody>
</table>

It can be seen from the table that (adjacent) point B can be generated from point A by exchanging two variables. Non-basic \( x_i \)
takes the place of basic $s_2$ in $A$. Thus $x_i$ which is the entering variable becomes basic and $s_2$ the leaving variable becomes non-basic at point $B$.

Depending on the above discussion, Taha (1989) summarises the steps of the Simplex Algorithm as follows.

**Step 1**: Determine a **starting basic feasible solution** by using the standard form and setting $(n-m)$ appropriate (non-basic) variables at zero level.

**Step 2**: Select an **entering variable** from among the current (zero) non-basic variables which can improve the value of the objective function when increased above zero. If none exists, the current basic solution is optimal, then stop. Otherwise, go to step 3.

**Step 3**: Determine the new basic solution by making the entering variable basic and the leaving variable non-basic. Go to step 2.

The above steps are examined in more detail by the help of the previous example, using the following steps.

**Step 1**: In the example the constraints were put into the standard form.
The standard form of the constraints are summarised in Table 5.2. It should be noted here that as all the constraints in this problem are in the form of "less than or equal to" inequalities, it is easy to set basic variables which consist of slack variables. The others are non-basic variables. The problems with "greater than or equal to" inequalities will be discussed in Section (5.3.2.1).

Table 5.2 The Standard Form of Constraints and Objective Function (After Taha (1989))

<table>
<thead>
<tr>
<th></th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$s_1$</th>
<th>$s_2$</th>
<th>$s_3$</th>
<th>$s_4$</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$</td>
<td>1</td>
<td>-3</td>
<td>-2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$s_1$</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>$s_2$</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>$s_3$</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$s_4$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Step 2:

(1) Select a column with the smallest negative (for maximisation) or the largest positive (for minimisation) element in the objective function equation row. This is called the 'entering column' (see Table 5.3).

(2) Divide the positive elements in the 'entering column' into the corresponding numbers in the last column. Select the row
with the smallest ratio. This row is called the 'pivot equation' (see Table 5.3).

(3) Locate the pivot element. That is at the intersection point of the 'entering column' and the 'pivot equation' (see Table 5.3). It is always positive.

(4) Divide the elements in the pivot equation by the pivot element. This gives a new pivot equation. Interchange the non-basic variable of the 'entering column' with the basic variable of the 'pivot equation' (see Table 5.4).

(5) For all other rows, follow (see Table 5.5) the equation below:

\[ A = B - C \times D \]

where;

A: New equation
B: Old equation
C: Entering column coefficient
D: New pivot equation
Table 5.3 Table Showing Entering Column, Pivot Equation, and Pivot Element (After Taha (1989))

<table>
<thead>
<tr>
<th>Basic</th>
<th>z</th>
<th>x₁</th>
<th>x₂</th>
<th>s₁</th>
<th>s₂</th>
<th>s₃</th>
<th>s₄</th>
<th>Solution</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>1</td>
<td>-3</td>
<td>-2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>s₁</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>6/1</td>
</tr>
<tr>
<td>s₂</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>8/2</td>
</tr>
<tr>
<td>s₃</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>s₄</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4 Table Showing Pivot Equation/Pivot Element, and Non Basic Variable x₁ Moving to be Basic Variable (Adopted From Taha (1989))

<table>
<thead>
<tr>
<th>Basic</th>
<th>z</th>
<th>x₁</th>
<th>x₂</th>
<th>s₁</th>
<th>s₂</th>
<th>s₃</th>
<th>s₄</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s₁</td>
<td>0</td>
<td>1</td>
<td>1/2</td>
<td>0</td>
<td>1/2</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>x₁</td>
<td>0</td>
<td>1</td>
<td>1/2</td>
<td>0</td>
<td>1/2</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>s₂</td>
<td>0</td>
<td>0</td>
<td>3/2</td>
<td>1</td>
<td>-1/2</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>s₃</td>
<td>0</td>
<td>0</td>
<td>3/2</td>
<td>0</td>
<td>1/2</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>s₄</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2/1</td>
</tr>
</tbody>
</table>

Table 5.5 New Equations For All the Rows (After Taha (1989))

<table>
<thead>
<tr>
<th>Basic</th>
<th>z</th>
<th>x₁</th>
<th>x₂</th>
<th>s₁</th>
<th>s₂</th>
<th>s₃</th>
<th>s₄</th>
<th>Solution</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>1</td>
<td>0</td>
<td>-1/2</td>
<td>0</td>
<td>3/2</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>s₁</td>
<td>0</td>
<td>0</td>
<td>3/2</td>
<td>1</td>
<td>-1/2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4/3</td>
</tr>
<tr>
<td>x₁</td>
<td>0</td>
<td>1</td>
<td>1/2</td>
<td>0</td>
<td>1/2</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>s₃</td>
<td>0</td>
<td>0</td>
<td>3/2</td>
<td>0</td>
<td>1/2</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>10/3</td>
</tr>
<tr>
<td>s₄</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2/1</td>
</tr>
</tbody>
</table>
Step 3: An optimum solution is reached when none of the non-basic variables have a negative coefficient (for maximisation) in the objective function equation (see Table 5.6).

If the optimum solution is not reached, Step 2 is repeated for the new tableau.

Table 5.6 The Optimum Solution (After Taha (1989))

<table>
<thead>
<tr>
<th>Basic</th>
<th>z</th>
<th>x₁</th>
<th>x₂</th>
<th>s₁</th>
<th>s₂</th>
<th>s₃</th>
<th>s₄</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1/3</td>
<td>4/3</td>
<td>0</td>
<td>0</td>
<td>38/3</td>
</tr>
<tr>
<td>x₂</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2/3</td>
<td>-1/3</td>
<td>0</td>
<td>0</td>
<td>4/3</td>
</tr>
<tr>
<td>x₁</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>-1/3</td>
<td>2/3</td>
<td>0</td>
<td>0</td>
<td>10/3</td>
</tr>
<tr>
<td>s₃</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>s₄</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-2/3</td>
<td>1/3</td>
<td>0</td>
<td>1</td>
<td>2/3</td>
</tr>
</tbody>
</table>

(5.4.2.1) Artificial Starting Solution

The above mentioned procedure is appropriate where the constraints are in the 'less than or equal to' form. For problems with 'greater than or equal to' constraints, one cannot be sure that determining a starting basic feasible solution by using the standard form and setting (n-m) appropriate (non-basic) variables at zero level will result in non-negative basic variables.

Although trial and error can be used by setting one variable at a time equal to zero, it would be time consuming. Thus a more
direct method is required for finding the starting basic feasible solution.

After obtaining the standard form (by subtracting surplus variables and adding slack variables) artificial variables are added to the equations which do not have slack variables (i.e., constraints which are equalities and inequalities of 'greater than or equal to'). These act like a slack variable in providing a starting basic variable. However, it should be noted that these variables are used only to start the solution and must be zero in the final solution provided that a feasible solution exists. This is achieved by penalising the artificial variables in the objective function. Two methods are used for this purpose:

(1) The Big M Method (Method of Penalty)

(2) The Two Phase Method

For the Big M Method, the artificial variables that are added to the appropriate constraints can be penalised in the objective function by assigning to them very large positive coefficients in the objective function. This is shown in the example below (after Taha(1989)).
Minimise $z = 4x_1 + x_2$
Subject to:
$3x_1 + x_2 = 3$
$4x_1 + 3x_2 \geq 6$
$x_1 + 2x_2 \leq 4 \quad x, x_2 \geq 0$

**Standard form:**
Minimise $z = 4x_1 + x_2$
Subject to:
$3x_1 + x_2 = 3$
$4x_1 + 3x_2 - x_3 = 6$
$x_1 + 2x_2 + x_4 = 4$
$x_1, x_2, x_3, x_4 \geq 0$

**Modified with the artificial variables:**
$3x_1 + x_2 + R_1 = 3$
$4x_1 + 3x_2 - x_3 + R_2 = 6$
$x_1 + 2x_2 + x_4 = 4$
$x_1, x_2, x_3, x_4, R_1, R_2 \geq 0$

Minimise $z = 4x_1 + x_2 + MR_1 + MR_2 \ (M > 0 \text{ and very large number})$

After the modification with artificial variables the procedure is the same as described before. See Table 5.7 for the final tableau.
The only difference between minimisation and maximisation problems is that for maximisation problems, the coefficient '-M (M > 0)' is assigned to the objective function.

Table 5.7: Optimisation Using the Big M Method
(After Taha (1989)) (the z column is eliminated as it does not change)

<table>
<thead>
<tr>
<th>Iter.</th>
<th>Basic</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>R1</th>
<th>R2</th>
<th>$x_4$</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$z$</td>
<td>$-4+7M$</td>
<td>$-1+4M$</td>
<td>$-M$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$9M$</td>
</tr>
<tr>
<td></td>
<td>$R_1$ enters</td>
<td>$R_1$</td>
<td>$3$</td>
<td>$1$</td>
<td>$0$</td>
<td>$1$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$R_2$</td>
<td>$4$</td>
<td>$3$</td>
<td>$-1$</td>
<td>$0$</td>
<td>$1$</td>
<td>$0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$x_4$</td>
<td>$1$</td>
<td>$2$</td>
<td>$0$</td>
<td>$0$</td>
<td>$1$</td>
<td>$4$</td>
</tr>
<tr>
<td>1</td>
<td>$z$</td>
<td>$0$</td>
<td>$(1+5M)/3$</td>
<td>$-M$</td>
<td>$(4-7M)/3$</td>
<td>$0$</td>
<td>$0$</td>
<td>$4+2M$</td>
</tr>
<tr>
<td></td>
<td>$x_2$ enters</td>
<td>$x_1$</td>
<td>$1$</td>
<td>$1/3$</td>
<td>$0$</td>
<td>$1/3$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$R_2$</td>
<td>$0$</td>
<td>$5/3$</td>
<td>$-1$</td>
<td>$-4/3$</td>
<td>$1$</td>
<td>$0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$x_4$</td>
<td>$0$</td>
<td>$5/3$</td>
<td>$0$</td>
<td>$-1/3$</td>
<td>$0$</td>
<td>$1$</td>
</tr>
<tr>
<td>2</td>
<td>$z$</td>
<td>$0$</td>
<td>$0$</td>
<td>$1/5$</td>
<td>$8/5-M$</td>
<td>$-1/5-M$</td>
<td>$0$</td>
<td>$18/5$</td>
</tr>
<tr>
<td></td>
<td>$x_3$ enters</td>
<td>$x_1$</td>
<td>$1$</td>
<td>$0$</td>
<td>$1/5$</td>
<td>$3/5$</td>
<td>$-1/5$</td>
<td>$0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$x_2$</td>
<td>$0$</td>
<td>$1$</td>
<td>$-3/5$</td>
<td>$-4/5$</td>
<td>$3/5$</td>
<td>$0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$x_4$</td>
<td>$0$</td>
<td>$0$</td>
<td>$1$</td>
<td>$1$</td>
<td>$-1$</td>
<td>$1$</td>
</tr>
<tr>
<td>3</td>
<td>$z$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$7/5-M$</td>
<td>$-M$</td>
<td>$-1/5$</td>
<td>$17/5$</td>
</tr>
<tr>
<td></td>
<td>Optimum</td>
<td>$x_1$</td>
<td>$1$</td>
<td>$0$</td>
<td>$0$</td>
<td>$2/5$</td>
<td>$0$</td>
<td>$-1/5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$x_2$</td>
<td>$0$</td>
<td>$1$</td>
<td>$-1/5$</td>
<td>$-1/5$</td>
<td>$0$</td>
<td>$3/5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$x_3$</td>
<td>$0$</td>
<td>$0$</td>
<td>$1$</td>
<td>$1$</td>
<td>$-1$</td>
<td>$1$</td>
</tr>
</tbody>
</table>
In the two phase method the use of the constant M is eliminated by solving the problem in two phases. These are

(1) Form a new objective function which would be the minimisation of the sum of the artificial variables, R1, R2, R3....Rn and with the same constraints of the original problem modified with the artificial variables. The problem has a feasible solution space if the minimum value for the objective function is equal to zero. Then, one could proceed to the next step. Otherwise, the problem has no feasible solution and there is no need to proceed.

(2) Use the optimum basic solution of phase 1 as a starting solution.

Thus, for the above example the first step would be:

Minimise \( r = R_1 + R_2 \)

\[ \begin{align*}
&= (3 - 3x_1 - x_2) + (6 - 4x_1 - 3x_2 + x_3) \\
&= -7x_1 - 4x_2 + x_3 + 9
\end{align*} \]

Then the starting tableau will be that shown in Table 5.8 below.
Table 5.8 The Starting Values While Using the 'Two Phase' Method (After Taha (1989)).

<table>
<thead>
<tr>
<th>Basic</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>R1</th>
<th>R2</th>
<th>$x_4$</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>7</td>
<td>4</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>R1</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>R2</td>
<td>4</td>
<td>3</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>$x_4$</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Finally, the optimum solution tableau will be that shown in Table 5.9.

Table 5.9 Tableau Showing the Optimum Solution Obtained by the 'Two Phase' Method (After Taha (1989))

<table>
<thead>
<tr>
<th>Basic</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>R1</th>
<th>R2</th>
<th>$x_4$</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$x_1$</td>
<td>1</td>
<td>0</td>
<td>1/5</td>
<td>3/5</td>
<td>-1/5</td>
<td>0</td>
<td>3/5</td>
</tr>
<tr>
<td>$x_2$</td>
<td>0</td>
<td>1</td>
<td>-3/5</td>
<td>-4/5</td>
<td>3/5</td>
<td>0</td>
<td>6/5</td>
</tr>
<tr>
<td>$x_4$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

The above tableau is obtained after two iterations. The number of iterations to obtain this result is the same with both the Big M Method and the Two Phase Method. Lau (1988) states that in general, these two methods may be regarded as equivalent as they produce identical sequences of tables and find the same optimal solution in the same number of iterations.
(5.4.2.2) Special Cases in Optimisation with the Simplex Method

Lau (1988) and Taha (1989) state that the following difficulties may arise while computing an optimal solution using the Simplex Method:

(1) **Most negative (or positive) coefficients**: If two or more non-basic variables have the most negative or positive coefficient (for maximisation and minimisation respectively) in the objective function, then the general rule is to select any one of them arbitrarily to become basic in the next iteration. Although a "wrong" choice may increase the number of iterations required to reach an optimal solution, there is no way of predicting this.

(2) **Equal minimum ratios**: When applying the minimum ratio rule, it is possible for two or more rows to have the minimum ratio. In this case, again the general rule is to select any one of the corresponding basic variables arbitrarily to become non-basic next. However, whichever basic variable is chosen, the others which are not chosen, and which therefore remain basic, will have the value of 0 in the next basic feasible solution.
Equal minimum ratios are the main cause of degeneracy. A basic feasible solution in which at least one basic variable is 0 is said to be degenerate, and the phenomenon of the occurrence of such basic feasible solutions is called degeneracy.

Equal minimum ratios also may cause further complications in the subsequent iterations. However, these are ignored in practice, although some problems do have degenerate basic feasible solutions.

(3) **Unbounded solution**: If all the ratios are infinite, i.e. if all the elements in the pivotal column are non-positive, then the minimum ratio rule fails. Whichever basic variable we choose to become non-basic next, the new basic variable will have the value of infinity. This means that the optimal value of the objective function is unbounded, i.e. the problem has an unbounded solution.

(4) **Infeasible solution**: When at least one artificial variable is positive in the optimum solution, the problem has no feasible solution.
(5.5) Summary

Linear programming has been chosen for the optimisation part of the integrated computer model. It has been selected as the most appropriate technique after examining the advantages and disadvantages of using other optimisation techniques such as non-linear, heuristic, dynamic and integer programming. Four main criteria have been proved important in choosing the optimisation technique. These are firstly the practical representation of time and cost relationships, secondly the fact that the model is designed for multi storey buildings (i.e. repetitive construction), thirdly the linear programming procedure is found to be straightforward from the model development standpoint and finally that the development of the model requires dealing with large numbers of constraints and variables.

The methods of solving linear problems have been discussed with the emphasis on the two approaches of the 'Simplex Method' (i.e. the 'Big M' and the 'Two Phase' methods) both of which require similar procedures.

The application of the 'Simplex Method' for the optimisation part of the computer model is discussed in Chapter 7.
CHAPTER 6
(6.1) Introduction

Duration and cost estimation of construction projects involves handling a number of interacting variables some of which are easily predictable and quantifiable, whereas others rely on intuition and experience. The selection of manpower, materials and plant and possible method of work are some of the many factors which affect project duration and cost. In an environment where decisions have to be made in a short period the construction manager may find it too time consuming to estimate the time and cost of a project by optimising the various combinations of elements which make up the project and their quantities.

As discussed in Chapter 2 when the decisions have to be made in a short period of time and with many uncertainties, the managers may tend to use only qualitative analysis. However, effective decision making requires both qualitative and quantitative analysis. Computer modelling would save time and hence give the decision maker the opportunity to make more effective use of quantitative analysis.

The state of the art computer based simulation modelling related to time and cost determination at the project level was
discussed in Chapter 3. In this chapter, the development and the characteristics of the computer based model, which simulates the effect of different resource levels (labour, material and plant) for multi-storey reinforced concrete office buildings, is discussed.

(6.2) Structure of the Simulation Model

The structure of the simulation model can be divided into 3 main sections (see Figure 6.1). These are the time/cost model, the data files and the bar chart. The user inputs the required information and data into the time/cost model. The input is stored in data files. The stored data are processed by the time/cost model and are used for drawing the automated linked bar chart (see Section 6.12.2).

![Figure 6.1: The Structure of the Simulation Model](image)

(6.3) Development Methodology

Due to the structure of the simulation model (Figure 6.1) the development was in two stages. The time/cost model has been developed first in parallel with the data files. This was
followed by the development of the linked bar chart. Figure 6.2 shows the development methodology for the simulation model.

Figure 6.2 Development Methodology of the Simulation Model
(6.3.1) Development Software

Leonardo (version 3) has been used for the development of the time/cost model. Leonardo (version 3) is an expert system shell which is normally used to develop expert systems. However, as in its application in this research, Leonardo can also be used for the development of programmes which are not expert systems. The following advantages of programming with Leonardo are the main reasons for using it in this research.

(1) **Flexible development environment**: Leonardo systems are quite different from most conventional computer programmes. Leonardo provides a more flexible development environment than conventional computer programmes. For example, a conventional programme will not work if a single line is removed from the source code, but a Leonardo application will continue to work with rules missing. Also, it is open ended, i.e. new rules can be added as the developer collects more information about the problem area.

By using Leonardo, the programme can be built up step by step and each stage of development can be checked as it goes.

(2) **Ease to provide user friendliness to the model**: The screen design utility of Leonardo 3, i.e. the version used during
this research, provides a fast and efficient method of developing user input or output screens.

(3) **Ease of interaction with other programmes:** If needed, external programmes that are written in conventional languages, including C, FORTRAN, PASCAL and QBasic can be called by Leonardo. This can be achieved by writing, compiling and linking the external programme from the host operating system to create a standard executable file. This programme is called by Leonardo in exactly the same way as an internal procedure. At execution time the external programme will be loaded and executed and, after execution, control will return to Leonardo.

Additional to the above points, the importance of integration of models that provide quantitative analysis (i.e. models based on techniques like simulation and optimisation) with knowledge-based expert systems has been pointed out by various authors like Touran (1990), Connell and Powell (1992) and Dewhurst and Gwinnett (1992). Thus one important point that was considered when choosing an expert system shell for the development of the simulation model is that, this would enable development of a knowledge based system which is integrated with simulation and optimisation techniques in an integrated computer model.
It should be stated here that there are many expert system shells in the market and some of these may provide more advantages in programming than Leonardo. However, one of the main reasons for choosing Leonardo directly among all the other expert system shells was that Leonardo was readily available within University of Glamorgan.

QBASIC has been used for the development of the bar chart. This is because not only is QBASIC good in dealing with graphics, and in addition the programmes compiled with QBASIC can be called from a programme developed using Leonardo, but also learning and using this language has been found by the author to be relatively easier than the conventional programming languages of Pascal and C.

(6.4) Data Acquisition and Model Building

Jelen (1970) describes data acquisition as the step where the 'real situation' is examined and then the 'key features' are extracted from the 'real situation'.

Reinforced concrete (in-situ) framed buildings have been chosen as the building type to be studied during the development of the integrated model. The reasons for the choice of the building type are discussed below.
Framed buildings are the most common building type built during the second half of this century. Greeno (1990) defines the framed building as constructed from beams and columns of either reinforced concrete (in-situ or precast) or steel sections, where non-load bearing partitions, external walls and floors may be built onto the frame or suspended on the frame. All of these frame types have certain advantages and disadvantages in relation to the design, construction and occupation of the building.

During his discussion on the disadvantages of in-situ concrete framed type, Illingworth (1993) points out that during construction, all activities require large amounts of labour and plant and especially formwork, falsework and reinforcement are labour intensive. As it will be discussed later in this chapter (Section 6.10) according to CIOB (1994) the greatest cause of increased cost due to the accelerated work is the reduction in labour productivity. Thus in situ reinforced concrete framed buildings provide a good basis for the application of integration of simulation and optimisation methods for project cost/duration estimations.

To be able to extract the key features related to the duration and cost estimation of reinforced concrete multi storey office buildings relevant data/information were collected from the following sources.
(i) Bills of quantities and bar charts of reinforced concrete office buildings were obtained from two main contractors, Wimpey Construction and Kyle Stewart Ltd. (KS) in the UK and also from the University of Glamorgan resources.

(ii) Information was acquired during interviews with construction Planners, Estimators and Researchers. Seven two-hour interviews were conducted with two Chief Planners. Two one-hour interviews were conducted with two Chief Estimators and the in-house Researchers at KS provided cost analysis data related to the subcontracting work (see Appendix 2).

(iii) Wessex Building Price Book and SMM7.

(iv) Output rate calculation guide for excavation plant was provided by the plant manufacturers JCB, Bomag and Wacker (see Appendix 3).

The discussion in sections 6.5 to 6.13 will focus on the key features which were extracted from the above resources and on building the model which is based on these features.

(6.5) The Construction Activities

Ashworth and Skitmore (1990), Horner (1991) stated that 80% of the cost of a project was represented by only 20% of the bill items (Pareto's Law of Distribution). Lietctenberg (1974), Bennett (1984), Cusack (1984) and Zakieh (1991) pointed out that this ratio should be a basis for the selection of the costs that would be included in a cost model in order to provide a reasonable element of accuracy. Some selection is essential in order to restrict the basic elements of the programme to a manageable size.

For the selection of activities which were to be included in the model, two principal criteria were employed. Firstly, the effect of the activity on the overall cost and secondly the effect of the activity on the overall duration of the project.

From a cost perspective, it was decided to include the items which cover 80% of the costs for reinforced concrete multi-storey office buildings. When the cost analysis published by Building Magazine (Oct., 1993, Oct., 1994) was combined with the interviews and the research undertaken about cost analysis of sub-
contracting (see Appendix 2) by one of the contractors, the following items were identified as contributing approximately 80% of the total cost for reinforced concrete multi storey office buildings.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>% of the Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame &amp; Cladding, Roof</td>
<td>50</td>
</tr>
<tr>
<td>Services</td>
<td>30</td>
</tr>
</tbody>
</table>

Illingworth (1993), Ashworth and Skitmore (1990) and interviews undertaken by the author showed that the following should be included in the activity list when duration criteria are considered.

(1) Site establishment and clearance
(2) Foundations
(3) Finishes

Activities (1) and (2) (site establishment and foundations) are the first activities undertaken on a construction site, and impose physical constraints on scheduling. The 'finishes' were stated during the interviews to be the most critical activities for the completion of the project on time.
The time/cost model is divided into two modules, Module A and Module B, in respect of duration/cost calculations. This is because two different procedures for duration and cost calculations were employed and activities with the same calculation procedures were grouped into the same module.

It is stated in the CIOB Report (1991) that in practice duration may be derived by calculation, by quotation from a specialist, or by assessment on past experience. In the current programme both duration and costs of construction tasks and activities under Module A are calculated by using the user input data while both cost and duration of Module B activities are asked to be quoted by the user.

In addition to these two modules, there are three other main sections in the time/cost model. Two of these sections are for the input of indirect cost and lag values (see Figure 6.3). During the development of the model it has been found that calculations are made easier when the indirect costs and lag values are dealt with at a project level rather than at an individual activity level. The third section is for the display of the total duration and cost values for all the project.
Module A includes the activities of site establishment and clearance, substructure, superstructure and building envelope (see Figure 6.4). These activities have been presented as the combination of certain construction tasks.

**Activities Under Module A:**

1. **Site Establishment and Clearance:**
   a. Excavation of topsoil to be removed/preserved
   b. Excavation to reduce levels
   c. Excavation for basements
   d. Excavation for trenches
   e. Compaction of bottom of excavations

2. **Substructure: (Reinforced) Concrete Foundations:**
   a. Formwork erection
   b. Reinforcement construction
   c. Plain/reinforced concrete placement
(3) Superstructure:
   (a) Formwork erection
   (b) Reinforcement construction
   (c) Plain/reinforced concrete placement

(4) Building Envelope:
   (a) Brickwork and blockwork construction
   (b) Roofing: Reinforced concrete roof structure
      * Formwork erection
      * Reinforcement construction
      * Plain/reinforced concrete placement
      * Roof Asphalting

Figure 6.4 The Structure of 'Module A'

For each of the construction tasks under the main activities the following information and data are built into Module A (also see Section 6.7):

(1) Resources required for carrying out these tasks,
(2) Output rates of plant and labour,
(3) Formulae for cost/duration calculations.
(6.6.2) Module B

Finishes and Services are presented in Module B (see Figure 6.5).

![Diagram of Module B structure]

Figure 6.5 The Structure of 'Module B'

Due to the detailed and specialist work involved for these 2 activities, the user is asked to input the total duration and cost estimate for the tasks listed below.

**Activities Under Module B**

(1) Finishes:
   
   (a) Internal Finishes  
   (b) Wall Finishes  
   (c) Floor Finishes  
   (d) Ceiling Finishes  
   (e) External Finishes

(2) Services:
   
   (a) Lifts
(6.7) Calculation of Costs and Durations

For the calculation of project cost and duration the following steps have been undertaken.

1. Calculation of direct cost and duration for each task and consequently for each activity under Module A.

2. Calculation of direct and indirect cost, and duration of the entire project by combining results from Module A and the input to Module B.

The formulae used for the calculation of direct cost ($A_c$) and duration ($A_d$) for each task is:

$$A_c = (U_{c1} \times A_d \times N) + (Q_w \times U_{cm})$$

$$A_d = Q_w / (O_r \times N)$$

where:

- $A_c$ = Direct cost of a construction task.
- $A_d$ = Duration of a construction task.
- $Q_w$ = Quantity of work (q).
- $O_r$ = Output rate of particular equipment/labour per hour.
- $U_{c1}$ = Labour/plant unit cost (£/hr).
- $N$ = Number of labourers/plants employed.
- $U_{cm}$ = Material unit cost (£/q).
- $q$ = Unit of quantity (m, m², m³, ton).
- $U$ = Units required.
The calculation of direct cost using the above formulae is based on 'unit rate estimating'. Unit Rate Estimating is described in the Code of Estimating Practice (1983) as the calculation of the activity cost which is based on the quantity of work and the total time available to perform the task. This is stated as being the frequent case with reinforced concrete structures. Additionally, Baldwin and Thorpe (1990) state that 'unit rate estimating' is best suited to building or repetitive works where the sequence of equations is well defined.

After calculating the direct costs and duration of tasks within each main activity, the direct costs of each main activity can be calculated. The total cost of an activity includes the indirect costs as well as the direct costs. Within the time/cost model, indirect costs are those costs which are assessed for the entire project and are not related to individual activity duration. Thus, in the time/cost model indirect costs are not dealt with on an activity basis. They are used only while the total project cost is calculated by adding the direct costs of all activities to the indirect costs.

Unlike the calculation of the activity and project costs, it is not enough to sum up the duration of each task to arrive at an activity and consequently at a project duration value. The lag values between the tasks must also be considered. The following example explains how these are considered.
Example:

The main activity X is composed of three construction tasks A, B, C. The duration of tasks A, B and C are 2, 3 and 2 days respectively. The lag values with the start to start relationships are 1 day between A and B; and 0 day between B and C, i.e. they start together. Calculating the duration of the activity X will be as follows.

Bar Chart Representation:

![Bar Chart](image)

It is easily seen from the bar chart representation that the duration of the activity X will be 4 days. However, this method could not be used with the computer based calculations. Thus an arithmetic method was formulated to find the duration of the activities and also the project. The general formula constructed to determine the duration time $D_x$ of the main activity constructed, is given below:
\[ D_x = \text{Max} \left( \left( D_i, (D_{i+1} + \text{lag}_{i+1}), (D_{i+2} + \text{lag}_{i+1} - \text{lag}_{i+1} - (i+2) \right) \right) \]

where:

- \( D_i \) = Duration of the task \( i \).
- \( \text{lag}_{i+1} \) = Lag value between two tasks.
- \( \text{Max} \) = Highest numerical term

For this example the above formula works as:

\[ D_x = \text{Max} \left( 2, (3+1), (2+1) \right) = \text{Max}(2, 4, 3) = 4 \text{ days} \]

This formula is basically the arithmetic representation of the procedure, i.e. forward pass analysis, undertaken during the 'network analysis' to estimate a project duration from the activity duration. The task duration and lag values given in this example can be presented as the following network diagram. The forward pass shows that the project duration will be 4 days.

Network Diagram Presentation of the Example
The preceding discussion shows that in order to calculate the 'cost' and 'duration' of both the activities and of the whole project, user input is needed to provide the following information.

(1) The quantity of work,
(2) the type, quantity and the unit costs of the resources required, i.e. plant, labour and material,
(3) the output rates of plant and labour,
(4) the lag values, and
(5) indirect costs.

(6.7.1) Resources Required For Carrying Out the Tasks,

Related Output Rates and Unit Costs

Resources required for carrying out the tasks are materials, labour and plant.

There are more than 20 screens designed for the input of quantity of materials (see Figure 6.6 as an example).

The input screens were designed to suit the format of a typical Bill of Quantities (employing SMM7) for ease of input. Alternatively, the information can be taken from building drawings, specifications and schedule of rates. The planners interviewed by the author stated that there needed to be more
material types to be added to the "Building Envelope" section. Thus additional input screens were provided to include extra materials for cladding (see Figure 6.7)

Table 6.20: Formwork for Formwork for Rectangular and Circular Columns

<table>
<thead>
<tr>
<th>Width (mm)</th>
<th>Length (m)</th>
<th>Dia. (mm)</th>
<th>Area (m2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 200</td>
<td></td>
<td>&lt; 300</td>
<td></td>
</tr>
<tr>
<td>200-400</td>
<td></td>
<td>300-600</td>
<td></td>
</tr>
<tr>
<td>400-600</td>
<td></td>
<td>600-900</td>
<td></td>
</tr>
</tbody>
</table>

Please input the area (m2) of formwork for vertical face of walls.

- One side of wall shuttered
- Both sides of wall shuttered

Figure 6.6 Typical Input Screen For 'Quantity of Materials'

Please note that the materials described in this screen should make a group under a task, as the same gang is assumed to be used for all.

Please state whether this task can be considered under 'external' or 'internal' cladding.

Figure 6.7 Input Screen For Extra Materials for Cladding
Input screens were also designed for the requirements of labour for each task (see Figure 6.8). Where a gang of labourers is needed for an activity to be carried out, the user inputs the number of labourers to be employed within that gang.

Figure 6.8 shows that two values (normal and maximum) for the gang sizes are requested. These values are needed for the optimisation calculations and are discussed in detail in Section 6.10.

<table>
<thead>
<tr>
<th>GANG SIZE TO BE EMPLOYED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Please state the normal and maximum gang sizes that would be employed to undertake the following tasks for foundations.</td>
</tr>
<tr>
<td>Normal</td>
</tr>
<tr>
<td>BLINDING LAYER</td>
</tr>
<tr>
<td>FORMWORK</td>
</tr>
<tr>
<td>REINFORCEMENT</td>
</tr>
<tr>
<td>CONCRETE</td>
</tr>
</tbody>
</table>

Figure 6.8 Typical Input Screen for 'Gang Sizes'

To minimise user input the Wessex Building Price Book was used as a source of output rates for labour during the development of the model. However, the interviews with the planners indicated that construction firms preferred using their own rates and they would not wish to employ a model with fixed rates in it. Consequently, although the labour output rates are built into the model, the user also has the option of inputting different values (see Figure 6.9).
Please input the required output rate values.

<table>
<thead>
<tr>
<th>FORMWORK FOR:</th>
<th>Output rate (hr/m²)</th>
<th>REINFORCEMENT FOR:</th>
<th>Output rate (hr/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Columns and Walls</td>
<td></td>
<td>- Columns and Walls</td>
<td></td>
</tr>
<tr>
<td>- Staircases</td>
<td></td>
<td>- Staircases</td>
<td></td>
</tr>
<tr>
<td>- Slabs and Beams</td>
<td></td>
<td>- Slabs and Beams</td>
<td></td>
</tr>
</tbody>
</table>

Output rate (hr/m³)

REINFORCED CONCRETE FOR:
- Columns and Walls
- Staircases
- Slabs and Beams

Figure 6.9 Typical Input Screen for Output Rates

Lion (1980) states that building construction is more material and labour intensive than plant intensive. Additionally Illingworth (1993) points out that especially formwork, falsework and reinforcement are labour intensive in construction of reinforced concrete structures. Plant costs represent a comparatively small proportion of construction costs ranging around 5%. Although this may be the case for overall building construction; 'site establishment and clearance' is highly plant intensive. Thus it was important to incorporate plant utilisation in the model. The range of plant available is however too diverse for full inclusion in the model (Refer to British Standard 6031 Earthworks for general descriptions). Wessex Dayworks Plant Guide 1992/93 states that a typical list of plant used in building
operations would include JCB 3CX, Hymac 580, Drodt with 4m³ bucket, light and heavy vibrating roller and concrete mixer. The plant manufacturers JCB, Wacker and Bormag were contacted (see Appendix 3) and from the information provided the following were included in the model as choices of excavation and vibration plant: ten backhoes and crawlers with bucket sizes ranging from 0.04 m³ to 2.25 m³, and eight vibration rammers and plates with output rates ranging from 150 m²/hr to 1050 m²/hr (see Figure 6.10 and 6.11).

<table>
<thead>
<tr>
<th>Backhoe/Crawler exc.</th>
<th>Bucket Capacity (m³)</th>
<th>BCT (secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) JCB 3C, 3CX, 3D</td>
<td>0.30</td>
<td>8.0</td>
</tr>
<tr>
<td>(2) JCB 4CT</td>
<td>0.17</td>
<td>9.0</td>
</tr>
<tr>
<td>(3) JCB 2CX</td>
<td>0.24</td>
<td>10.5</td>
</tr>
<tr>
<td>(4) JCB 801</td>
<td>0.04</td>
<td>15.0</td>
</tr>
<tr>
<td>(5) JCB 803</td>
<td>0.11</td>
<td>15.0</td>
</tr>
<tr>
<td>(6) JS 110</td>
<td>0.45</td>
<td>14.0</td>
</tr>
<tr>
<td>(7) JS 150</td>
<td>0.70</td>
<td>14.0</td>
</tr>
<tr>
<td>(8) JS 240</td>
<td>1.25</td>
<td>14.0</td>
</tr>
<tr>
<td>(9) JS 300</td>
<td>1.75</td>
<td>14.0</td>
</tr>
<tr>
<td>(10) JS 450</td>
<td>2.25</td>
<td>14.0</td>
</tr>
</tbody>
</table>

Specify a plant number (1 to 10), and the number to be used on each task.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Number</th>
<th>Total volume of excavation (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavate topsoil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excavate to reduce</td>
<td></td>
<td></td>
</tr>
<tr>
<td>level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excavate for</td>
<td></td>
<td></td>
</tr>
<tr>
<td>basements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excavate for</td>
<td></td>
<td></td>
</tr>
<tr>
<td>trenches</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.10 Input Screen for the Choice of Excavation Plant
Please specify the total area of all excavation bases to be levelled and compacted.

Please specify one of the following pieces of plant and the number (amount) to be used on the compaction and levelling of excavation bases.

<table>
<thead>
<tr>
<th>Model</th>
<th>Plate</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPU 2950A</td>
<td>700x500</td>
<td>660</td>
</tr>
<tr>
<td>DPU 6055</td>
<td>900x710</td>
<td>940</td>
</tr>
<tr>
<td>BS 105Y</td>
<td>385x400</td>
<td>280</td>
</tr>
<tr>
<td>BS 40Y</td>
<td>330x200</td>
<td>150</td>
</tr>
<tr>
<td>BS 60Y/62Y</td>
<td>320x280</td>
<td>210</td>
</tr>
<tr>
<td>DPU 2430</td>
<td>700x300</td>
<td>450</td>
</tr>
<tr>
<td>BPU 3345R</td>
<td>900x600</td>
<td>760</td>
</tr>
<tr>
<td>DPU 7060RC</td>
<td>1075x800</td>
<td>1050</td>
</tr>
</tbody>
</table>

Figure 6.11 Input Screen For Amount of Compaction and Compaction Plant

The information on output rates for excavation and compaction plant was also obtained from the selected manufacturers, JCB, and Wacker. This was considered preferable to using published data for two reasons: firstly there are different types of plant that can be used during the excavation and the compaction tasks, whereas published data only give output rates for one machine; secondly the output rates of excavation plant depend on individual site conditions which have to be taken into consideration.

The procedure and the formula obtained from the manufacturers for the calculation of plant output rates was...
welcomed by the planners as it was found to be realistic and reliable. The reliability of the manufacturers' output rate calculations for excavation and compaction work is also stressed in the Wessex Dayworks Guide.

The formula (supplied by JCB) to calculate output rates for excavation plant is:

$$O_e = E \times 60 \times B_c / C$$

where:

$O_e$ = output rate of an excavator (m$^3$/hr)
$E$ = efficiency factor (dimensionless)
$B_c$ = bucket capacity (m$^3$)
$C$ = corrected cycle time (hr)

The bucket capacities of the excavation plant are provided by the manufacturers. The user can see these on the input screen while choosing the excavation plant (see Figure 6.10). This allows the user to choose the machine that fits most closely to requirements.

To determine the plant output rate it is necessary to determine the corrected cycle time from the basic cycle time.

Basic cycle time is the time taken for an excavation plant to load, manoeuvre, dump and return to dig. However, in working
conditions the cycle time is not equal to the sum of these actions as the performance of excavation plant is affected by various factors. These are:

(1) Depth of the excavation,
(2) type of material to be excavated,
(3) type of target into which the excavated material will be unloaded,
(4) slew angle of the excavator,
(5) ground conditions, and
(6) the status of the operator.

Corrected cycle time is calculated by adding the compensation figures for the above factors to the basic cycle time of the particular excavator. Additional to the above factors that affect the cycle time, there may be some interruptions due to operator breaks, maintenance and job hold ups. The effect of these factors are accounted for by the efficiency factor (E). All the factors and basic cycle time for each excavator were provided by the JCB manufacturer (see Appendix 3).

Additional to the choice of resources required to be used and input of output rates corresponding to these resources, the unit costs of the resources are also asked to be input by the user (see Figure 6.12).
The values for the material unit cost (muc) and the labour unit cost (luc) for the following can be updated if required.

<table>
<thead>
<tr>
<th>Width (mm)</th>
<th>muc (£/m)</th>
<th>luc (£/hr)</th>
<th>Diameter (mm)</th>
<th>muc (£/m²)</th>
<th>luc (£/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 200</td>
<td>---</td>
<td>---</td>
<td>&lt; 300</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>200-400</td>
<td>---</td>
<td>---</td>
<td>300-600</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>400-600</td>
<td>---</td>
<td>---</td>
<td>600-900</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>&gt; 600</td>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>muc (£/m²)</th>
<th>luc (£/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One side of wall shuttered</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Both sides of wall shuttered</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

Figure 6.12 Typical Input Screen for 'Unit Costs'

(6.8) The Precedence Relationships and Lag Values

The precedence relationships of activities are dependent on the constraints on scheduling. Echevery et al. (1991) divides these constraints into 4 groups. These are physical relationships among building components, trade interactions, path interferences, and code regulations.

(1) **Physical relationships among building components.** Physical constraints are laws of nature that impose practical restraints on tasks based on current construction technology. For example, the slab cannot be built until the supporting columns are built.
(2) **Trade Interactions:** Trades affect each other and the sequence of the activities during construction in ways such as; space congestion, resource limitations, unsafe environmental effects, damage to installed building components and services requirements.

(3) **Path Interferences:** For the installation of building components path interferences are important as the components have to be moved around site.

(4) **Code Regulations:** Sequencing should not ignore construction phase safety considerations.

Baldwin and Thorpe (1990) state that the sequence of works are well defined in repetitive works. Birrell (1991) emphasises that multi storey office building construction requires sequential waves of work especially for the shell. More specifically, Kartham and Levitt (1990) state that the physical relationships themselves can be used to generate much of the needed sequence logic for multi storey reinforced concrete office building projects. However, it should be noted that for the cases of external and internal cladding, and finishes and services, there cannot be a particular task that can be generalised as being the preceding task. Therefore, it is assumed (by considering the bar charts drawn by the planners) that internal
cladding can start any time after the start of staircases from ground to first floor, external cladding can start any time after the start of formwork-reinforcement-concrete (FRC) for slabs and beams for ground floor, and finishes and services can start any time after the start of external cladding. Thus, the user has to specify the floor of the staircases and the slabs/beams that will be succeeded by the external and internal cladding, and consequently by finishes and services (see Figure 6.13 (a), (b), (c) below).

<table>
<thead>
<tr>
<th>Lag Values (days) (start to start relationship)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explanation:</td>
</tr>
<tr>
<td>Excavate Topsoil</td>
</tr>
<tr>
<td>Floor no 1 = Ground to 1st</td>
</tr>
<tr>
<td>Excavate to reduce levels</td>
</tr>
<tr>
<td>Floor no 2 = 1st to 2nd</td>
</tr>
<tr>
<td>Excavate &amp; Compact Foundations</td>
</tr>
<tr>
<td>Floor no 3 = 2nd to 3rd</td>
</tr>
<tr>
<td>Blinding Foundations</td>
</tr>
<tr>
<td>Floor no: □ Frc Stairc.</td>
</tr>
<tr>
<td>Formwork to Foundations</td>
</tr>
<tr>
<td>Internal Cladding</td>
</tr>
<tr>
<td>Reinforcement to Foundations</td>
</tr>
<tr>
<td>Floor no: □ Frc Slab/Beam</td>
</tr>
<tr>
<td>Concrete to Foundations</td>
</tr>
<tr>
<td>External Cladding</td>
</tr>
<tr>
<td>Frc Ground Floor Slab</td>
</tr>
<tr>
<td>Frc Cols/Walls Gr to 1st</td>
</tr>
<tr>
<td>1st Floor Frc Slab/Beams</td>
</tr>
<tr>
<td>Frc Staircases</td>
</tr>
<tr>
<td>Roof Slab/Beam (concrete)</td>
</tr>
<tr>
<td>Roof Asphalt</td>
</tr>
</tbody>
</table>

Figure 6.13 (a) The First Screen Displayed for the Input of Lag Values
Please input the lag values (days) between the following tasks for reinforced concrete floors.

<table>
<thead>
<tr>
<th>COLUMNS &amp; WALLS</th>
<th>SLABS &amp; BEAMS</th>
<th>STAIRCASES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforcement</td>
<td>Formwork</td>
<td></td>
</tr>
<tr>
<td>Formwork</td>
<td>Reinforcement</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>Concrete</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.13 (b) The Second Screen Displayed for the Input of Lag Values

Please input the appropriate lag values (days) between 'external cladding' and the following tasks.

**FINISHES:**
- Internal Finishes
- Wall Finishes
- Floor Finishes
- Ceiling Finishes
- External Finishes

**SERVICES:**
- Lifts
- Mechanical Services
- Electrical Services

Figure 6.13 (c) The Last Screen Displayed for the Input of Lag Values

The precedence relationships between tasks require that before a task can start, all the tasks that precede it, should be partially or wholly completed. For this, six types of precedence relationships can be established between two sequential tasks. These are finish to start, start to finish, start to start, finish to finish, part complete to start, part complete to finish dependencies, where each can include a lag value. Bar charts reported in the literature and those used by the participating...
Construction firms showed that start to start and finish to start precedence relationships are the most widely used sequencing. Based on these bar charts and on the ones drawn for the validation of the programme (see Figures 8.1 and 8.2), start to start precedence with lag values was incorporated in the model although a finish to start relationship can also be easily adopted. It should also be noted here that although a number of different relationships can be used between project tasks, this has proved in some cases to be of disadvantage as the user finds alternatives to be too complicated (Harris and McCaffer (1995)). Additionally, previous research has shown evidence that project duration tends to be underestimated when extensive overlapping of tasks is used in planning (Harris and McCaffer (1995)).

(6.9) Indirect Costs

Scott and Kagiri (1992) and Tah et.al (1994) have presented different approaches to what constitute the indirect costs. The items included within this model are the ones which are stated under the 'Project Overheads Schedule' in Code of Estimating Practice (1983). These are:

1. Supervision and site administration
2. Site labour
3. Insurances
4. Plant and equipment
5. Scaffolding
These costs are required to be input by the user.

(6.10) Crash Values and Productivity

It has been pointed out in Chapter 4 that shortening the project duration by overtime work or by employing more labour will result in an increase in the direct project cost. CIOB (1994) states that probably the greatest cause of increased cost due to the accelerated working is the reduction in labour productivity. Thus, in this research the crash time and cost calculations will only consider the productivity loss.

The formulae in Section 6.7 are used for duration and cost calculations of normal work. To consider productivity loss for
crash duration and cost calculations, these formulae have been modified.

\[ A_{cc} = (U_{cl} \times A_{dc} \times N) + (Q_w \times U_{cm}) \]

\[ A_{dc} = Q_w \times (1+P) / (O_r \times N) \]

where:

- \( A_{dc} \) = Crash duration of a construction task.
- \( A_{cc} \) = Direct cost of a construction task at crash duration.
- \( Q_w \) = Quantity of work (q).
- \( O_r \) = Output rate of particular equipment or labour per hour (q/hr).
- \( U_{cl} \) = Labour/plant unit cost (£/hr).
- \( N \) = Number of labourers/plant employed to crash the task.
- \( U_{cm} \) = Material unit cost (£/q).
- \( q \) = Unit of quantity (m,m²,m³,ton).
- \( P \) = % Productivity loss due to overtime work or increase in number of labourers in a gang.

To be able to include the productivity loss in the calculations, the time/cost model provides the user with the choice of either employing overtime work or increasing the number of resources to accelerate the construction of each task (see Fig 6.14 below).

Figure 6.14 Input Screen for the Ways of Accelerating the Project Duration
If overtime work is chosen by the user, the amount of working hours/week is asked to be input (see Figure 6.15(a)). This information is used to calculate the task duration and cost under accelerated work conditions either by assuming a productivity loss of 1% for every extra hour per week, adopted from the CIOB report (1994) (see Figure 6.15 (b)), or (if the user requires to use his/her own % productivity loss assumptions) by the user's % productivity loss input (see Figure 6.15 (b)).

Input the amount of working hours/week to accelerate work.

\[\text{hours/week}\]

The productivity loss due to the increase in working hours will be assumed to be 1% for every extra hour/week (this is adopted from CIOB's report (1994)).

Please input into the box below if a different value is required to be used.

\[%\text{ productivity loss}\]

Figure 6.15(a) Input Screen For Productivity Loss/Working Hours

Figure 6.15 (b) Productivity loss vs working hours
(source CIOB report (1994))

6-34
If employing more resources is chosen by the user for accelerating the task, two values of gang sizes (or number of plant) has to be input by the user (see Figure 6.8 & Section 6.7.1). However, it should be noted that even if the overtime work is chosen for accelerating the work, the gang size screen will still have to be displayed for the input of 'normal' gang sizes. In this case, 'maximum' gang sizes can be set to be '0' by the user. As for the overtime work, the information about the gang sizes is used to calculate the task duration and cost values for accelerated work by assuming a productivity loss of 0.32 %, or reducing productivity by 0.1 % for every 1% increase in the gang size (see Figure 6.16 (a) & (b)), or by taking the user's % productivity loss assumptions (see Figure 6.16 (c)).

![Graph showing productivity loss vs. increase in size of labour force](image)

**Figure 6.16(a) Average Data for Productivity Loss vs. Increase in Gang Size (adopted from CIOB (1994))**
Figure 6.16(b) A Simpler Form of Graph based on Figure 6.16(a)

The productivity loss due to the increase in gang size will be assumed to be 0.32% for every 1% increase until 95% increase of gang size. After 95% increase the loss in productivity is 0.1% for each 1% increase in gang size. (this is adopted from CIOB's report (1994)).

Please input into the box below if different values are required to be used.

% productivity loss
(the increase in gang size is up to 95%)

% productivity loss
(the increase in gang size is more than 95%)

Figure 6.16(c) Input Screen For Productivity Loss/Gang Size
(6.11) Running the Model

(6.11.1) Starting the Model

C:\ OPTIMUM allows the user to get into the model and then the 'Main Menu' is displayed (see Figure 6.17).

<table>
<thead>
<tr>
<th>NAME</th>
<th>SECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>SETUP</td>
<td>Site Set Up</td>
</tr>
<tr>
<td>FOUND</td>
<td>Substructure (Reinforced Concrete Foundation)</td>
</tr>
<tr>
<td>FLOOR</td>
<td>Superstructure (Reinforced Concrete Floors)</td>
</tr>
<tr>
<td>ENVELOPE</td>
<td>Building Envelope</td>
</tr>
<tr>
<td>ROOF</td>
<td>Roofing (Roof Asphalt)</td>
</tr>
<tr>
<td>FINISH</td>
<td>Finishes</td>
</tr>
<tr>
<td>SERVICE</td>
<td>Services</td>
</tr>
<tr>
<td>LAG</td>
<td>Lag Values Between Tasks</td>
</tr>
<tr>
<td>TOTAL</td>
<td>Total Duration/ Cost Values For the Whole Project</td>
</tr>
<tr>
<td>BARCHART</td>
<td>Linked Bar Chart</td>
</tr>
<tr>
<td>STORE</td>
<td>Directions For Storing A Completed Project</td>
</tr>
<tr>
<td>EXIT</td>
<td>Leave the Programme</td>
</tr>
</tbody>
</table>

Figure 6.17 'Main Menu'

(6.11.2) Accessing the Different Sections

Different options are displayed on the 'Main Menu' screen. The user can access the different sections of the model by scrolling up or down to highlight the section required and pressing <enter>

For the sections ('Setup', 'Found', 'Floor', 'Envelope') composed of sub sections a 'sub menu' is displayed (see Figure 6.18 for a typical 'sub menu') to enable the user to access the
input or output screens. The user also has the option to return back to the 'Main Menu'.

| (0)  | Number of Floors          |
| (1)  | Quantities of work        |
| (2)  | Unit costs of labour/plant/material |
| (3)  | Gang sizes                |
| (4)  | Quantities /unit costs of extra materials |
| (5)  | Optimization information  |
| (6)  | Normal duration/cost values |
| (7)  | Go Back to Main Menu      |

Figure 6.18 A Typical 'Sub Menu'
(For the Section 'Floor')

When the user selects one of the options from the 'sub menu' the related input screens are chained to each other. The user can go back to the previous input screen in the chain using the <F5> key and move to the next screen by using the <F6> key.

The screens can be printed by pressing <Print Screen> on the key board.

(6.11.3) Storing All the Project Information Before Starting a New Project

The 'STORE' option on the 'Main Menu' explains the procedure to store the project information before a new project is started (see Figure 6.19).
STORING THE FILES OF A COMPLETED PROJECT

It is not possible to keep the input for a completed project within the programme when another project is on the way. Thus it is recommended that the data files for each project to be saved on a disk (or hard disk) under a directory with the name of the project.

STORAGE

* EXIT from the programme
* Open a directory named for example PROJECT1.
* Copy all the data files of the project in the directory.
  ex: c:\opt>copy *.dat a:\project1

RE LOADING

* Copy all the data files under the project directory back into the programme.
  ex: C:\opt>copy project1 c:

** NOTE: Do not forget to store the existing project file (as described above) before re-loading an old one into the programme.

Figure 6.19 The Screen Displayed Under 'Store' Section from the 'Main Menu'

(6.11.4) Getting Help

Pressing the <F4> key provides the available help relevant to what the user is doing.

(6.12) Output

The output is displayed in 2 forms, the output screens and the linked bar chart.
There are 2 different output screens that can be displayed under the 'sub menu' of each section in Module A.

The first type of output screen provides the gang sizes for normal and accelerated work and the duration and cost values corresponding to these for each task. This screen enables the user to compare the results between normal and accelerated work (see Figure 6.20).

![Figure 6.20 Typical Output Screen Displaying the Time/Cost Values For Normal and Accelerated Work](image)

The second type of output screen is a simpler one. It only displays the normal time and cost of each task under the main activity and the total time and cost of that activity. This screen is designed for the users who may use the time/cost model for only normal time and cost calculations (see Figure 6.21).
### Final Values of Duration and Cost for the Tasks of Reinforced Concrete Foundations

<table>
<thead>
<tr>
<th>Task</th>
<th>Cost (£)</th>
<th>Time (hr)</th>
<th>(day)</th>
<th>(week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setting Formwork</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinforcement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plain Concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinforced Concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Removal of Formwork</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 6.21 A Typical Output Screen For Normal Duration and Cost Information**

In addition to the output screens for each activity, the total project costs and duration can also be displayed separately (see Figure 6.22).

<table>
<thead>
<tr>
<th>Normal Work</th>
<th>Accelerated Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Project Duration</td>
<td></td>
</tr>
<tr>
<td>Total Project Direct Cost</td>
<td></td>
</tr>
<tr>
<td>Total Indirect Cost</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 6.22 Output Screen For the Total Project Cost and Duration Values**

(6.12.2) Data Files

The following data is stored in sequential data files.

1. Duration of tasks and activities.
2. Lag values between tasks.
(3) Number of floors.

The user is asked at the beginning of each run if the old project is continuing or a new project is to be started.

If the old project is continuing, the values that have been input in the previous run are automatically displayed on the input screens. If any of these values are changed by the user, the old values are then replaced by the new values in the data files.

If a new project is to be started, all the data values are set to be '0' in the data files before the user starts to input values for the new project.

(6.12.3) Linked Bar Chart

The stored data is also utilised for the automated drawing of the bar chart. The linked bar chart is displayed when the 'bar chart' option is chosen from the 'Main Menu'. Exiting the bar chart brings the user back to the time and cost model.

The user can scroll up, down, right and left to see the different parts of the bar chart. Figure 6.23 (a) shows the first display from the bar chart. Figure 6.23 (b) shows the display after the bar chart is scrolled down.
Figure 6.23 (a) The First Display on the Bar Chart

Figure 6.23 (b) The Last Display on the Bar Chart
(6.13) Summary

The development and the characteristics of the simulation part of the integrated computer model have been discussed in this chapter.

The duration and cost of construction of a reinforced concrete multi storey building is estimated by the model depending on various input data related to the quantities, unit costs of resources, output rates of labour and plant, indirect costs, lag values between tasks and various combinations of resources to be employed. The output from the simulation model is displayed both in numerical form and bar chart form. The output values are used as input data for the optimisation model which is discussed in the following chapter.

The validation of the simulation model is discussed in Chapter 8. The limitations, future developments and the benefits obtained by the model are additionally emphasised in Chapter 9.
CHAPTER 7
(7.1) Introduction

In Chapter 5, it was stated that the most appropriate optimisation procedure for satisfying the aims of this research is linear programming. Thus, linear direct cost curves for each task, a linear indirect cost curve for the whole project and subsequently a multi-linear direct cost curve and total cost curves for the whole project are used, for the reasons discussed in Section (5.1). Additionally, the steps for the linear programming method (Simplex) chosen to solve the optimisation problem for this research has been explained.

The computer optimisation model has been developed using the above procedures. In this chapter, the development and the structure of the computer model are discussed.

(7.2) The Structure of the Optimisation Model

Figure 7.1 The Structure of the Optimisation Model
(7.3) Input from the Simulation Model

The data files that are created within the Simulation Model are discussed in Section 6.12.2. These files are not only used to provide data for the automated drawing of the bar chart but are also used as an input to the programmes designed to perform the linear programming formulation.

(7.4) Linear Programming Formulation

As discussed in Chapter 5, to be able to solve an optimisation problem using a linear programming technique, the problem has to be presented in a certain form. This is:

1. There has to be an objective function to be maximised or minimised.

2. This function has to have linear relationships with the decision variables.

3. There have to be constraints on the decision variables and these should be in the form of linear inequalities or equations.

4. All the decision variables have to be non-negative.
To be able to determine the minimum total project cost corresponding to the optimum project duration, the above 4 steps have to be considered and formulation has to be done accordingly. The formulation has been based on the discussion by Stark and Mayer (1983). However while the aim of Stark and Mayer’s formulation is to minimise the cost of completing the project within a given period and provide one project duration/cost solution, the aim in the current model is to determine sets of project duration/cost solutions.

(7.4.1) Objective Function

The formulation of the objective function which is to minimise the total project cost while accelerating the project duration starts with the formulation of the project cost at the normal project duration.

\[
\text{TPC} = \text{IPC}_n + \sum_{i=1}^{n} \text{DC}_n(i) \quad \ldots \ldots \ldots (1)
\]

where:

\begin{align*}
\text{TPC} & \quad = \text{Total project cost} \\
\text{IPC}_n & \quad = \text{Indirect project cost under normal conditions} \\
\text{DC}_n(i) & \quad = \text{Direct cost of task } i \text{ under normal conditions} \\
\text{n} & \quad = \text{number of tasks}
\end{align*}

Additional to the above formula the changes in direct and indirect costs have to be formalised. While accelerating the
project, the direct cost of each accelerated task increases. This is represented by the following two formulae.

\[ DC_a(i) = DC_n(i) + U(i) \times T(i) \quad \ldots \ldots (2) \]

and

\[ U(i) = \frac{(DC_c(i) - DC_n(i))}{(D_n(i) - D_c(i))} \quad \ldots \ldots (3) \]

where:

- \( DC_a(i) \) = Direct cost of task \( i \) due to the accelerated duration.
- \( DC_n(i) \) = Direct cost of task \( i \) under normal conditions.
- \( U(i) \) = Increase in direct cost per one unit duration time (days) of a task, i.e. cost slope.
- \( T(i) \) = Number of days in which the task \( i \) should be compressed.
- \( DC_c(i) \) = Direct cost of the task \( i \) under the all crash conditions.
- \( D_n(i) \) = Duration of the task \( i \) under normal conditions.
- \( D_c(i) \) = Duration of the task \( i \) under all crash conditions.

As the project duration is accelerated, the indirect cost of the project decreases linearly and can be expressed as:

\[ IPC_c = IPC_n \times \frac{Dur_a}{Dur_n} \quad \ldots \ldots (4) \]

where:

- \( IPC_n \) = Indirect project cost at the normal duration.
- \( IPC_c \) = Indirect project cost at the accelerated duration.
- \( Dur_n \) = Normal duration of the project.
- \( Dur_a \) = Accelerated duration of the project.

Consequently, the objective function \( Z \), which is the minimisation of the sum of the direct and indirect costs of the project while accelerating the project duration, results from the formula:
\[ Z = \text{Min}( (\sum_{i=1}^{n} \text{DC}_n(i)) + (\sum_{i=1}^{n} \text{IPC}_c(i)) + (\sum_{i=1}^{n} \text{U}(i) \times T(i))) \quad \ldots (5) \]

For a particular project, the first part (i) of equation (5) will be a constant value which is calculated within the Simulation Model according to the user's input. The second part (ii), (i.e. indirect project cost at an accelerated duration) is directly proportional to the project duration and can be calculated using the formula (4). This leaves only part (iii) of equation (5) to be minimised with only the T(i) values being unknown. Thus, the objective function takes the form of minimising the direct cost increase while accelerating the project.

(7.4.2) Constraints

The following constraints are formulated with the information available from the user input into the Simulation Model (Section (7.3)).

\[ X_p \leq A \quad \ldots \ldots (6) \]
\[ X(pi) - X(i) + T(i) \geq L(i) \quad \ldots \ldots (7) \]
\[ T(i) \leq T_s(i) \quad \ldots \ldots (8) \]
\[ T_s(i) = D_n(i) - D_c(i) \quad \ldots \ldots (9) \]
where:

\[ X_p \] = Project duration.
\[ X(i) \] = Earliest start time of the task i.
\[ X(pi) \] = Earliest start time of the task pi which is following activity i.
\[ T(i) \] = Number of days in which the task i should be compressed.
\[ L(i) \] = Lag value between task i and the following task pi.
\[ Ts(i) \] = Maximum amount of time by which each task can be shortened.
\[ D_n(i) \] = Duration of the task i under normal conditions.
\[ D_c(i) \] = Duration of the task i under crash conditions.
\[ A \] = Project duration under normal conditions.

The above discussion can be made more clear with the following example.

**Example:**

<table>
<thead>
<tr>
<th>SUPERSTRUCTURE</th>
<th>X(1)</th>
<th>Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) FRC Cols/Walls</td>
<td></td>
<td>Normal Crash</td>
</tr>
<tr>
<td>Grd-1st Floor</td>
<td></td>
<td>9 5</td>
</tr>
<tr>
<td>X(2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) FRC Slab/Beams</td>
<td></td>
<td>7 4</td>
</tr>
<tr>
<td>Floor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X(3)</td>
<td></td>
<td>10 8</td>
</tr>
<tr>
<td>(3) Staircases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4) FRC Cols/Walls</td>
<td></td>
<td>8 5</td>
</tr>
<tr>
<td>1st-2nd Floor</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lag (days)</th>
<th>Between 1 &amp; 2</th>
<th>Between 2 &amp; 3</th>
<th>Between 2 &amp; 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Assume that the whole project is composed of only these 4 activities X(1) to X(4). In the example the duration of the project under normal conditions, will be 12 days.
The above information can be presented in the form of linear programming constraints as follows:

\[
\begin{align*}
X(2) - X(1) + T(1) & \geq 2 \\
T(1) & \leq 4 \\
X(3) - X(2) + T(2) & \geq 2 \\
T(2) & \leq 3 \\
X(4) - X(3) + T(3) & \geq 1 \\
T(3) & \leq 3 \\
X_p & \leq 12
\end{align*}
\]

The above logic has been used to formulate the constraints for reinforced concrete multi storey buildings and these are presented in Appendix 4.

The discussion on the linear programming formulation can be presented as in Figure 7.2.

\[
\begin{array}{ll}
\text{Fixed } T_s(i) & \\
U(i) & X_p \leq A \\
L(i) & T(i) \leq T_s(i) \\
\text{Variable } T(i) & X(pi) - X(i) + T(i) \geq L(i) \\
\text{Min } Z = \sum U(i) \times T(i) & i = 1
\end{array}
\]

Figure 7.2 The Model of the Linear Programming Formulation
The abbreviations in Figure 7.2 have been explained in this section and in Section 7.4.1.

(7.5) **Coefficients of the Variables in the Objective Function and the Constraints**

As discussed in Section 5.4.2, the procedure while using the Simplex Method is based on a matrix which requires a knowledge of all the coefficients of all variables within the objective function and all the constraints. Thus, two computer programmes OPT1 and OPT2 have been designed to create data files to present the coefficients of the variables in the objective function and the constraints, respectively. The data files contain the following data, respectively:

(1) OPT2 generates equality or inequality signs ('eq','le','ge') and the coefficients of the variables of the constraints that will be used during the optimisation procedure (see constraint equations in Section 7.4.2). The total number of constraints and variables change with the number of floors and is equal to \((21 \times \text{number of floors} + 46)\) and \((18 \times \text{number of floors} + 41)\) respectively. These numbers have been determined by running OPT2 for different numbers of floors.
(2) Coefficients of variables of the objective function, i.e. U(i) values for each task included within the Simulation Model are generated by OPT1.

(7.6) Optimisation Programme

Figure 7.3 shows the flow chart of the programme. The programme first reads the number of floors, the normal direct costs, the indirect costs and the project duration. The coefficients of variables of the constraints and of the objective function are read by the optimisation programme and processed by the Simplex Algorithm. Although normal direct costs, indirect costs and project duration time are not used directly by the Simplex Algorithm, their values are used to calculate total project cost at a particular duration, after the minimum direct cost increase has been determined by using the Simplex Algorithm.
List of terms for Figure 7.3:

hindir: total indirect cost.
dirtot: total direct cost.
n: number of constraints.
m: number of variables.
kode(n): equation sign of the nth constraint.
d(i): coefficient of variable (i) in the objective function (at the end of each run d(i) values represent the starting times (in days) of tasks and the acceleration values (in days) of tasks).

ratio(i): coefficient of variable (i) in the objective function.
a(i,j): coefficient of variable (j) of the constraint (i).

Xp: Project duration (normal project duration at the first run, accelerated project duration at the other runs)

zcm: Coefficient of the entering column.

aj: Number of the entering column.
b(j): The right hand side value of the constraint equation j.
b(1): Optimum value, i.e. minimum increase in project direct cost.
d(1): Duration of the project when objective function has the minimum value b(1).

xx: Pivot element.

iter: iteration number.

new_ind: Indirect cost at an accelerated duration.

new_indl: Decrease in indirect cost due to the acceleration in project duration from normal duration.

cost_increase: Direct project cost increase due to the acceleration in project duration from normal duration.

new_total: total project cost at the accelerated duration.
START
Read nof, hindir, dirtot, Xp

\[ n = 18 \text{nof} + 41 \]
\[ m = 21 \text{nof} + 56 \]
\[ \text{kod} = 1 \]
\[ \text{tol} = 0.0001 \]
\[ \text{zcm} = 0 \]

\[ i = 1 \]

Read d(i)
\[ \text{ratio}(i) = d(i) \]

Is \( i > m \)?

Yes
\[ j = 1 \]

Read kode(j)
\[ j = j + 1 \]

No

Is \( j > n \)?

Yes
\[ i = 1 \]
\[ j = 1 \]

Read a(j,i)
\[ i = i + 1 \]

No

Is \( i > m \)?

Yes

stage 2

Figure 7.3 (a) Stage 1 of the Flow Chart For the Optimisation Programme
Figure 7.3 (b) Stage 2 of the Flow Chart For the Optimisation Programme
Figure 7.3 (c) Stage 3 of the Flow Chart For the Optimisation Programme
Figure 7.3 (d) Stage 4 of the Flow Chart For the Optimisation Programme
Figure 7.3 (e) Stage 5 of the Flow Chart For the Optimisation Programme
Figure 7.3 (f) Stage 6 of the Flow Chart For the Optimisation Programme
Figure 7.3 (g) Stage 7 of the Flow Chart For the Optimisation Programme


Figure 7.3 (h) Stage 8 of the Flow Chart For the Optimisation Programme
In the first iteration, the value of the objective function, (i.e. the minimum direct cost increase and the corresponding project duration) is determined. After the first iteration the duration of the project is decreased at 1 day intervals from the minimum direct cost duration, and the project costs (direct, indirect and total) are calculated for each 1 day interval. The procedure continues until the duration that is not feasible to complete the project is reached (i.e. after all crash duration is reached). At the end of the execution of the programme the following information can be obtained by the user for every 1 day acceleration of the project duration between all normal and all crash durations:

(a) The change in direct and indirect costs of the project,

(b) new project direct, indirect and total project costs,

(c) the name of the tasks to be accelerated.

Additionally the optimum duration corresponding to the minimum total project cost is provided as an output.
(7.7) Running the Model

After all the input into the Simulation Model has been completed and the output (i.e. normal and crash costs and duration for all the tasks and the whole project) has been determined, the user has to exit from the Simulation Model through the 'EXIT' choice on the 'Main Menu'. The user will see the '<c:\opt>' on the screen. Then, he/she has to run the optimisation model by only typing 'c:\opt\optimum'. After this, the user has to type 'c:\opt\data' to see the output from the programme.

(7.8) Development Software

The programmes for the linear programming formulation has been developed using QBasic, whereas the optimisation programme has been developed by using FORTRAN 77. The main reason for this is because FORTRAN 77 with a DOS Extender called DBOS is better in dealing with big arrays than QBasic (see Bailey (1989)).

(7.9) Summary

The optimisation part of the integrated computer model is discussed in this chapter. The input for the Optimisation Model is provided by the Simulation Model. This input is formulated in order that it can be used by the Simplex Method.
The aim of the optimisation part is to determine the minimum total project cost corresponding to the optimum project duration. However, the objective function takes the form of minimising the direct cost increase while accelerating the project from an all normal situation to an all crash situation. This is because the total project cost consists of direct and indirect costs and indirect costs of the project decrease linearly as the project duration is decreased. The objective function is subject to the constraints that the project duration cannot be less than the duration calculated within the Simulation Model under normal conditions i.e. a task cannot be compressed more than the difference between its normal and crash duration (both of which are calculated within the Simulation Model) and the lag values between two preceding tasks cannot be less than either the lag value input in the Simulation Model or the difference between the duration of the preceding task and the lag value if the following task starts after the finish date of the preceding task.

Under the given constraints and objective function, the programme firstly finds out the minimum direct cost increase and corresponding duration. Then, the project duration is accelerated by 1 day and the increase in direct cost is determined. The output includes the changes in direct and indirect costs to accelerate the project duration from all normal to that particular duration, new direct, indirect and total project costs for every one day acceleration from all normal duration to all
crash duration, the name of the tasks to be accelerated, and the optimum duration corresponding to the minimum total project cost.
CHAPTER 8
(8.1) Introduction

Bowman and Lomas (1985) state that validation is concerned with testing the validity of a model's theoretical basis and its ability to reproduce observed performance. Thus, according to Taha (1989) a model is valid if, despite its inexactness in representing the system, it can give a reasonable prediction of the system's performance. Additionally, Anderson et.al (1985) state that another approach is to have the overall model reviewed by people who are most familiar with the operation of the real system.

The above comments have been considered while validating the integrated model. The validation of the model includes validation of the Simulation Model, validation of the Optimisation Model (which are discussed in this chapter) and obtaining the opinions of the practitioners regarding the integrated model and its acceptance by construction firms (see Appendix 2).
(8.2) Validation of the Simulation Model

(8.2.1) Validation of the Duration and Cost Results Under All Normal Conditions

For the validation of the duration values under all normal conditions, the author prepared bill papers including the items used within the Simulation Model. Then, a bill of quantities for a hypothetical 6 storey reinforced concrete office block was prepared by the author and a planner from Wimpey Construction. (For simplicity, this planner will subsequently be termed the 'first planner'.) The drawings and the bill of quantities for the hypothetical building are presented in Appendix 5. The planner calculated the duration for undertaking each item by using the formula stated in Section (6.7). A linked bar chart was then drawn according to the calculated duration values (see Figure 8.1).

The bill of quantities and the drawings of the hypothetical building were then given to the chief planner in KS (termed the 'second planner') and he also calculated the duration values for each item by using the formula stated in Section (6.7) and drew a linked bar chart (see Figure 8.2).

When the two bar charts in Figure 8.1 and Figure 8.2 are compared, it is seen that different duration values were
calculated by the two planners for the same tasks (41 and 35 weeks, i.e. 205 and 175 days, excluding the weeks for the holidays). This is due to the differences in output rates, gang sizes and the lag values used by the two planners. Table 8.1 (a) and (b) show the different values of task duration results from the two planners which resulted from their use of different output rates as a consequence of different documentation based on the previous experiences of each company.

The model was run twice for the purposes of validation. During the first run, the quantities of materials for the hypothetical building were input into the model with the gang sizes, output rates and lag values used by the first planner. Appendix 6 shows the input screens from the Simulation Model used for the input of quantities of materials for the hypothetical building. During the second run, the values of gang sizes, output rates and lag between tasks were changed according to the second planner's data. Inevitably, different results were obtained for the duration of tasks and the project duration (see Appendix 7). The duration values for tasks (in weeks) obtained during the two validation runs are summarised in Table 8.1 (a) and (b).
Figure 8.1 Linked Bar Chart Drawn By the Planner from Wimpey
Figure 8.2 Linked Bar Chart Drawn By the Planner from Kyle Stewart
<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
<th>Unit</th>
<th>Output Unit</th>
<th>man hours</th>
<th>man weeks</th>
<th>Gang Size Planner</th>
<th>Gang weeks Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SUBSTRUCTURE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excavate topsoil (removed)</td>
<td>180</td>
<td>m3</td>
<td>25 m3/hr</td>
<td>8</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>Excavate topsoil (preserved)</td>
<td>90</td>
<td>m3</td>
<td>25 m3/hr</td>
<td>4</td>
<td>0.1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Reduce levels</td>
<td>510</td>
<td>m3</td>
<td>30 m3/hr</td>
<td>17</td>
<td>0.4</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>Excavate foundations</td>
<td>155</td>
<td>m3</td>
<td>6 m3/hr</td>
<td>26</td>
<td>0.7</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>CONCRETE FOR:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blinding</td>
<td>9</td>
<td>m3</td>
<td>4.5 hr/m3</td>
<td>41</td>
<td>1.0</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>Isolated bases</td>
<td>1</td>
<td>m3</td>
<td>hr/m3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beds</td>
<td>240</td>
<td>m3</td>
<td>0.5 hr/m3</td>
<td>120</td>
<td>3</td>
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Table 8.1(b) Comparison of Normal Duration Values Obtained by the Second Planner and the Simulation Model

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8-7
During each run, a linked bar chart was drawn automatically and Figures 8.3 and 8.4 respectively show the first and the final screens of the linked bar chart drawn for the second case. Other screens of the bar chart are presented in Appendix 10.

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<td>(5) Formwork</td>
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Figure 8.3 First Screen of the Bar Chart
For the validation of the cost results, it was not possible to get unit cost data from the estimators. Thus, for the validation, empirical data (mainly from Wessex Major Works (1994)) were input into the relevant screens within the Simulation Model, in addition to the data from the second planner. The print-outs of the input screens are presented in Appendix 8. Additionally, the output screens in Appendix 9 show the activity cost results from the model. The validation of these results was achieved by comparing them with the results calculated through a spreadsheet by using the same formulae that had been used within the model (see Section 6.7). Table 8.2 shows the figures obtained from the spreadsheet calculations and the model. It should be noted here that the validation of the cost
results from the model by only comparing their mathematical accuracy with the spreadsheet results can be found to be more of a verification than a validation. However, it was not possible to get any more information related to cost estimation from the contractors due to the confidentiality of this information.

Table 8.2 Comparisons of the Total Cost Values Obtained by Using A Spreadsheet and the Simulation Model.

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<th>Material Cost</th>
<th>Labour/Plant Cost</th>
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<th>Total Cost (Model)</th>
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(8.2.2) Validation of the Duration and Cost Results Under Crash Conditions

After validating the normal cost and duration values, the validation of the duration and cost results under crash conditions was achieved by ensuring that the calculations for the productivity loss (see Section 6.10) were undertaken correctly and consequently the duration and cost values were calculated as accurately as possible.

The validation was achieved by running the model twice. The first run was to effect acceleration of work by employing more labour and the second by overtime work. In both cases to achieve simplicity the productivity loss was input as being 0.1% for every increase of 1% in gang size and as 1% for every extra hour per week for all tasks.

Tables 8.3 (a), (b) and 8.4 (a), (b) show the results obtained from the calculations using a spreadsheet and using the computer model for accelerating the project by either respectively employing more labour or using overtime work (also see Appendix 11).
Table 8.3(a) Comparison of the Duration Results from the Simulation Model with the Spreadsheet Calculations for Accelerating the Project by Employing More Labour

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Table 8.3(b) Comparison of the Cost Results from the Simulation Model with the Spreadsheet Calculations for Accelerating the Project by Employing More Labour

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Table 8.4(a) Comparison of the Duration Results from the Simulation Model with the Spreadsheet Calculations for Accelerating the Project by Using Overtime Work

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Table 8.4(b) Comparison of the Cost Results from the Simulation Model with the Spreadsheet Calculations for Accelerating the Project by Using Overtime Work

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8 - 15
(8.2.3) Discussion of Results

The following points can be made regarding the validation of the results.

(1) Comparison of the results obtained by the two planners with the results obtained from the Simulation Model (see Figures 8.1, 8.2, 8.3, 8.4 and Table 8.1), show that the procedures applied within the model are exactly the same as the procedures applied in practice when calculating the duration of tasks.

(2) The duration of tasks obtained during the 2 validation runs of the model are exactly the same as, or are within the range of 0.2 weeks of the values calculated by the two planners (Table 8.1). For the project duration, the difference between the planners' results and the model's are 2 days and 3 days respectively for the first and the second runs for a total project duration of 207 and 172 days respectively.

(3) The discrepancies in the results of the normal cost calculations between those of the model and those of the spreadsheet are at most 0.04% (for 'external brickwork) (see Table 8.2).

(4) There is at most 0.4 days difference for the duration results while accelerating the project between the model and the
spreadsheet. The discrepancies in the results of the cost calculations between those of the model and those of the spreadsheet while accelerating the project, generally do not exceed, 0.4% (see Tables 8.3 (a), (b) and 8.4 (a), (b)).

(5) The discrepancy in the duration results for 'reinforcement for foundations' is due to the fact that the same gang size is used for both 'steel bars' and 'mesh reinforcement' within the model (see Tables 8.1(b), 8.3(a), 8.4(a)).

(6) The acceleration of the tasks involving excavation is assumed to be by changing the type of plant, as productivity loss due to acceleration of work has not been considered within the model for these tasks.

The validation of the results from the Simulation Model proved that the model works as intended and gives acceptable results. The degree of precision of the results is influenced by the fact that the model makes calculations only to the first place of decimals which causes discrepancies between the results from the model and the spreadsheet. However, these differences can be ignored, because during the planning process values are usually rounded to the nearest whole number.
(8.3) Verification and Validation of the Optimisation Model

(8.3.1) Verification of the Programme OPT1

As discussed in Section (7.4.2), the aim of developing OPT1 was to calculate the coefficients of the variables of the objective function, i.e. U(i) values. U(i) values are calculated by using the input data from the Simulation Model, and then stored in a data file so that they can be read by the optimisation programme OPTIMUM. To be able to check if the U(i) values are calculated and stored correctly, these values were calculated using a spreadsheet and were compared with the ones in the data file <opt2.dat> (see Table 8.5).
Table 8.5 Checking the Accuracy of the Coefficients of Variables of the Objective Function.

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<th>Normal Direct Cost (£)</th>
<th>Crash Direct Cost (£)</th>
<th>Normal Duration (days)</th>
<th>Crash Duration (days)</th>
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<th>U(i)* Cost Slope (Model)</th>
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It should be noted here that for the validation of the optimisation model, it was assumed that all of the activities were crashed by employing more labour and the values in Tables 8.1(b), 8.2, 8.3(a) and 8.3(b) were used.
(8.3.2) Verification of the Programme OPT2

OPT2 was developed to produce data files containing the equation equality, inequality signs and the coefficients of the variables for each constraint (see Section 7.5).

Due to the large amount of data, which is more than \((378 \times \text{(number of floors)})\), it was not possible to check the results from this programme in as simple a way as it had been with the programme OPT1.

The only way to verify OPT2 was by checking if the optimisation programme OPTIMUM gave feasible solutions. The optimisation programme OPTIMUM did not give feasible solutions until the coding for the order of the coefficients of variables for every constraint were correct (see Section 7.5). Thus, the results of the programme OPT2 required running OPTIMUM and checking if it gave <infeasible solution> or not. When the execution of OPTIMUM was halted due to <infeasibility>, the number of the equation which caused the <infeasibility> in the solution was printed on the screen so that it was easy to check the equation and its coding from OPT2.

After feasible solutions were achieved from the programme OPTIMUM, these results were validated (see Section 8.3.3). The
validation results established that the constraints had been formulated and coded in the right way.

It should be noted here that, validation of the results of OPT2 constituted the most time consuming procedure due to the large numbers of variables and constraints.

(8.3.3) Validation of the Programme OPTIMUM.

As discussed in Chapter 7, OPTIMUM is the computer programme that uses the Simplex Algorithm to solve the optimisation problem.

The first step for the validation of the programme was to validate the Simplex Algorithm by using a small amount of data. After it was confirmed that the Simplex Algorithm worked as intended, the programme was run with the data used during the validation of the Simulation Model. As mentioned in Section 8.3.2, the first results from OPTIMUM were in the form of 'infeasible solution' as there were originally coding mistakes in the programme OPT2. Once, these mistakes were corrected, feasible solutions could be achieved from OPTIMUM and then it was easy to validate the results.

The optimisation programme has the object of finding the minimum increase in direct cost, and gives in the first run zero
increase in direct cost. This, inevitably corresponds to the project duration under all normal conditions.

As discussed in section 7.6 after the first run, the project duration was decreased by 1 day at a time and the minimum increase in the direct cost corresponding to this 1 day decrease in duration was determined. This process was continued until the all crash duration was reached. The key results are presented in Table 8.6 (see also Appendix 12). In addition the resulting costs are plotted against duration in Figures 8.5(a) to (d) and the bar chart showing the critical path for the construction of the hypothetical building (before starting the optimum procedure, i.e. for all normal situation) is given in Figure 8.6. Table 8.7 gives the order of tasks from the lowest cost slope to the highest cost slope.

The following abbreviations are used in Table 8.6.

- **DC Increase**: Increase in direct cost of the project to accelerate the project duration from all normal duration to a particular duration.
- **IC Decrease**: Decrease in indirect cost of the project to accelerate the project duration from all normal duration to a particular duration.
- **TC Increase**: Increase in total project cost to accelerate the project duration from all normal duration to a particular duration.
- **New DC**: Project direct cost at a particular duration.
- **New IC**: Project indirect cost at a particular duration.
- **New PC**: Total project cost at a particular duration.
- **Task numbers**: 1 to 6 = 'reinforcement for columns/walls' from ground/1st floor to 5th/roof, 7 = 'excavate topsoil', 8 = 'reduce levels', 9 = 'roof asphalt', 10 = 'concrete for roof slabs/beams', 11 = 'formwork for foundations'.
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Figure 8.5 (a) Project Direct Cost-Duration Curve
FIG. 8.5 (b) Indirect Cost-Project Duration Curve

Project Duration (days)

Indirect Cost
Figure 8.5(c) Total Project Cost-Duration Curve

Project Duration (days)

Total Cost (E)
Figure 8.5 (d) A Section of the Project Total Cost-Duration Curve Showing the Minimum Project Duration (days)
Substructure
1 Excavate topsoil
2 Reduce level
3 Excavate found.
4 Blinding concrete
5 Frc foundations
6 Frc ground slab

Superstructure
7 Frc cols grd - 1st
8 Frc 1st flr slab
9 Frc stairs grd-1st
10 Frc cols 1st-2nd
11 Frc 2nd flr slab
12 Frc stairs 1st-2nd
13 Frc cols 2nd-3rd
14 Frc 3rd flr slab
15 Frc stairs 2nd-3rd
16 Frc cols 3rd-4th
17 Frc 4th flr slab
18 Frc stairs 3rd-4th
19 Frc cols 4th-5th
20 Frc 5th flr slab
21 Frc stairs 4th-5th
22 Frc cols 5th-roof
23 Frc roof slab

Envelope
24 Internal blockwork
25 External brickwork
26 External blockwork
27 Asphalt Roofing

Figure 8.6 Linked Bar Chart Showing the Critical Path
Table 8.7 The Order of Tasks From Lowest Cost Slope to the Largest Cost Slope

<table>
<thead>
<tr>
<th>Task</th>
<th>Cost Slope (direct cost increase per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforcement (columns/walls)</td>
<td>1.7</td>
</tr>
<tr>
<td>Reinforcement (slabs/beams)</td>
<td>2.67</td>
</tr>
<tr>
<td>Blinding concrete for foundations</td>
<td>4.3</td>
</tr>
<tr>
<td>Concrete (columns/walls)</td>
<td>11.8</td>
</tr>
<tr>
<td>Excavate foundations</td>
<td>54.0</td>
</tr>
<tr>
<td>Formwork (columns/walls)</td>
<td>61.0</td>
</tr>
<tr>
<td>Excavate topsoil</td>
<td>61.7</td>
</tr>
<tr>
<td>External brickwork</td>
<td>80.63</td>
</tr>
<tr>
<td>Reduce levels</td>
<td>81.6</td>
</tr>
<tr>
<td>Roof asphalt</td>
<td>84.51</td>
</tr>
<tr>
<td>Internal blockwork</td>
<td>90.53</td>
</tr>
<tr>
<td>Formwork (foundations)</td>
<td>96.1</td>
</tr>
<tr>
<td>Formwork (slabs/beams)</td>
<td>111.02</td>
</tr>
<tr>
<td>Reinforcement (foundations)</td>
<td>119.5</td>
</tr>
<tr>
<td>Concrete (slabs/beams)</td>
<td>129.6</td>
</tr>
<tr>
<td>External blockwork</td>
<td>144.95</td>
</tr>
<tr>
<td>Concrete (foundations)</td>
<td>168.53</td>
</tr>
</tbody>
</table>

(8.3.4) Discussion of Results

The results in Table 8.6 show the significant effect of the value of the indirect cost decrease on project cost while accelerating the project duration. These results show the importance that should be given to what is included in the estimation of indirect costs. They also raise a question as to the accuracy of the results when a linear relationship is assumed between project indirect costs and duration.

As discussed in Section 4.6.1, a multi-linear direct cost curve should be convex in shape and the slopes of the lines should get steeper as project duration is reduced as is the case
for Figure 8.5(a). Any concave portion in the curve that is produced from the results of a linear programming solution would be due to an arithmetic error or a logically incorrect order during the crashing procedure. The validation of the results has been based on this convexity theorem. It may be beneficial to remind the reader here that the convexity theorem suggests that the task with the lowest cost slope (i.e. $U(i)$ values from the objective function formulation) should be accelerated first (see Table 8.7). Then the crashing will continue with the second lowest and so on. However, having the lowest cost slope (i.e. $U(i)$ value) is not the only factor that has to be considered whilst deciding if a task can be crashed. The task should also be on the critical path, as otherwise, crashing that task would not affect the project duration but only increase the project cost.

Table 8.7 shows that according to the cost slope priority 'reinforcement for columns/walls' should be crashed first. It can be observed from the bar chart in Figure 8.6 that 'FRC for columns/walls' for each floor is on the critical path. When the activity 'FRC for columns/walls' is investigated in detail the following figure would be achieved.
The above figure shows that both tasks 'reinforcement for columns/walls' and 'formwork for columns/walls' are on the critical path. This is due to the fact that the task 'formwork for slabs/beams' which is the starting task of another critical activity, i.e., 'FRC slabs/beams' on the bar chart, starts after the finish date of both (i.e. both tasks 'reinforcement for columns/walls' and 'formwork for columns/walls' having total floats being equal to 0) Thus, crashing 'reinforcement for columns/walls' would affect the project duration. It can be seen from Table 8.5 that this task can be crashed for 2 days for each floor. This brings the project duration down to 160 days.
Figure 8.8 Detailed Presentation of FRC for Columns/Walls After Crashing Reinforcement for Columns/Walls

Although 'reinforcement for slabs/beams' has the second lowest cost slope (see Table 8.7), when Figure 8.9 is examined it can be seen that crashing this task would have no effect on the critical path.

Figure 8.9 Detailed Presentation of FRC for Slabs/Beams with Reinforcement for Columns/Walls
'Blinding concrete for foundations' has the third lowest cost slope. However, as this task starts at the same time with its following task 'formwork for foundations' crashing it would therefore not have any effect on the project duration.

As it can be seen from the Figure 8.8, 'concrete for columns/walls' has also no effect on the critical path and thus this task is also skipped by the model.

The above logic is applied during the crashing of all the tasks. Thus, while task 'excavate foundations' is not crashed as crashing this would not affect the project duration, 'formwork for columns/walls' is not crashed due to the constraints on lag values (see Section 7.4.2 and 7.9). The task 'excavate topsoil' which is on the critical path is crashed for 1 day.

The task 'reduce levels' is crashed for 1 day and 'roof asphalt' is crashed for 15 days resulting in 143 days project duration with total project cost of £ 691064.8 (which is the minimum cost corresponding to the optimum duration). After 'roof asphalt', 'concrete for roof slabs/beams' and 'concrete for foundations' are crashed for 2 days and 4 days respectively.

It should be stated here that there is a contradiction for the brickwork-blockwork tasks between the Optimisation and the Simulation Models. The bar chart drawn within the Simulation
Model presents both of these tasks as 1 activity by adding their duration. However, in the Optimisation Model these two activities are considered separately and follow the same activity, i.e.; ‘FRC slab/beams’ for the user defined floor. Thus, although the followed critical path is the path leading to the 'Roof Asphalt' throughout the optimisation procedure, the critical path might have changed to one leading to the ‘External Brickwork/Blocwork’ which would have changed the crashing order of the tasks.

One additional point should also be made. During the interviews, the planners stated that while crashing the task durations some of the lag values may also change. However, within the integrated model only one lag value between two tasks is considered. Thus, for the tasks with end floats (i.e. being partially critical-critical duration equal to the lag value with the preceding task), having a shorter lag value would mean considering the difference between the normal and the crash lag values while crashing the tasks. However, such an approach would mean splitting each task into different tasks and constructing the constraints accordingly. It is the author’s opinion that to apply such an approach would be impracticable as it would increase the number of constraints to at least double, and dealing with a large number of constraints was found to be a particular disadvantage of the linear optimisation method.
Validation of the results from the integrated model has been discussed. The validation procedure has been undertaken mainly in two steps which are the validation of the Simulation Model and the validation of the Optimisation Model.

The validation of the results from the Simulation Model showed that the procedure applied within the model is exactly the same as the procedure applied in practice when calculating the duration of tasks. Additionally, the results from the cost and duration estimations were found to be in good agreement with the results calculated by the construction planners and the results by using the spreadsheet.

The results from the Optimisation Model have been validated by checking if they maintain the convexity theorem for duration and direct cost relationships. This has proved that the model works in a logically correct order during the crashing procedure.

In Chapter 9, the benefits obtained from the integrated model, its limitations and possible future developments will be discussed by considering the results of the validation and the conclusions of the previous chapters.
CHAPTER 9
(9.1) The Strengths of the Integrated Computer Model

The strengths of the integrated model can be stated as follows:

(1) The outputs from a computer model should not only be self explanatory but also be presented in different ways ensuring that different decision makers receive only that part of the output which is relevant to their action. It is the current author's contention and the interviewed practitioners' opinion that the integrated model provides these criteria for pre-tender (or even for pre-contract stages). This is because the output from the model is clearly presented in different formats. These are:

(a) An output screen for each main activity showing direct cost and duration values for all tasks under normal conditions.

(b) An output screen for each main activity showing direct cost and duration values for all tasks under normal conditions and direct cost under all crash conditions.
(c) An output screen showing the project direct, indirect and total costs for all normal and the project direct costs for all crash situations.

(d) A linked bar chart showing the sequence and duration values of tasks for normal duration situations.

(e) Display of the direct, indirect and total project cost values corresponding to different duration times for undertaking the project and the name of tasks that have been crashed to accelerate the project duration.

Additionally, all the input data can be displayed and printed, when the relevant input section is entered through the 'Main Menu'.

(2) The output from the model is not just in the form of one time vs. cost value but time vs. cost values for each unit time (day) interval between all normal and all crash duration. This provides the user with the facility to examine the various time-cost possibilities available when undertaking the project.

(3) The effect on duration and cost, of changes in quantities of materials, output rates, gang sizes, unit costs, and lag values, can be rapidly observed. The effect is also automatically displayed in the linked bar chart. The data input for a project
can be used or updated for subsequent projects as all user input is stored into data files and called back by the model.

(4) The model has potential application not only as a teaching or training aid but also as a decision support system for inexperienced planners/estimators in large contracting firms and for estimating/planning purposes in small to medium contracting companies. As a training aid, it would help students to become familiar with SMM7, with bills of quantities, and with some of the procedures of planning and estimating and the interaction between them.

(5) The model can be modified in stages without affecting the current structure of the model as Leonardo provides a flexible development environment.

(6) The optimisation model is based on the Simplex Algorithm which most construction practitioners would not have any knowledge of. However this is not a disadvantage in that human judgement is allowed to be exercised for both input and output of the optimisation process. The input to the model is through the Simulation part where the user can exercise different possible outcomes in a user friendly environment. Also, the output from the model allows the user to check if the right task (i.e., the task with the lowest cost slope on the critical path) has been crashed.
(9.2) The Weaknesses and Possible Future Developments of the Model

The model which has been developed for this project has, like all models certain weaknesses and deficiencies which are outlined below. Some of these deficiencies can be overcome by further developments of the model and where this is the case suggestions are made as to how this can be achieved.

(1) The simulation model has been developed for multi storey (any building with more than two floors) reinforced concrete office buildings. The time/cost model can be developed for other frame types by adding information in the 'Superstructure' section. However, a new bar chart has to be developed for the new frame type. More importantly, the model would be more beneficial for practitioners if it could be integrated with the commonly used construction programming computer programmes.

(2) The 'uniqueness' of every construction project may require additional activities to be included. For example the choice of only one type of foundation and roof, and the limited types of materials included would impose restrictions for some projects. However further modules can be developed within the model for calculation of duration and cost of these additional activities.
(3) Module B which comprises finishes and services can be extended to make it possible to calculate the duration and cost of activities included within this module.

(4) For the acceleration of activities, only one of the possible methods (i.e. employing more labour/plant or overtime work) can be chosen for each construction task under each ‘Main Activity’. The model can however be modified to enable both choices to be made in combination for each construction task.

(5) During the crashing procedure of the activity durations some lag values may change. Considering that for partially critical activities the lag values would affect the crashing procedure it is necessary to treat these as different activities and construct the linear programming constraints accordingly. However, such an approach would undoubtedly at least double the number of constraints, and impracticable due to the time limitations of this research, as dealing with a large number of constraints was found to be a particular disadvantage of the linear optimisation method.

(6) While assuming a linear relationship between activity cost and duration, the gang sizes are assumed to be increasing one man at a time. However, for some trades (like steel fixers, brickmen and carpenters) the gang sizes would not be increased by one man
only as the men work in groups of two or more. Thus, an incremental increase in gang sizes would be more realistic.

(7) During the interviews, the linked bar chart drawn by the computer model was stated to be sufficient for the current development of the time/cost model. However, two weaknesses of the integrated model, related to the bar chart drawing, should not be ignored. Firstly, it would make it easier for the model to be accepted by the industry if it could also interact with currently in use bar chart drawing computer programmes. Secondly, the linked bar chart is provided only for the project duration under all normal conditions. This is due to the fact that repetition of the same duration for the same activities on different floors was assumed within the programming logic for the bar chart and this logic does not work while accelerating the project. However if required the computer programme can be modified to provide bar charts for all crash duration and for the optimum project duration.

(8) The bar chart can be improved to show the dates of the activities and holiday times during the project duration.

(9) Although the detail in the output presentation is sufficient for different management levels, it was stated by the planners that it would be an advantage to display the costs of labour, material and plant separately.
(10) The model can be modified to provide a cash flow curve as the use of S curves has been increasing in the industry especially after the introduction of the Private Finance Initiative.

(11) During the interviews, the details of the computer model were stated to be ideal for pre-tender and pre-contract planning stages. However it was also stated that future development of the model should consider the fact that the 'superstructure' section of the model can be modified to provide a useful tool in itself not only for tender programming but also for detailed contract programming.

(12) The effectiveness of the model as a training tool needs to be tested. The model can be introduced to undergraduate students and their feedback can be used for further modifications.

(13) Although the validation of the model showed that the model works as intended and employs estimating and planning procedures acceptable by the interviewed practitioners, this may not be found to be enough for the acceptance of the model by some of the end users, due to the relatively small sample size during validation (i.e. use of data/information from two planners). Thus a more extensive survey should be undertaken to obtain the opinions of a much wider range of practitioners on the strengths, weaknesses and possible future developments of the model.
However, a questionnaire survey would not be the appropriate method of collecting such information and the process of interviewing such a wide range of practitioners would be very time consuming and would itself form a major research project. It is also generally accepted that it is very difficult to obtain what may be sensitive commercial information/data related to tendering processes (especially estimating) and construction practitioners do not often have the available time from what is often a very busy schedule.

(9.3) General Conclusions

In the light of the first objective of the research it has been established that the decisions undertaken by the building contractor, starting during the pre-tender stage till the end of the contract, are normally subject to four constraints; time, cost, the quantity and the quality of the work required. While the quality and the quantity of the work are defined in the project drawings and specifications, the contractor has more control over the time and cost of executing a project.

In the tender documents provided by the client, the period for the execution of the contract is generally stated and in a competitive tendering process the winning tender is usually the one with the lowest price. Although it is important for the contractor to arrive at a minimum price to be successful in a
tender, an unrealistically low price would result in loss to the company at the end of the project. Thus, during pre-tender estimates, the contractor has to make sure that the estimated cost is sufficient for the contract to be executed within the stated contract period under normal working conditions and with the resources available. If this period is too short the contractor has to consider the extra cost of achieving completion for the period required. Thus, while preparing the tender figure it is beneficial for the contractor to be aware of minimum cost corresponding to the optimum duration, and then base the tender figures according to this. The client would also benefit from knowing minimum cost vs. optimum duration because this would demonstrate to the client the effect of early completion of the project on his/her investment.

To obtain an optimum value for project cost/duration, firstly, the possible alternative solutions, which affect project time and cost (i.e. manpower, materials and plant and possible methods of work) must be compared, and the best combination under normal working conditions and resource restrictions must be chosen. Secondly, time-cost relationships for all the activities have to be modelled, by considering the acceleration of activities, by increasing or changing resources, by introducing overtime or shift work and by using different methods of construction. Finally the minimum cost vs. optimum duration must be determined by using standard activity time-cost models.
The interviews carried out by the author showed that while the possible alternatives affecting time and cost of a project are investigated by taking the current market situation in the area that the project is undertaken, generally the other procedures mentioned above are not considered. It is not practical and it is usually impossible, to undertake the above procedure or even one part of the procedure manually in the short periods of time that construction managers have available to make decisions.

While reviewing the state of art of computer based time/cost models (which constitutes second objective) it has been demonstrated that various computer based time and cost models have been developed since the 1980s where simulation and optimisation methods are used. The use of such models not only provides an aid to cut out the repetitive calculations for similar or common items but also eases both transfer of data and the integrated work of different construction practitioners. Additionally time savings resulting from the use of these models may result in overhead cost savings due to the possible decrease in the cost of the tendering team. However, no evidence has been found in the literature of an integrated model which uses a combination of both methods. Thus, the current development of an integrated computer time/cost model, which enables rapid comparison of alternative solutions affecting project costs and duration, which simulates the relationships between construction activities, which models the activity cost/duration
relationships, and which determines different project duration cost solutions including the minimum cost corresponding to optimum duration, represents a new development.

A multi storey reinforced concrete office building has been chosen on which to base the model. The disadvantages of construction of in situ concrete framed buildings, especially in that these are more labour intensive than the other frame types, provide a considerable basis for the application of a combination of simulation and optimisation techniques. Although, the choices are restricted to specific types of foundations, roof and building envelope the model does have the potential for further development to include wider choices. The flexibility provided by Leonardo will allow a staged development without affecting the basic structure of the model.

The decision making processes involved in building construction and the factors affecting the quantitative decisions in relation to time/cost estimation and the project time/cost relationship have been reviewed at the beginning of the research to achieve the first objective. However throughout the research objectives 1 and 3 have been inseparable from each other. Thus the succeeding paragraphs discuss the findings of this research in relation to the development of the integrated model which not only achieves the third objective but also the first objective. It is most desirable for an integrated time-cost model to contain
the minimum number of elements needed to achieve the required accuracy and overall objectives. Previous research has shown that the use of Pareto's Law of Distribution provides a reasonable element of accuracy for cost estimation. However, in an integrated model, inclusion of only the cost-significant items, will not necessarily be successful for time estimating and control. Thus, the activities that are included within a model must include the critical ones necessary for the completion of the project. The cost and time significant activities for reinforced concrete multi storey office buildings have been established to be frame, cladding, roof, services, site establishment and clearance, foundations and finishes. Interviews also showed that formwork has a special importance in terms of time and cost relationship for reinforced concrete structures as the direct cost of the project is affected by the multiple use of the formwork when the project duration is extended, or vice versa.

In practice, direct cost and duration can be derived by calculation, quotation from a specialist, or by assessment on past experience. Due to the specialist work involved in finishes and services, the cost and duration figures are required to be input by the user (quotation from a specialist). For activities of site establishment and clearance, substructure, superstructure and building envelope, the activity duration and direct costs are calculated. Although different methods of estimating can be used
for direct cost calculations, unit cost estimating is best suited for repetitive works where the sequence of equations are well defined and most frequently used for reinforced concrete structures. Thus, use of unit cost estimating within the model requires user input for quantity of work, output rate of plant and labour, the number of plant, gang sizes, unit costs of labour, plant and materials. While the project cost is calculated by adding the costs of every activity and the indirect costs of the project, precedence relationships and lag values between the project activities are of great importance for the calculation of the project duration in addition to the activity duration.

Precedence relationships of activities depend on the constraints on scheduling. The constraints can be divided into four groups including physical relationships among building components, trade interactions, path interferences, and code regulations. The physical relationships can be used to generate much of the needed sequence logic for multi storey reinforced concrete building projects. Precedence relationships between two sequential activities can be finish to start, start to finish, start to start, finish to finish, part complete to start, and part complete to finish with lag values. Although a number of different relationships can be used between project activities, this has proved in some cases to be of disadvantage as the user finds the alternatives both confusing and complicated. Additionally, previous research has shown evidence that project
duration tends to be underestimated when extensive overlapping of activities is used in planning. From reports in the form of literature and from the interviews carried out by the author it was established that start to start and finish to start are the most widely used when sequencing construction activities during pre-tender and pre-contract stages. The validation of the Simulation Model showed that the use of only start to start relationships was adequate for the accuracy of the duration calculations.

All the input data are stored within the model and can be displayed, printed or amended, when the relevant input section is entered. Additionally, output from the model is presented in five different formats where different decision makers can receive only that part of the output which is relevant to their action. One of the output presentations is in the form of a linked bar chart for all normal conditions. Although the selection of any planning technique is dependent upon many factors like complexity, size and type of project, and also the company type and size, in general simple, easy to learn and follow, and flexible plans are preferred to be used by the construction planners. Thus bar charts are the most preferred tools of planning by the construction practitioners.

A project duration can be shortened by accelerating project activities which are on the critical path. Acceleration of an
activity can be by increasing or changing resources, overtime or shift work and using different methods of construction. While the first two result in an increase in direct costs, it is not necessarily the same for the last one. However any project duration decrease inevitably results in a decrease in the indirect costs whatever the method of acceleration is.

Reduction in labour productivity due to overtime work and increase in gang size is the most important reason for the increase in direct cost. Thus, in a deterministic time and cost model the effect of productivity loss, or any other factors, on activity cost and duration should be included as otherwise the activity costs would result in the same value for all possible activity durations.

Theoretically, direct cost-duration relationships of activities are represented as a continuous convex curve. The literature shows that there have been models based on non linear activity cost curves and these curves are derived from historical activity cost/duration data. When the mathematical accuracy of the minimum cost solutions from these models are compared with the models based on multi-linear cost curves there may be differences in the absolute accuracy between the results. However, the reasons causing these differences cannot be clearly established as the results are only based on cost/time estimates. On the other hand one may say that the differences might have
been due to the estimation inaccuracies in piecewise linear procedures or due to the varying quality of historic activity cost/duration data. However, in practice multi-linearity is the most frequent situation for activity duration/direct cost relationships as there are only a certain number of ways to crash an activity. Except for some special cases such as non-convexity and non-optimality, the multi linear direct cost curves are of a convex shape where the slopes of lines get steeper as the duration is reduced. For project cost curves, this is due to the fact that project acceleration is undertaken by crashing the critical path activities with the lowest cost slopes. The validation results establish that the current model satisfies these criteria while crashing the activities. Although such a relationship between cost and duration can deal not only with linear programming techniques but also with dynamic, heuristic and integer linear programming techniques, the last three techniques have been eliminated. This is mainly because of their inability or weakness to deal with linear problems (i.e. non linear and dynamic programming), their disadvantages for modelling repetitive construction (i.e. heuristic methods that are based on network planning techniques) and their weakness in dealing with large sized linear problems (i.e. integer linear techniques). Thus the relationship between cost and duration has been approached using linear programming. The objective function minimises the direct cost increase and is subject to linear cost/duration relationships and resource and physical
constraints. However, such a formulation gives the minimum direct cost increase as being equal to zero at the normal duration. Thus, the project is accelerated one day at a time and the optimisation procedure provides the value of the minimum direct cost increase to achieve that duration. The aim of achieving the minimum total project cost is then fulfilled by comparing each of the total project cost values (which are the total of direct and indirect costs, where indirect costs are assumed to be directly proportional to project duration and to start from zero cost value for traditional procurement) at one day intervals between all normal and all crash durations.

The above logic suggests that there should be a minimum direct cost increase to accelerate the project one day at a time between all normal and all crash duration. The Simplex Method is suitable for such a linear programming problem as it considers that the optimum solution is associated with an extreme point of the solution space where the problem constraints provide the solution space boundaries and every point within the solution space or on the boundaries provides a feasible solution. Thus while accelerating the project from an all normal to an all crash duration, any 'infeasible solution' result from the model would be due to errors in the constraint formulations.

For the aim of simplicity, the multi-linear activity cost curves can be approximated to a linear form. Linear activity
cost/duration relationships have been utilised within the current integrated model. This minimises the amount of input data required from the user for crashing the activities but, when the multi-linear relationship is approximated, greater direct cost values are obtained. However, reports in the literature suggest that a high percentage (90%) of the activities in a construction project have multi-linear time/cost curves with no more than three sections. Additionally, when the activity is accelerated by overtime work, the cost/duration relationship is linear without any approximations. Thus, although it may seem to be in the contractor's interest to use models that utilise multi-linear relationships between activity cost and duration to arrive at a more accurate minimum project cost, the additional effort for modelling and the input requirements from the user may not be justified when the two results are compared.

The constraint formulations are the most time consuming procedures when developing computer models by employing linear programming techniques. However, although it is stated within the literature that greater accuracy cannot be justified while time and cost are only estimated, once the model has been developed greater mathematical accuracy is achieved than is achieved by heuristic models when subjected to the same assumptions during estimating. Additionally, the integration of simulation with optimisation allows human judgement to be exercised over the optimisation process in a user friendly environment. Finally, if
required, the accuracy of the output from the model can easily be validated by the user by checking if the activity with the lowest cost slope on the critical path has been crashed.

Although it is stated within the literature that the concept of optimality may not, in strictly mathematical terms be of major significance for construction practitioners, the current developments in computer technology enable computer models to be both mathematically accurate and practically valuable as decision support systems.

(9.4) Recommendations For Future Research

It is the author's opinion that integration of simulation with optimisation provides a wide perspective for the end user to understand the interaction of different variables and their effect on project cost and duration. However, due to the time restrictions, the possible acceptance of such integrated models within the industry has not been investigated. Further research therefore needs to be carried out to determine their potential application within the construction industry.

During the interviews, one of the planners pointed out that use of integrated time/cost models could change the structure of the industry in relation to the tendering procedures by helping the integration of estimating and planning. A further survey
should therefore be undertaken to assess the general perception in the industry of the possibilities of such changes.

The interviews and the literature review showed that the linear relationship between indirect costs and project duration is an estimating assumption accepted by the industry. However, the validation results in this research showed that the effect of indirect cost decrease while accelerating the project duration is significant in determining minimum total cost/duration. Thus it may be beneficial for the future time/cost optimisation model developments to investigate project indirect cost/duration relationship in more detail.

If uncertainties and interferences are included within a simulation model, output analysis may require expert knowledge. It is a well known fact that construction practitioners generally reject any computer model for which they cannot understand the underlying logic and/or the output. Thus, the integration of simulation with expert systems should provide a more user friendly and acceptable time and cost model in which the expert system would help in respect of providing a more understandable front end to the simulation package.

Expert systems technology provides the basis for incorporation of both quantitative and qualitative analysis. Future model developments should focus on expert systems that are
based on the knowledge of the practitioners and that are able to suggest different strategies that affect the project cost and duration and carry out optimisation.
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