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**OPTIMISING EARTHMOVING BY
LINEAR PROGRAMMING AND
COMPUTER SIMULATION**

by

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*A Doctoral Thesis submitted in partial fulfilment of the
requirements for the award of Doctor of Philosophy of
the Loughborough University of Technology*

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To
My parents,
Wife Sumithra and
Daughter Chaturika

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ABSTRACT

The accuracy of planning and estimating of earthmoving operations in any highway construction is important for both successful tendering and high profit margins. Mass-haul diagrams and experienced engineering judgement together with deterministic methods have been the key factors in planning and estimating earthmoving operations. Despite this, the limited use of Mass-haul diagrams and inaccuracy of deterministic estimates are well known. Although Stochastic and Linear Programming methods were developed to overcome some of these limitations, those available hitherto are relatively fundamental and are not bold enough to incorporate most real life problems.

After identifying the need for a relatively quick and accurate planning and estimating procedure, a new approach was developed by combining Computer Simulation and Linear/Integer Programming. The developed model was named RESOM; an acronym for Roadwork Earthmoving System Optimisation Model and was developed in three basic stages: simulation model; LP/IP model; and network model. RESOM can be applied to any road project to obtain an optimum earthmoving plan including material distribution, plant utilisation incorporating real life problems and constraints.

The main aims of the simulation model were to obtain realistic unit costs and production rates using balanced plant teams. Various cycle element times of earthmoving equipment were obtained from standard distributions fitted onto field data collected from four sites in Sri Lanka. Comprehensive LP/IP formulations were developed incorporating constraints like project duration, plant availability, sequence of operations etc. to obtain an optimum earthmoving plan using the simulated results. The third stage of RESOM involved the presentation of the selected earthmoving plan in the form of network diagrams and barcharts.

RESOM was successfully validated using two actual case studies (Anamaduwa Gam Udawa, Sri Lanka, and the A42 - Measham and Ashby By-pass, UK). Application and experimentation with RESOM were explained using two other case studies (the M40 - Banbury By-pass and a hypothetical example) and proved that about 20% cost savings can be obtained. The experimentation process revealed that RESOM could be of considerable help in planning, estimating and obtaining optimum earthmoving plans.

DECLARATION

No portion of the research referred to in this thesis has been submitted in support of an application for another degree or qualification at this or any other university or other institution of learning.

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ABBREVIATIONS

C-S	Chi Squared statistical test
CCP	Chance Constrained Programming
CDE	Ceylon Development Engineering
CPB	Caterpillar Performance Book
ECSL	Extended Control and Simulation Language
FIFO	First In First Out
K-S	Kolmogorov - Smirnov statistical test
LINDO	Linear INteractive Discrete Optimiser
LP	Linear Programming
LP/IP	Linear/Integer Programming
OR	Operational Research
PERT	Program Evaluation and Review Technique
QD	Quadratic Programming
RCDC	Road Construction and Development Company Ltd.
RDA	Road Development Authority
RESOM	Roadwork Earthmoving System Optimisation Model
RVDB	River Valleys Development Board
SD&CC	State Development and Construction Corporation

CHAPTER ONE

INTRODUCTION

- 1.1 Background to Research
- 1.2 Objectives
- 1.3 Method of Approach
- 1.4 Main Achievements
- 1.5 Organisation of the Thesis

1.1 Background to Research

Earthmoving operations in highway construction is always a major bid item. An inaccurate estimate of this item may result in either the reduction of contractor's profit margin or the total loss of the contract. This, together with the increasing competition in the construction industry today, compels contractors to arrive at lower bid prices adopting accurate estimating techniques at the planning and estimating stage.

The conventional mass-haul diagram, which is a graphical tool (Anderson 1985, Oglesby 1982, Stark 1983), and the experienced engineering judgment have been the key factors in selecting optimum plant teams and appropriate material distribution. Unfortunately, the potential of the mass-haul diagram diminishes in situations when:

- (a) cut/fill quantities are imbalanced (excess or in short of material);
- (b) different soil strata are available at cut sections and borrow pits;
- (c) different degrees of compaction are required at various layers (subgrade, subbase sidefill etc.);
- (d) hauling costs are not directly proportional to haul distance;
- (e) a selection of borrow pits or disposal sites is required;
- (f) cuts and fills are not equal in size (distance inaccuracies);
- (g) stage construction;
- (h) haul route obstructions; and
- (i) soil characteristics vary along the roadway (particularly, swell and shrinkage).

However, the linear programming model which was first suggested by Stark and Nicholls (1972) and later developed by Mayer and Stark (1981), Nandgaonkar (1981) and Easa (1987,1988) can be applied to overcome some of the limitations of the mass-haul diagram.

Although, these models aim to determine the cheapest solution to an earthmoving system, given the true cost of moving earth among sections, constraints like project duration and plant availability have heretofore not been considered. Hence, the management is disadvantaged in not knowing whether the available resources could be utilised towards the project completion within the target time. Clearly, these aspects are important for initial decision making.

Furthermore, it was identified that most of the estimators adopt deterministic methods, described in various estimating manuals and plant manufacturers' handbooks (Caterpillar 1987), to estimate production of their plant teams. It has been repeatedly mentioned in the past that the production obtained by these methods is more than reality due to negligence of interferences and stochastic variations encountered in real life (Gaarslev 1969).

Several attempts have been made to incorporate this aspect, in particular, by computer simulation (Gaarslev 1969, Willenbrock 1975, Clemmens 1978) and Queuing Theory (Griffis 1968, Cabrera 1973, Maher 1973, Maher 1975, Carmichael 1986(a), Carmichael 1986(b)) applying them to individual haulage operations.

However, none of the above methods can be satisfactorily applied to an overall earthmoving problem to find realistic answers to earth quantities, cut/fill distributions, selection of cost effective borrow/disposal sites and appropriate plant teams, by incorporating constraints and real life problems like project duration, interferences, stochastic variations, soil type variations and different degrees of compaction.

Except for the conventional mass-haul diagram, contractors are reluctant to use other techniques, due to their limitations, in particular, the incompleteness of these optimisation procedures. It was recognised that contractors need to have relatively quick and accurate methods to arrive at optimum solution to an earthmoving system at the planning and estimating stages.

1.2 Objectives

With these factors in mind, this research programme was implemented with a view to developing a relatively quick and more accurate method applicable to any road project to achieve an optimum solution for the earthmoving operations. An optimum solution is the cheapest overall cost of moving material between sections and the corresponding construction plan (material distribution, plant utilisation etc.) satisfying the constraints like project duration and available resources. To this end, the prime objective of the research was to develop a solution to the aforementioned problem in the form of a model, thereby enabling the contractors to:

- (a) incorporate real life problems, probabilistic and stochastic variations;
- (b) select optimum borrow pits and disposal sites;
- (c) select optimum plant teams from available teams to complete the project within the specified time;
- (d) take into account different types of soils and different strata;
- (e) treat different degrees of compaction at various layers;
- (f) select optimum material distribution; and more importantly
- (g) identify whether the available plant could be utilised towards the project completion within the specified time.

The sub-objectives were:

- (i) to study and comment upon current earthmoving practices in Sri Lanka;
- (ii) to develop probability distributions representing real life cycle element times of various earthmoving equipment as input to simulation model;
- (iii) to explain the potential use and the applicability of the developed model for typical earthmoving projects; and
- (iv) to carry out a production comparison among deterministic methods, model output and reality.

1.3 Method of Approach

It was identified that the Computer simulation in conjunction with Linear/integer programming (LP/IP) can be applied to achieve the aforementioned objectives. To this end, the research primarily comprised model development work and data collection from several sites. A schematic representation of research carried out is given in Table 1.1. After initial investigations involving several interviews and a literature review of earthmoving optimisation, a methodology was devised and the model development was carried out in three basic stages.

- Stage 1 - Development of a simulation model for individual haulage operations to obtain realistic unit costs and production rates corresponding to different teams tested, soil types and degrees of compaction incorporating real life problems, stochastic variations etc. The realistic unit costs and production rates are those corresponding to balanced plant teams which can be achieved during simulation.
- Stage 2 - Development of a LP/IP model to obtain:
- (a) **Minimum overall earthmoving cost** and the corresponding, project duration, material distribution, borrow/disposal sites used, and plant utilisation from available teams.
 - (b) **Minimum project duration** and the corresponding, minimum overall earthmoving cost, material distribution, borrow/disposal sites used, and plant utilisation from available teams.
 - (c) **Minimum overall earthmoving cost to complete the project within the given project duration** and the corresponding, material distribution, borrow/disposal sites used, and plant utilisation from available teams.
- Stage 3 - Application of the results obtained at stage 2 to draw up a construction schedule.

Six projects were selected and data was collected covering, Loader operations, Dozer operations, Loader-truck operations, Scraper-pusher operations and Compacting operations. The data basically comprised cycle element times, delay times, equipment utilisation times, production rate for each cycle, causes of delays and other relevant information about different haulage operations.

Table 1.1 - Schematic representation of work carried out

Stage	Description of work carried out	Aim
1	Literature review phase 1	To review already developed optimisation techniques, their applicability and limitations
2	Literature review phase 2	To further study stochastic and probabilistic approaches and assess LP/IP techniques applied to earthmoving operations
3	Interviews with earthwork contractors both in the UK and Sri Lanka	To study the techniques adopted for earthwork planning and estimating. This includes borrow/disposal selection, plant selection, material distribution and ways to account for delays etc.
4	Development of methodology	To develop a methodology to optimise the entire earthmoving system at estimating stage, by taking stochastic and probabilistic variations, project duration and real life constraints into account
5	Questionnaire to construction engineers	To identify important factors affecting different cycle elements of earthmoving plant. This data is needed for model development
6	Data collection in the form of cycle element times for various earthmoving equipment covering loading, dozing hauling (loader-truck and scraper-pusher) compacting and also overall project data including equipment teams used	To identify significant factors affecting various cycle element times, categorise them and develop input parameters, and also to validate and experiment with the model
7	Development of simulation model for individual haulage operations	To obtain realistic cost incurred for each haul corresponding to different teams, soil types and degrees of compaction
8	Development of Linear/integer programming model	To select: optimum teams from available teams in distributing material for timely project completion using optimum borrow/disposal sites and also to test the feasibility of project completion within the target time and more...
9	Validation of the model	To validate the model by applying actual field data and by demonstrations
10	Application and experimentation with the model	To obtain most suitable strategies and to explain the potential of the model

In addition, data and information on two other road projects in the UK were used to supplement the data bank. These data were split in three and used for input parameter evaluation, validation and experimentation with the model. The overall methodology is illustrated in detail in Chapter 4.

1.4 Main Achievements

Preparation of construction plans and estimates for earthmoving operations in road construction is mainly based on traditional mass-haul diagrams, skilled engineering judgement and deterministic estimating methods. Information available from work studies, in plant manufacturers' machine performance books and other published and unpublished estimating guide-lines assist this process, but the estimator still has to make bold decisions in selecting appropriate equipment and calculating production rates and associated costs.

Situations where even a simple mass-haul diagram is not utilised are quite common particularly for small jobs. Due to ad hoc estimating and planning practices and the absence of proper investigations of site conditions, cases have been reported in Sri Lanka, where the project duration and the associated costs have been increased by even 100%. If the UK industry is considered the contractors are fairly confident about their estimates but the optimality and the accuracy of these plans are arguable.

Existing optimisation techniques like stochastic models and linear programming models are relatively unknown in the industry (both in Sri Lanka and the UK). The main reasons for their unacceptability are the incompleteness of these optimisation procedures and unavailability of user friendly software packages embodying them.

Although RESOM (Roadwork Earthmoving System Optimisation Model) developed in this thesis does not overcome all these limitations, it provides a complete optimisation procedure to be used in obtaining an optimum construction plan. During its development it was found that the computer simulation combined with linear/integer programming can be applied to obtain an optimum construction plan satisfying real life constraints like project duration, resource limitations etc. RESOM facilitates to overcome much of the limitations of the existing optimisation techniques. It can also be used to test various strategies by experimentation. For example, situations where an optimum construction plan, when the project is to be completed within a given duration with available plant, the cheapest earthmoving plan with available plant irrespective of

the project duration, or the shortest possible duration with available plant irrespective of the cost, can easily be investigated.

Application of RESOM to an actual earthmoving project showed that about 20% of earthmoving costs can be saved over other estimating methods. In this way, the model is of considerable help in obtaining much needed information to an earthwork estimator or a planning engineer.

1.5 Organisation of the Thesis

This thesis contains two main areas of research which can be summarised as: a review of existing optimisation techniques and those which are used in the industry; and development of a computer model for earthwork optimisation using computer simulation and linear/integer programming. The work carried out in these two areas was organised into eleven chapters as shown in Figure 1.1 and can be described as follows.

Chapter 1 provides the introduction to the research by briefly describing the work done by past researchers on earthwork optimisation, the limitations of their models and also the reasons for implementation of this research programme. This also provides a list of objectives, a brief description of the methodology and the main achievements.

A detailed literature review of existing optimisation techniques is presented in Chapter 2. This includes a description of traditional mass-haul diagram, queuing theory and simulation models developed for both scraper-pusher and loader-truck operations, and also work carried out on linear/integer programming.

A series of discussions were held with both the UK and Sri Lankan road contractors to gather their expert knowledge on currently used earthwork planning and estimating methods. Their views, requirements, shortcomings of the methods and recommendations are described in Chapter 3.

After identifying the requirement of a relatively quick and more accurate earthwork optimisation procedure a detailed description of the methodology adopted in this thesis is presented in Chapter 4. In particular, the linear/integer formulations are fully developed and the requirement of the combination of the computer simulation and linear programming was emphasized.

Objectives of Chapter 5 are two fold. Firstly, it describes the theory of modelling in general, with particular reference to computer simulation by describing and comparing different modelling approaches. Secondly, it evaluates these methods and selects the most suitable techniques for earthwork simulation.

After identifying the requirement of data collection for both model building and validation, Chapter 6 identifies the required information to be collected and describes the actual data collection procedure. The first part of Chapter 7 statistically analyses the collected data and identifies the significant factors affecting various cycle element times. The second part develops the cycle element time generators to be used in the simulation model by fitting appropriate theoretical distributions to observed data.

RESOM model building process is systematically carried out in Chapter 8. The first part of the chapter develops the simulation model (first stage of RESOM) for both loader-truck and scraper-pusher operations. The linear/integer programming model (stage 2 of RESOM) is further explained with particular reference to the solution process and the software package used. The network scheduling model (stage 3 of RESOM) is also explained.

Chapter 9 describes the RESOM validation process carried out using two actual case studies, whereas Chapter 10 presents the application and experimentation with RESOM using two more case studies.

The conclusions derived throughout the thesis are presented in Chapter 11. Recommendations relating to the implementation of the research findings and further research are also put forward.

Additional information relevant to this research is presented in seven appendices. System variable definitions used during the development of LP/IP formulations are presented in Appendix A. The questionnaire form used to identify possible factors affecting various cycle element times is presented in Appendix B. Appendix C provides specimen observation forms used during data collection whereas Appendix D shows some sample outputs obtained during data analysis. A brief description of computer programming techniques used is provided in Appendix E and a specimen calculation of team production together with the associated travel time charts used in model validation is presented in Appendix F. Finally, Appendix G provides simulated results, LP/IP formulations and specimen LINDO outputs of selected cases of case studies 3 and 4.

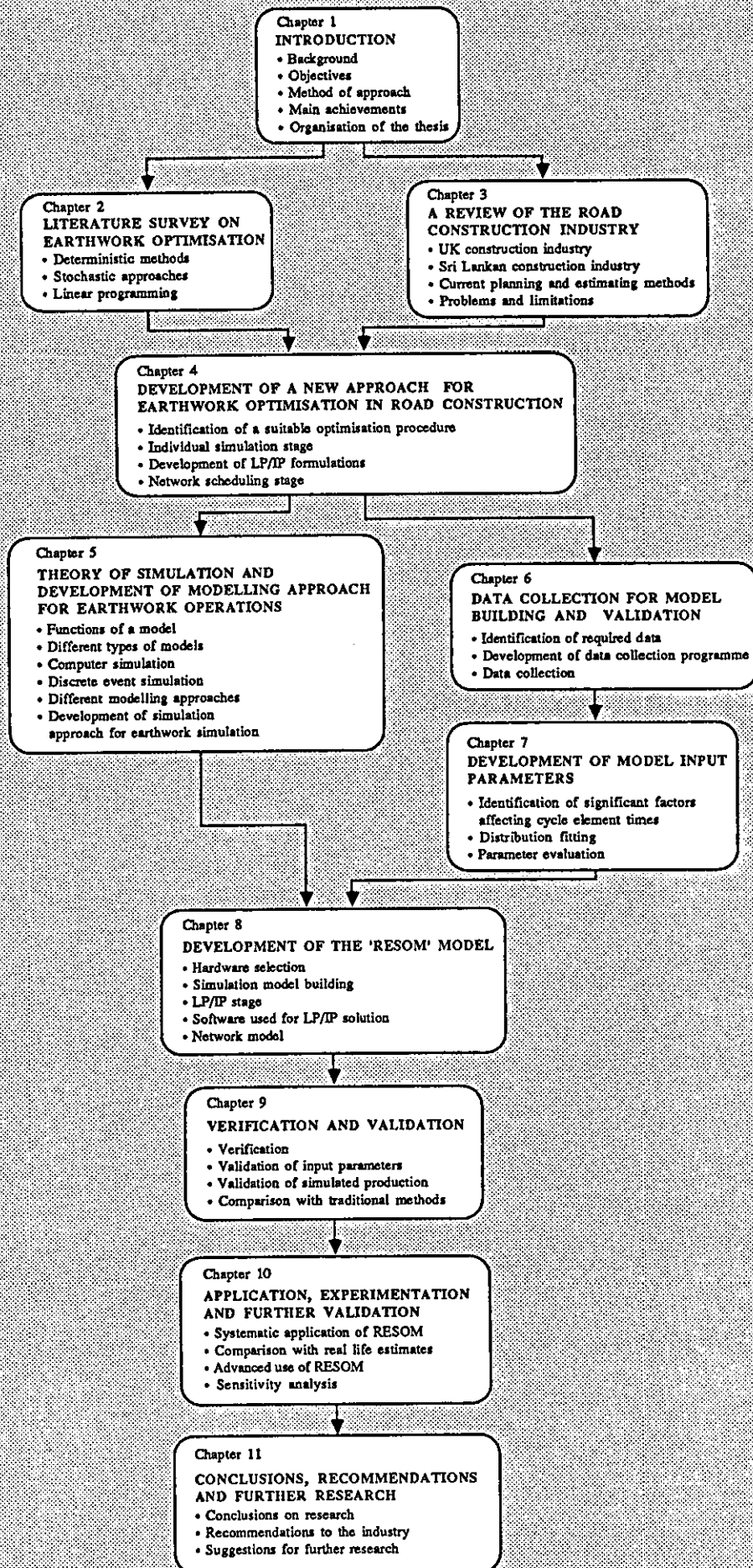


Figure 1.1 - Layout of the thesis

CHAPTER TWO

LITERATURE SURVEY ON EARTHWORK OPTIMISATION

2.1 Introduction

2.2 Deterministic Methods

2.3 Stochastic Approaches

2.3.1 Loader-truck operations

2.3.1.1 Early developments

2.3.1.2 James Douglas

2.3.1.3 Axel Gaarslev

2.3.1.4 J. H. Willenbrock and T. M. Lee

2.3.1.5 Other developments

2.3.2 Scraper-pusher operations

2.3.2.1 J. P. Clemmens and J. H. Willenbrock

2.3.2.2 Recent developments

2.4 Linear Optimisation

2.4.1 R. H. Mayer and R. M. Stark

2.4.2 F. T. Uhlik

2.4.3 S. M. Easa

2.5 Conclusions

2.5.1 General conclusions

2.5.2 Conclusions on input distributions used for stochastic models

2.1 Introduction

In any construction project, it is the responsibility of the management to adopt the most suitable planning techniques and to utilise available resources most effectively in minimising the project cost and maximising profit. 'Optimisation' is the generally used term for this entire process and can be defined as:

The process of achieving the most suitable and economical solution (usually by computer techniques) to a problem satisfying the various constraints.

This chapter reviews the previous work carried out on optimisation of earthmoving operations and is described under three main headings:

1. Deterministic methods;
2. Stochastic approaches; and
3. Linear optimisation.

2.2 Deterministic Methods

The mass-haul diagram is the most widely used earthwork optimisation technique in the industry. It is a graphical representation of the amount of earthworks involved in a highway scheme, and the manner in which they may be most economically handled. It shows accumulated volume at any point along the proposed centre line and from this the economical directions of haul and positioning of borrow pits and disposal sites can be estimated (O'Flaherty 1978).

An example of a mass-haul diagram is shown in Figure 2.1. This consists of a graph showing the algebraic summation of cut and fill (adjusted by swell [shrinkage] factors) along the centre line of road.

Some characteristics of mass-haul diagram are as follows.

- (i) The y ordinate at any station represents the earthwork accumulation to that point.

- (ii) The maximum positive or negative y ordinate indicates change from cut to fill or vice versa respectively. These ordinates may not necessarily coincide with the apparent point of transition.
- (iii) A rising curve at any point indicates an excess of excavation over embankment and a falling curve indicates the reverse.
- (iv) Steeply rising or falling curves represent heavy cuts and fills.
- (v) The shape of the loop indicates the direction of haul. A convex loop represents material movements from left to right and a concave loop from right to left.
- (vi) Any line parallel to the base line which cuts off the loop at two points indicates that the amount of cut is equal to that of fill. These lines are called balancing lines and the intersection points are called balancing points.
- (vii) The area between balance line and the mass-haul curve is the measure of the haul (in $\text{km} - \text{m}^3$) between the balance points, and the average haul distance between these points is the ratio of the area to the maximum ordinate between balance line and the curve.

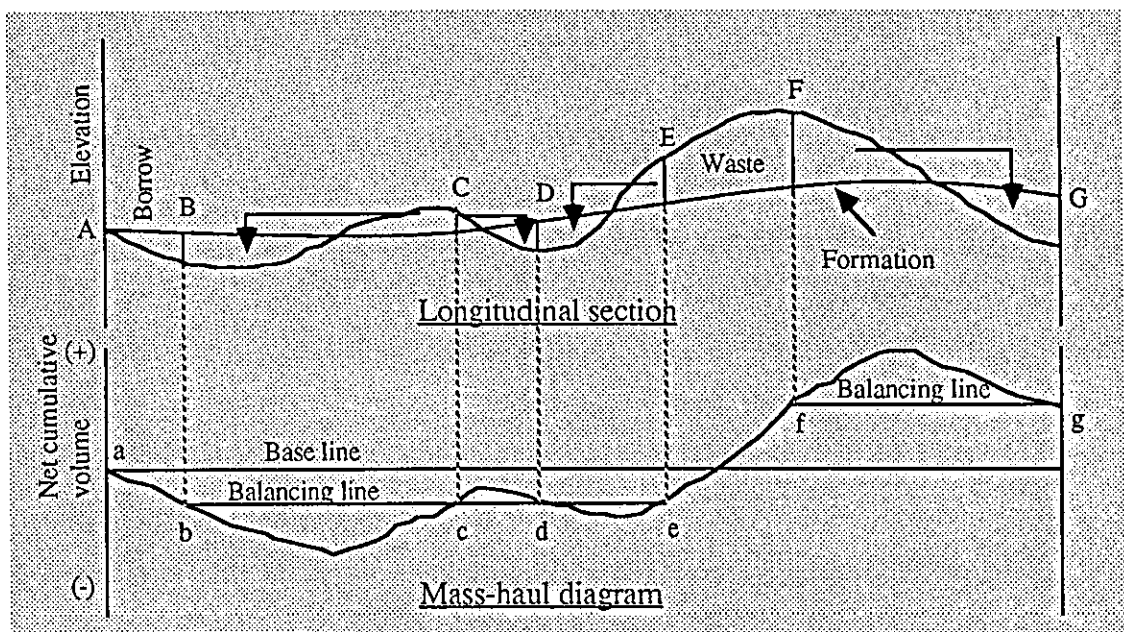


Figure 2.1 - Example of a mass - haul diagram

A detailed description of the mass-haul diagram and its applications are not intended here since they are well described in any highway engineering text book (O'flaherty 1978, Oglesby 1982, Anderson 1985).

Another widely adopted technique in the industry for optimisation of material distribution is the arrow allocation diagram. These diagrams are drawn on the simple principle that the cut is distributed to the nearest available fill. If the quantities are not balanced (excess or in short) decisions must be made as to the maximum haul length and locations of borrow/disposal sites. More information of the arrow allocation diagrams can be obtained from other sources (Uhlik 1984, Alkass 1988).

2.3 Stochastic Approaches

The idea of application of statistical computer approaches for equipment balancing problems, was first conceived by professor C. H. Oglesby of Stanford University. Under his supervision Benjamin V. Chatfield worked on a Master's degree in 1958, and concluded the feasibility of such an approach and encouraged further development (Douglas 1967).

2.3.1 Loader-truck operations

2.3.1.1 Early developments

After Chatfield, the work was continued by Grant K. Hagestad in 1959, and developed the first simulation model for loader-truck operations. The cycle element times were assumed to be normally distributed and the program was written for and run on the IBM 650 computer (Douglas 1967).

Subsequently, in 1960, Paul Teicholz and Peter Swanson worked on the development of a general simulation program which involved breakdown and equipment standby costs. After this, Teicholz worked independently on a doctoral degree and developed a general model for the simulation of link-node material handling systems which could be used to analyse many construction situations. Teicholz also studied the loader-truck combination into detail developing a queuing model to approximate simulation results (Douglas 1967).

2.3.1.2 James Douglas

In 1964 and 1967, Douglas simplified the general model developed by Teicholz to tackle earthmoving production from a loader and its associated trucks - a two link system with one carrier in one of the links. It was designed to provide a valuable and easy to use tool in the field. The model was written in Balgol for execution on the IBM 7090 computer, utilising probability distributions to compute probable cycle element

times associated with equipment operations. The field data collected has confirmed that the Log-normal distributions are the most appropriate for these purposes. Delays were assumed to occur during either the haul or return phases of the cycle.

In setting up the simulation model he classified delays as:

- (a) *weather* - not treated;
- (b) *external* - delays caused by factors external to the equipment operations, for example repairs/breakdowns, moving equipment, smoothing the excavation area with shovel etc.; and
- (c) *balancing* - delays caused by interaction of equipment such as trucks waiting for shovel or shovel waiting for trucks etc.

Basically, his simulation model can be used to obtain the following:

- (a) proper size of trucks to a shovel;
- (b) determination of the best number of trucks to use for a given haul distance;
- (c) determination of effect of changing different parameters such as external delays, probabilities of delay etc.;
- (d) determination of effect of using a hopper at the shovel;
- (e) prediction of production for use in estimating a job; and
- (f) prediction of production in order to determine the actual output on a job already in progress.

Douglas compared the results obtained by simulation and conventional methods, and showed that the maximum difference in production occurred at the equipment balancing point. He further stated that for fairly long haul distances the minimum estimated unit cost could be obtained with several fewer trucks than indicated by conventional methods.

Furthermore, he used a factor called 'D factor' to convert the conventional estimates (calculated deterministically) to simulated estimates. However, comprehensive tests on both the D factor and simulation have not been carried out. By using Douglas' model reliable estimates can only be obtained when it is used with considerable engineering judgement.

2.3.1.3 Axel Gaarslev

In 1969, Axel Gaarslev (1969) of Stanford University continued research on material handling systems developing queuing models and simulation models, whenever possible for output comparison. He also treated material handling systems as a kind of

link-node systems. His delay classification, which is given below, was more or less similar to the Douglas' classification.

- (a) Delays not caused by the system (for example, weather, strikes, other contractors, material suppliers, conflicts etc.).
- (b) Delays caused by breakdown of part of the system (external).
- (c) Balancing delays (interaction of equipment).

The first type of delay was accounted by using a 50 minute working hour and the second type was accounted for by testing a carrier for probability of occurrence during haul and return from a delay distribution. The third type evidently, was incorporated into the logic of the model.

Gaarslev mentioned that an Exponential distribution is a very good approximation for inter-arrival time of trucks and reflects the phenomenon called *bunching* which is often encountered in the field. Furthermore, he mentioned that this is a valid assumption only so long as the number of trucks is not too small and there is a certain degree of dependence amongst the trucks.

He argued that previously assumed exponentially distributed service times are unrealistic and the production can be under-estimated as much as 10%. The mere reason for this assumption was its mathematical simplicity for queuing models. Gaarslev found that the service times normally follow either a Log-normal distribution or a Normal distribution. However, to provide a certain degree of flexibility, the service time distribution was assumed to follow Erlang distribution in the queuing theory approach.

During simulation all element times; load, haul, dump and return were assumed to be log-normally distributed. The respective distributions were adjusted to reflect the stipulated mean, standard deviation and the starting point of the axis. The external delay (minor delay) also was assumed to be log-normally distributed.

Basically, the models developed by Gaarslev can be summarised as follows.

Two link systems - single server case

- (i) Queuing model by taking inter-arrival time as exponentially distributed and service time as erlang distributed. Always used FIFO (First In First Out) basis.

- (ii) Simulation model by taking all element times of each link as log-normally distributed. He developed a production curve by varying the number of trucks served. The trucks used were identical.

Two link systems - multi server case

- (i) Queuing model and a simulation model when servers are independent.
- (ii) Only simulation models when servers are partially or entirely dependent.

Multi link systems

Only simulation models were developed. The procedures adopted for the latter two cases were similar to that of two link systems-single server case.

2.3.1.4 J. H. Willenbrock and T. M. Lee

Several years later in 1975, Jack H. Willenbrock and Thomas M. Lee of Pennsylvania State University developed a simulation model for loader-truck operations using SIMSCRIPT II.5, a special purpose simulation language, considering it as a typical link-node system. Time lapse photography was used, in contrast to the conventional stop watch studies, as an advance technique for collecting data, to base the input parameters to the simulation model.

Two time lapse cameras stationed at cut and fill positions were used for data collection covering three large construction sites. He calculated loading and dumping times by synchronising the two films, but failed to obtain reliable results to haul and return times due to cumulative error of the time between two consecutive frames. For this reason, ultimately, both time lapse photography and stop watch studies were used at the same time in order to calculate all cycle element times.

Willenbrock identified that the truck cycle time consists of the following:

$$C_t = Q_{t1} + L_t + HT + Q_{tf} + D_t + RT$$

where; C_t = Complete cycle time

Q_{t1} = Queuing time of truck at the loader

L_t = Time required to load a truck

HT = Hauling time

Q_{tf} = Queuing time of the truck at fill

D_t = Dump time

RT = Return time

The three projects studied were quite different to one another, in particular, the truck types and the behaviour of trucks at cut and fill positions. (In some projects trucks had to wait until the preceding truck finished dumping. In others, trucks had to be pushed out from the fill due to swampy nature.) Consequently, various types of delays occurred and were categorised as follows.

- (i) *Truck delays* - Delays occurred during haul and return, and were calculated by deducting the minimum recorded travel time from the observed time.
- (ii) *Loader caused delays* - Delays caused by loader breakdowns, outside interference like waiting for other operations, cleaning the work area while trucks were waiting etc. These were calculated by analysing time lapse films.
- (iii) *Equipment wait times* - There were two types; waiting of the truck to be served and waiting of the loader for trucks. In both cases, they were calculated by analysing the time lapse films.

The results obtained from the data analysis were as follows:

Time to load a truck

The data collected for loading operations comprised individual loader service times (l_i) and the resultant relative cumulative frequency distribution was used as input to the simulation model to generate service times, after failing all attempts to 'fit' a theoretical distribution. The truck spot time was considered to be included in the first loader cycle time, as it did not exceed 75% of one loader service time in all cases.

Time to dump truck

Unlike loading, which can be fully controlled, the dump time varied from cycle to cycle as well as from project to project. Similar to loader element times the cumulative frequency distributions were used after failing all attempts to fit a theoretical distribution.

Other cycle element times

Truck delays were calculated by subtracting the minimum observed haul and return time from each of the observed haul and return time. Delays caused by the loaders were obtained as the time delayed due to loader breakdowns, interrupting to loading operation by others and also when the loader was engaged in levelling the working area. Equipment wait times were identified as the truck queuing time at cut or fill and

loader idle time. The time spent by loader to clear the work area when there is no truck to be loaded was also taken as loader idle time.

In brief, the cycle element times (loader service time, truck dump time, truck delay time) were generated from frequency polygons developed from time lapse films. Loader delay times and intervals between such delays were treated as exponentially distributed. Truck travel times were calculated deterministically during simulation. However, a proper validation of the model has not been carried out.

2.3.1.5 Other developments

While the above research was more or less concerned about simulation, queuing theory has also been a popular approach in optimising earthmoving plant. In 1968, Griffis attempted to optimise haul fleet size using queuing theory. In 1973, Cabrera presented a convenient graphical solution for the optimisation of excavator-truck combinations, by considering it as a cyclic queue. He determined the optimum number of trucks as a function of ratios; hourly excavator cost/hourly trucks cost and transit time/service time and concluded that there is a point at which the optimum number of trucks is independent of the variability of service and transit times.

Recently in 1986, more work on loader-truck queues was carried out by Carmichael (1986(a) & (b)) by applying finite source queuing theory which is usually represented by $(-/-/-)/-$. The four slots correspond to the probability distribution of the back cycle time, the probability distribution of service time, the number of servers and the number of customers. The first two distributions can either be Exponential (denoted by M), Erlang (denoted by E_l , where l is the shape parameter), or constant (denoted by D). According to Carmichael the most suitable queuing models for loader-truck operations are of the form $(E_m/E_l/C)/K$, where m and l take the range of about 25 to 50. Unfortunately, a complete theoretical solution to this form has not yet been developed and only approximated model of the form $(M/E_l/C)/K$ is presently available. Consequently, his optimising examples were developed as a $(M/E_l/C)/K$ by using $(M/M/C)/K$ and $(D/D/C)/K$ as boundary models as these two take two extremes. The disadvantages of this method over simulation are intractability of complex mathematics and its limited applications.

2.3.2 Scraper-pusher operations

2.3.2.1 J. P. Clemmens and J. H. Willenbrock

Unlike loader-truck operations, application of stochastic methods for scraper-pusher operations was not attempted until Clemmens (1978) developed his simulation model in 1978. His main objective was to develop a valid simulation model for estimating purposes by identifying the appropriate probability distributions of various scraper cycle element times.

Clemmens' data collection covered eleven scraper sites and a wide variety of plant teams, configurations and also project conditions, to find out the time distributions for various cycle elements. Prior to data collection he identified the important production variables as; type of scraper, size of scraper, type of material, grade of haul road and the haul distance which later became the parameters under which the various cycle elements were grouped during analysis and comparison.

The basic methods of study employed were: random period method where the work week was divided into equal time intervals and the observation time for each such period was decided randomly; and all day study period where the operation was observed right through the shift. His view was that both these methods provide a true sample.

Spot studies lasting for one-half to two hours were also conducted for pusher cycles. The compacting equipment was not considered, as a factor for scraper cycle elements since there was no queue at the fill areas.

Factor Analysis

Clemmens carried out a factor analysis in order to find out the most important factors affecting scraper cycle elements. They were categorised as experimental and classification. Classification factors were uncontrollable and hence accounted for only stochastically, whereas experimental factors were further divided into qualitative and quantitative. The following were found to be the important factors for various scraper cycle elements.

Loading time : The only important factors were the type of scraper and the number of pushers. They were combined to one called *loading method* for simplicity and the different loading methods considered were:

1. loading with a single pusher;
2. 2 pushers operating in tandem;
3. push-pull loading; and
4. self-loading (elevating).

Dumping and turning : Although there were small differences between various sizes and types of scrapers, they were negligible compared to overall cycle time. Hence both dumping and turning times were combined for what was called *constant time*.

Travelling : Travel time was identified as the most sensitive and hence a detailed study was carried out to identify the important factors. He disregarded the return time by combining both haul and return to one time called *travel time*. The effect of size of the scraper was also disregarded due to the similarity of travel times observed for different sizes applied to a single project. The only variables found to be significant were the type of scraper and the haul distance.

To find out the effect of other qualitative factors namely; the type, haul road condition and grade, Clemmens plotted graphs of travel time versus haul distance for each combination. For example, the graph of travel time for single engine with negligible grade. He noticed the linearity of the distribution and hence a simple regression analysis was carried out for each treatment level by assuming haul distance as the independent variable and travel time as the dependent variable. Step-by-step he disregarded unimportant variables and ultimately found out that only the type of scraper and the haul distance to be the critical variables.

A similar analysis was carried out for pusher cycle elements combining the pusher boosting time, reversing and contact manoeuvring time to one time called *return time*.

Summary of significant factors are shown below.

<u>Cycle element</u>	<u>Significant factors</u>
(i) Scraper loading time	Loading method
(ii) Scraper constant time	None
(iii) Scraper travel time	No. of engines and one way haul distance
(iv) Pusher loading time	Pushing method
(v) Pusher return time	None

Other remaining factors were taken into account in stochastic variability.

Delays

Clemmens identified numerous delays during both scraper and pusher operations and they were categorised as:

- (i) *Major delays* : Delays lasting more than 15 minutes and usually caused by unpredictable causes such as weather, breakdowns, management policy changes etc. and were accounted for by past experience since they could not be predicted.
- (ii) *Minor delays* : Delays lasting less than 15 minutes, caused by operational delays, maintenance, personal delays etc. These could be predicted by using the probability distributions, obtained from observed data histograms.
- (iii) *Wait delays* : Caused usually due to random variations and could be incorporated into the logic of the computer model.

Clemmens has shown that the shifted Erlang distribution (falls into Gamma distribution family) typically exemplifies the most of scraper and pusher cycle elements. The only exception was the scraper travel time which was found to be normally distributed.

The minor delay distribution also was assumed to be Erlang.

The regression equation used to describe the travel time took the form;

$$Y_i = b_0 + b_1 x_i + e_i$$

where; Y_i = Value of travel time in the i th trial
 b_0, b_1 = Parameters
 x_i = Haul distance in the i th trial
 e_i = Random error term

The parameters calculated by Clemmens are summarised in Tables 2.1 and 2.2.

2.3.2.2 Recent developments

In 1988, Touran and Taher applied a combination of queuing theory and simulation to determine optimum scraper-pusher team sizes under given operating conditions. The model basically comprised a computer program which interfaced Gaarslev's queuing model (Gaarslev 1969) and Caterpillar's vehicle simulation program.

Table 2.1 - Summary of input parameters for cycle element times using Erlang distribution (source - Clemmens 1978)

Cycle element		No. of observations	Average (seconds)	Minimum (seconds)	Order (K)
Scraper	Load - one pusher	642	37	15	4
	Load - two pushers	290	31	15	7
	Load - push-pull	561	50	57	5
	Load - elevating	318	54	56	7
	Constant	3425	33	21	6
	External delay	8330	114	0	1
Pusher	Load - one pusher	642	37	15	4
	Load - two pushers	290	31	15	7
	Return	360	23	20	4
	External delay	360	52	0	1

Table 2.2 - Input parameters for travel time using regression analysis (source Clemmens 1978)

Single engine

$$b_0 = 82$$

$$b_1 = 0.093$$

$$s_1 = 76$$

Twin engine

$$b_0 = 94$$

$$b_1 = 0.0558$$

$$s_1 = 60$$

2.4 Linear Optimisation

Application of linear programming to earthwork optimisation was first suggested by Shaffer (1963) followed by an alternative approach by Stark and Nicholls (1972). Essentially, the underlying principle of the technique is to maximise or minimise a certain objective under various constraints. In this case the objective was to determine the optimum material distribution between cut and fill sections, cut sections to disposal sites, and borrow pits to fill sections, assuming the cost of moving material among sections.

2.4.1 R. H. Mayer and R. M. Stark

Several years later, in 1981, Mayer and Stark improved the technique considerably, to incorporate setting-up costs when establishing new borrow/disposal sites. Extensions to cover different degrees of compaction at various sections and treatments to different soil strata were also noted. During the same period, Nandgaonkar (1981) working in Afghanistan studied the application of an Operational Research (OR) model for earthwork transportation allocations and brought out that the OR technique as a suitable tool for arriving at an optimum estimated cost of the work at the precontract stage.

2.4.2 F. T. Uhlik

In 1984, Uhlik developed a model incorporating probabilistic estimates in conjunction with linear programming for optimising earthwork operations. He applied stochastic characteristics into different unit cost elements (excavation, hauling, placing and compaction) and also to haul distance to find out the total unit cost distribution for the entire job. He identified that the above components can be regarded as random variables of a Beta distribution. The three value estimate of Beta distribution (PERT type estimate) was used to describe each random cost element. The mean value calculated for each of these cost elements was applied to the above equation to find out the total unit cost which later became cost coefficients for the linear programming (LP) model.

Uhlik's LP formulation was similar to that of Mayer and Stark, but was extended to include the type of material handled and the variability of rock quantity in cut sections. He argued that the rock quantity calculated at different times perhaps by differing the available information would result in quantities that follow a Normal distribution. Consequently, his cut constraints in the LP formulation consisted of random variables for rock quantities resulting the inapplicability of standard LP solution.

Chance Constrained Programming (CCP), a technique that transforms stochastic constraints to deterministic ones, was applied for the above purpose.

Subsequently, the LP model was used to obtain the optimum cost components and the solution variables were replicated by *Monte Carlo* simulation to obtain a probability distribution and a cumulative probability distribution for the total unit cost. A Double Triangular distribution was selected to represent stochastic cost elements during the above process. Ultimately, Uhlik compared the total unit cost for the entire project,

obtained by simulation with that of sensitivity analysis of the LP solution. Combining these two he came up with a unit cost for the job corresponding to a certain degree of confidence level. Alternatively, the total unit cost is a kind of probability distribution which can be used by the estimator to obtain an appropriate unit cost estimate.

Uhlik's main conclusion was that LP incorporated with CCP for the rock quantities in cut areas, and expected values for the cost coefficients (calculated using three value PERT system), would when correctly applied provide the optimum cut/fill distribution.

2.4.3 S. M. Easa

In 1987, Easa extended the model developed by Mayer and Stark to incorporate nonconstant unit costs applied to borrow pits considering the unit cost of purchase and excavation for borrow pits as a three step cost function. All other unit cost components were assumed to be constant. One year later, he extended the same investigation and presented a Quadratic Programming (QP) model of earthwork allocations accommodating linear unit cost functions of purchase and excavation of borrow pits (Easa 1988). In both these cases the formulations were solved by implicit enumeration technique.

2.5 Conclusions

2.5.1 General conclusions

1. Delays in scraper operations can be mainly categorised into: major delays (lasting more than 15 minutes - for example, weather, breakdowns, management policy changes etc.); minor delays (lasting less than 15 minutes - for example, operational delays, maintenance, personal delays etc.); and wait delays (interaction of equipment). The first type is unpredictable and can only be incorporated by past experience. The second type can be predicted by appropriate probability distributions and the third type can be incorporated stochastically.
2. There seems to be no consensus among researchers in categorising types of delays encountered in loader-truck operations.
3. Loader-truck operations in earthmoving can typically be represented by a kind of link-node system.

4. Earthwork production obtained by deterministic methods always over-estimate the actual production, and hence application of stochastic techniques is necessary to resemble reality.
5. In complex situations, the application of simulation techniques is more powerful and convenient than queuing models whose applications are limited to relatively simple situations.
6. Linear programming techniques are a powerful optimisation techniques which can be applied to optimise material distribution, selection of borrow disposal sites in most practical situations.

2.5.2 Conclusions on input distributions used for stochastic models

1. In order to calculate cycle element times, it is advisable to use valid theoretical distributions rather than empirical distributions derived from actual data.
2. An Erlang distribution with appropriate shape parameters typically resembles all the scraper and pusher cycle element times except travel time which follows a Normal distribution. External delays can also be represented by an Erlang distribution.
3. Exponential distributions are a very good approximation for inter-arrival time of trucks. This is further justified when the number of trucks is not too small and there is a certain degree of dependency among trucks.
4. There seems to be no consensus amongst researchers for truck cycle element time distributions. Gaarslev (1969) has argued that Log-normal distributions closely resemble all truck cycle elements (haul, dump and return) including external delays. Carmichael (1986) has mentioned that Erlang distributions with shape parameters in the range of 25 to 50 are a good representation for service time and back cycle time (haul + dump + return).

CHAPTER THREE

A REVIEW OF THE ROAD CONSTRUCTION INDUSTRY

3.1 Introduction

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3.3.5 Ceylon Development Engineering (CDE)

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3.4 Conclusions

3.4.1 Conclusions derived from the UK industry

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3.4.3 The next step forward

3.1 Introduction

Clearly, any research programme implemented to solve a problem in the construction industry should benefit the industry itself. In effect this required a detailed survey to try and understand the current practices and trends towards earthmoving optimisation in road construction. Based on this idea a series of discussions were held with experts in the industry both in the UK and in Sri Lanka with the following objectives in mind.

- (i) To obtain a wider understanding of road construction including various types of problems, delays and constraints encountered by the contractor.
- (ii) To understand the extent of information available to a contractor at the tendering stage.
- (iii) To identify current estimating methods and planning strategies.
- (iv) To identify earthwork optimisation techniques currently in use and their limitations.
- (v) To investigate ways of incorporating real life problems into production estimates.
- (vi) To understand the extent of computer usage in earthwork planning.
- (vii) To obtain the contractors' views on the research problem and the intended model development at hand.

Due to the nature of the research program, much information was obtained from Sri Lanka during the author's intermediate research period. However, several discussions were also held in the UK in particular with two contractors. Clearly, it is not recommended to derive conclusions on UK road construction practices from a handful of contractors, however, it was sufficient and indeed intended to compare the practices between the UK and Sri Lanka.

The following discussion is intended to describe the road construction industry as a whole particularly in Sri Lanka with a view to finding solutions to the aforementioned objectives.

3.2 Views of Contractors in the United Kingdom

3.2.1 Galliford and Sons Ltd.

Galliford and Sons Limited is a medium size civil engineering contractor located in the Midlands area, carrying out civil engineering contracts including roadwork in the Midlands. The estimated cost of roadwork contracts it handles varies from about £0.25 - £5 million.

During discussions, it was confirmed that the conventional mass-haul diagram is the key in selecting optimum cut/fill distribution. The type of earthmoving plant for a particular haulage operation is selected merely on the basis of intuition and experience by considering factors like haul distance, type of soil, quantities involved, location of site, topography, configuration of cut and fill, availability of plant, to name a few. The contractor prefers to use loaders and trucks instead of scrapers for two reasons. Firstly, scrapers are more susceptible to bad weather and secondly the availability of large dump trucks and loaders capable of achieving higher production at a comparable or even cheaper cost.

Production estimates are usually based on computerised historical data base and occasionally by consulting estimating manuals or plant manufacturers' handbooks. Different plant teams are tested during the estimating stage to choose cheaper ones, and the workstudy technique 'Activity Sampling' is usually adopted during first 2-3 days of construction, to optimise production.

Sometimes trial holes are drilled to supplement the sub-surface information provided by the client to find out the suitability of materials during tendering stage. No computers are used in either estimating stage or during construction to optimise production.

3.2.2 George Wimpey

George Wimpey is a large civil engineering contractor based in London and carries out a wide range of construction activities covering simple single storey buildings to very large structures and small roads to large motorways.

Similar to Galliford and Sons, the company also uses mass-haul diagrams in optimising material distribution and past experience in selecting the type of plant for a particular application.

However, the attitudes and the estimating process of these two contractors are quite different. According to Wimpey, material distribution and the selection of plant are not critical, what is important is finding the appropriate borrow/disposal sites and the suitability or unsuitability of underlying strata. Their argument is that any mistake in these during estimating will be expensive compared to finding optimum material distribution and plant teams. Consequently, much of the estimators' time is spent in finding the nearest borrow/disposal sites, quantities involved etc. rather than adopting highly mathematical optimisation procedures.

Although priority is usually given to the above purpose, at least two plant teams are tested involving dump trucks and scrapers where appropriate, and for each case cycle times are calculated by combining their own cycle element times and appropriate efficiency factors. A team production is obtained in this manner to find out unit cost. The efficiency factors used and the cycle element times may vary from project to project and the argument is that each project has its unique features and hence different calculations are required.

The procedure in calculating the cycle time and the production is similar to that described in the Caterpillar Performance Book (Caterpillar 1987). No computerised estimating procedure is adopted at any stage.

After selecting plant teams and appropriate production output, they are shown to site personnel to get their approval. However, Wimpey agreed that on some occasions the selected plant teams have to be changed depending on the circumstances during construction.

3.3 Road Construction Industry - Sri Lanka

3.3.1 General description of the industry

3.3.1.1 Who are the clients and the contractors?

Until recently, the design, construction and maintenance of all Sri Lanka's major roads were done by a single organisation called Road Development Authority (RDA). In 1987, its works division broke away and formed a new fully government owned company called Road Construction and Development Company Ltd.(RCDC). Unlike in the UK road construction in Sri Lanka is almost monopolised by this company and the only competitors are large foreign contractors like Balfour Beatty Ltd. who have a long established relationship with Sri Lanka.

There are a considerable number of private contractors who most of the time work under RCDC as subcontractors. The two main reasons for this monopolisation by RCDC are, firstly the inexperience in road construction by other contractors and secondly the relative smallness thereby making it difficult for them to compete for larger jobs.

3.3.1.2 Restrictions in the Sri Lankan industry compared to the United Kingdom

Almost every Sri Lankan contractor owns a plant fleet with varying numbers of plant items depending on his budget. Unlike in the UK the unavailability of suitable plant items in contractors' own plant yard is usually a problem to a Sri Lankan contractor due to lack of plant hire companies to choose from. The existing plant hire companies are relatively small and sometimes do not possess a large range of equipment to satisfy contractors' demands. Consequently, most contractors are restricted to their own plant fleet or what is available in the market thereby underutilising their resources. One obvious example is that utilisation of entirely different size of trucks with a single loader making large queues at one time and loader idling at other times.

Most private road contractors evolved after the open economy policy in 1977 and still are in learning stage. Therefore, with all these difficulties and inexperience, it is unfair to put the blame only on contractors for underutilising their resources.

3.3.1.3 Estimating and tendering stage

Information received from the client usually includes detailed drawings, bill of quantities, specifications and occasionally, locations of borrow/disposal sites together with their capacities. If the availability of these sites is not provided it is the responsibility of the contractor to find them out but if the given information is vague it is a matter to be debated upon and clarified.

Unlike in the UK, detailed and more accurate information about the area, subsoil conditions, weather effects etc. are not readily available to a Sri Lankan contractor to arrive at an accurate bid value. Consequently, much uncertainties are involved thereby resulting in considerably inaccurate estimates and durations.

The contractor usually visits the project site to get further information about subsoil conditions, availability of borrow pits, topography etc. but no sub-surface explorations are actually carried out. Occasionally this process is not carried out at all and the project is estimated only from the information provided by the client.

In most cases, traditional mass-haul diagrams are drawn to obtain the optimum material distribution but there are occasions even when this simple tool is not utilised, particularly if the quantities involved are relatively small. Once the material distribution is identified, production estimates are obtained either from historical data, experience or from estimating guides prepared to suit Sri Lankan conditions. Effects of weather and other possible delays are also included into production estimates using meteorological data and past experience. As mentioned earlier, contractors attempt to utilise their own fleets as much as possible even though a better selection may be possible for the reasons discussed earlier.

The contractors' view is that the information provided by the client is sufficient for tendering but not adequate or sometimes inaccurate for accurate project costing, but they are not very much bothered about this since the extra cost has to be borne by the client in cases of erroneous information provided. It is interesting to note that there have been situations where the ultimate project costs were more than three times higher than the estimated cost due to inaccurate information provided by the client.

In urgent situations, the contract is negotiated and the rates are agreed upon by a technical committee according to standard norms provided by 'Highway Schedule of Rates' and the planning of the job is carried out during construction period.

3.3.1.4 Construction Stage

In most cases the pre-construction schedule cannot be adhered to and the estimated project cost and durations are exceeded. Inaccurate information provided by the client and improper planning are the main reasons for these higher costs and longer durations. According to contractors, the estimated cost may be exceeded by 5% to 100% or even more depending on the situation.

For urgent jobs, construction is commenced and available equipment are brought down to the site without any estimating or planning procedure. Clearly, this is a waste of money and resources which the contractors are aware of. In some situations, specifications are strictly adhered to whilst in other situations they are easily overlooked. This, of course, depends on the client, the contractor and also the importance of the job.

The usual types of delays encountered during construction can be categorised as:

- (a) unbalancing of equipment;
- (b) breakdowns;
- (c) weather;
- (d) poor supervision;
- (e) operator absenteeism;
- (f) lack of co-ordination and communication; and
- (g) unavailability of required plant.

Clearly, much of these problems and delays can be considerably reduced by adopting a systematic approach in all stages of a project.

3.3.2 Road Construction and Development Company Ltd.(RCDC)

As mentioned earlier, RCDC is the largest single roadwork contractor in Sri Lanka, having more than 450 construction equipment items at its disposal and employing about 1000 employees. It is a direct labour organisation capable of carrying out any road construction work functioning under the umbrella of the government but has future plans for privatisation.

RCDC has its own design branch facilitating to undertake 'Turnkey' jobs. Except for urgent jobs a detailed investigation of the site, a site survey, suitability of underlying strata, locations of borrow/disposal sites together with their limitations are carried out during design stage.

The mass-haul diagram technique is then applied in finding the optimum material distribution among cut and fill sections, borrow pits to fill sections and cut sections to disposal sites.

RCDC maintains a manually created historical data base for estimating purposes but agreed that the production obtained from that is only approximate and the actual production varies from site to site. Estimating manuals and other guides are very rarely used. It is interesting to note the different procedures adopted by Wimpey and RCDC. Wimpey identifies individual cycle element times and adds them together to obtain the total cycle time and then the team production but RCDC assigns a value for the number of trips per day to obtain a team production. Whether this production is achievable in the field is debatable.

No computer facilities are available at any stage of construction but the company has plans for computerisation of its data base as the first step. During construction, RCDC also maintains hauling reports consisting of total cycle event times, equipment utilised, quantities moved etc. for each job everyday, to be used for costing purposes as well as for upgrading the production database.

Finally, authorities agreed that if a proper plan with a systematic approach is adopted a large amount of money and resources can be saved, but it is very difficult if not impossible to adopt such a procedure due to other prevailing constraints.

3.3.3 River Valleys Development Board (RVDB)

RVDB is a government organisation geared to develop irrigation schemes, but it also undertakes road construction particularly within infrastructure projects like Mahaweli Development. It used to be a very dynamic organisation with both design and construction departments having a considerably large equipment fleet including a large fleet of heavy scrapers, but now, it is struggling for survival carrying out only construction work.

According to the authorities the main reason for this is lack of funds within the organisation thereby reducing employee motivation. Clearly, to rectify this situation a proper planning and a good training programme for employees seems to be a necessity.

In planning and estimating a job even a simple mass-haul diagram is not drawn and the material distribution is purely decided by experience which the firm agreed may not be the optimum solution. Production estimates are done using an estimating guide called 'Data for costing' prepared by the rate sub committee appointed by the secretary to the Ministry of Mahaweli Development.

Clearly, no proper planning is carried out and sometimes the responsible people do not even visit the project site at tendering stage, this no doubt increases the project duration and the actual cost thereby reducing the profit margin.

3.3.4 State Development and Construction Corporation (SD&CC)

State Development and Construction Corporation is again a large government organisation specialised in bridge construction. However, like RVDB, it also undertakes road construction work particularly within the framework of infrastructure projects. SD&CC possesses a considerably large equipment fleet but hiring additional equipment from plant hire companies is a usual practice.

Like in other government organisations, proper planning and estimating procedures are very rarely adopted. What the authorities say is that even sophisticated methods are utilised in planning and estimating, they cannot be implemented due to other limitations within and outside the organisation.

3.3.5 Ceylon Development Engineering (CDE)

CDE has about a 30 year history in earthmoving and used to be the largest private organisation and still dominates the industry as a larger contractor. It has widened its horizon to undertake other civil engineering works like multi storey buildings, bridges, and other such structures.

CDE also has a considerably large equipment fleet and it has now almost changed its fleet from scraper-pusher to loader-truck for the same reasoning given under Galliford and Sons Ltd. The contractor always attempts to utilise his own fleet to keep the bid value at its lowest. His argument is that the profit is duplicated if hired from outside increasing the bid value.

Fleet selection and production estimates are carried out similar to that adopted by RCDC, but the production data are more or less remembered by estimators than obtained from historical data. Optimisation of material distribution is very rarely needed for the type of work carried out and hence even mass-haul diagram is not usually adopted.

3.3.6 Other contractors

All the private small contractors who own a few plant items come under this category. Most of these contractors are relatively inexperienced in road construction, in the sense that they are unaware of proper optimisation techniques like mass-haul diagram and

even the specifications to be adhered to. They merely act as subcontractors under a main contractor for material haulage operations. In brief, a systematic approach for estimating, planning and construction is not at all carried out.

3.4 Conclusions

3.4.1 Conclusions derived from the UK industry

1. Information provided by the client at tendering stage usually includes, detailed drawings, site investigation report, bill of quantities, and also special instructions like an indication of borrow pits etc . which may or may not present.
2. There is a considerable competition in the construction industry requiring accurate and proper, planning and estimating procedures for successful tendering.
3. Mass-haul diagrams are a key factor in selecting material distribution among sections and the equipment types are decided purely on the basis of intuition and experience by considering factors like, haul distance, type of soil, quantities involved, location of the site, topography and configuration of cut and fill etc.
4. Production estimates are obtained either from historical data bases or estimating manuals depending on the contractor.
5. Alternative equipment teams are tested whenever possible to select the cheapest team at tendering stage.
6. Any suitable plant item is easily accessible to any contractor due to availability of large plant hire companies.
7. For large projects, priority is given to find the suitability of underlying soil and locations of nearest borrow pits and disposal sites.
8. Even during construction, considerable attention is given to optimise production, sometimes by adopting workstudy techniques.
9. No sophisticated earthwork optimisation techniques are adopted in general.

10. Incorporation of real life problems into production estimates is done either by including various efficiency factors depending on the type of the job and job conditions or from past records.
11. Computers are not used to a considerable extent in any stage of the project.

3.4.2 Conclusions derived from Sri Lankan Industry

1. Information provided by the client at tendering stage is more or less similar to that of the UK but to a lesser degree particularly the subsoil information.
2. Similar to the UK, the mass-haul diagram is the key factor in selecting optimum material distribution, but unfortunately even this simple tool is not adopted in some situations.
3. Equipment types are also selected similar to the UK but contractors tend to go for what is available in their own plant yard rather than hiring from outside.
4. Production estimates are obtained using historical data bases or from locally developed estimating guides.
5. Alternative equipment teams are not tested either at tendering stage or during construction.
6. Unlike in the UK, most suitable plant team or a balanced team is not easily obtainable due to lack of plant hire companies and also limited capabilities of existing companies.
7. For relatively small jobs, suitability of underlying material and locations of appropriate borrow/disposal sites are not investigated until construction is commenced.
8. During construction, many delays are encountered due to poor management, management policy changes or other factors due to improper planning.
9. More freedom and flexibility is available to Sri Lankan contractors than UK contractors particularly due to the fact that on most occasions the client and the

contractor are both government organisations sometimes under the same ministry.

10. No optimisation techniques are used except in attempting to balance plant teams during construction.
11. In contrast to the UK contractors more manual labour is utilised during earthmoving, for example, back filling of a culvert. The main reason for this is the availability of cheap labour.
12. Computers are not used at any stage of a project except in very rare occasions for costing purposes.
13. Actual project costs usually exceed the estimated cost by about 5% to 100% or even more due to improper planning and inaccurate information provided by the client.
14. Production efficiency can be considerably improved by providing the responsible people a proper training and making them aware of the consequences of bad planning and construction procedures.

3.4.3 The next step forward

From the results of the survey, it was clearly seen that practising planning and estimating techniques, both in the UK and in Sri Lanka, can be significantly improved to obtain accurate and cheaper estimates resulting greater profits. This reinforced the need to develop a new methodology and that proposed by the author is described in the next chapter.

CHAPTER FOUR

DEVELOPMENT OF A NEW APPROACH FOR EARTHWORK OPTIMISATION IN ROAD CONSTRUCTION

4.1 Introduction

4.2 Identification of Appropriate Optimisation Procedure

4.2.1 Feasible optimisation techniques

4.2.2 Selection of appropriate optimisation procedure

4.3 A Sequential Representation of the Problem Methodology

4.4 Individual Simulation Stage

4.5 Linear Programming/Integer Programming (LP/IP) Stage

4.5.1 Case 1 : Same type of soil throughout and existing borrow/disposal sites

4.5.2 Case 2 : Establishing new borrow/disposal sites

4.5.3 Case 3 : Different degrees of compaction at various layers of a fill and variation of soil strata at cut sections and borrow pits

4.5.4 Model extensions

4.5.4.1 Equipment sharing among teams

4.5.4.2 Equipment congestion

4.5.4.3 Sequence of operation

4.5.4.4 Obstructions due to other structures

4.6 Network Scheduling Stage

4.7 Summary

4.1 Introduction

Earthwork optimisation in road construction has drawn considerable attention from past researchers, particularly in the USA and Canada, resulting in development of computer simulation models to determine production outputs (Willenbrock 1975, Clemmens 1978), and LP/IP models for optimum material distribution (Mayer 1981, Easa 1987, Easa 1988). To be more specific, simulation models have been developed by incorporating real life problems, stochastic variations and various types of delays, to obtain either realistic production (or cost) or a balanced plant team. This technique was evolved to overcome the over-estimate of production obtained by deterministic methods. LP/IP models, on the other hand, can be applied to obtain optimum material distribution in a wide range of applications, and were developed to remove the limitations of traditional mass-haul diagram.

Although these techniques have considerable bearing on earthwork optimisation, they are either not fully developed or have limitations. For example, the existing loader-truck simulation models have quite a limited use, since they have not been properly built by systematically identifying various factors affecting cycle element times, analysing them for significance, and calculating the input parameters accordingly. Furthermore, the LP/IP models can only be applied to obtain the optimum material distribution including selection of borrow/disposal sites, but they fail to test alternate plant teams or incorporate constraints like the total project duration as described in Chapter 1.

After a thorough literature review and through discussions with management in the industry, new ideas gradually emerged to develop a novel approach to overcome the limitations of the existing models. The conclusions obtained were those for a typical road construction site, *given the following information:*

- (a) quantities involved in each cut corresponding to different soil types;
- (b) appropriate quantities required in each fill corresponding to different soil types and degrees of compaction;
- (c) possible locations of borrow/disposal sites, their capacities and setting-up costs;
- (d) available plant teams and their appropriate hiring rates or if owned their operating and maintenance costs;
- (e) anticipated project duration;

the model basically should provide amongst other things:

- (i) realistic unit costs of moving earth corresponding to different plant teams tested, by incorporating real life problems, interferences and stochastic variations;
- (ii) optimum material quantities for, cut and fill sections, borrow pits and disposal sites, corresponding to different material types and different degrees of compaction required;
- (iii) optimum combination of plant teams for individual haulage operations from available resources, for the entire job to be completed within a specified period;
- (iv) if the duration of the project is not critical, the optimum combination of plant teams from available resources to achieve the cheapest overall cost;
- (v) whether the available teams can be utilised towards the project completion within the target time and if not the minimum time during which it can be completed;
- (vi) the total cost of earthmoving operations corresponding to the above; and
- (vii) a sensitivity analysis to test the effects of plant alternatives, the variations of the project duration, and more.

This chapter systematically develops the methodology of the proposed model by: identifying feasible optimisation procedures, their advantages and disadvantages; selecting and synthesising the appropriate techniques; and subsequently developing them further to achieve the aforementioned objectives.

4.2 Identification of Appropriate Optimisation Procedure

Clearly, for an optimisation problem like this, there can be more than one approach to achieve the required objectives. Therefore, the first step in developing the methodology is to identify the most appropriate optimisation procedure by evaluating the various possibilities. This is done in the following sections.

4.2.1 Feasible optimisation techniques

It was identified that for a typical road construction project, one of the following techniques can be applied to fulfil the aforementioned objectives.

1. Having decided on the borrow pits, disposal sites, appropriate plant teams to be used (by intuition); the optimum material distribution is obtained as described by Mayer and Stark (1981). A network programme is then drawn up and the entire site is simulated according to the network schedule to find out the real output.

The main advantage of this method is its capacity to incorporate overall interactions into production estimates since the entire site is simulated at once. The main drawbacks are that the borrow pits, disposal sites and team sizes selected may not be the optimum ones and the cut fill distribution (determined by LP/IP) need not necessarily produce the optimum distribution since the cost components are calculated by deterministic methods. In other words, it optimises only the usage of pre-selected plant teams. Furthermore, it does not guarantee that the project can be completed within target time since the network schedule is drawn up based on deterministic production which is generally an over-estimate.

2. Simulation of individual haulage operations by utilising different plant teams having different speeds of operation at the same time avoiding obviously non optimum plant teams and hauls. In this way, realistic unit earthmoving costs can be obtained corresponding to each plant team and haulage operation. Subsequently, the proposed LP/IP technique is applied, incorporating project duration and different plant teams, to find out the optimum plant team/teams for individual operations and also to select optimum borrow/disposal sites together with appropriate cut/fill distribution. The only disadvantage of this method is its inability to incorporate interactions between two or more individual haulage operations when the overall project is considered.

4.2.2 Selection of appropriate optimisation procedure

After careful consideration it was decided to adopt the aforementioned second optimisation procedure for the following reasons.

- (i) It is a complete optimisation procedure when compared with the first in which the material quantities, selected borrow/disposal sites and plant teams may not be the most optimum.
- (ii) The main disadvantage of the second method is not significant since these types of interactions very rarely occur in a typical project. To reinforce this fact, no occasions of such delays were observed during author's data collection for the model (described later).
- (iii) Balancing of plant teams can be achieved during individual simulation stage.
- (iv) It can test different plant teams having various speeds of production, thereby selecting appropriate ones to complete the project within target time.
- (v) If a solution is feasible in the LP/IP stage, it guarantees that the available teams can be utilised for successful project completion.
- (vi) It can provide answers to all the requirements listed earlier.

4.3 A Sequential Representation of the Problem Methodology

The proposed methodology consists of three main stages; individual simulation, LP/IP optimisation and network scheduling (Figure 4.5). Each of these stages in turn consists of several steps, as shown below, some of which are input at that stage and listed for clarity.

Stage 1 : Individual simulation

- (i) Identify all feasible haulage operations between cut and fill sections, cut sections to disposal sites and borrow pits to fill sections.
- (ii) Identify all possible plant teams to be tested for each such operation.

- (iii) Identify appropriate swell/shrinkage factors corresponding to different soil types and operating conditions.
- (iv) Identify shift times, official breaks etc.
- (v) Carry out individual simulations and obtain realistic unit earthmoving costs for each haulage operation corresponding to plant teams tested under the prevailing operating conditions.

Stage 2 : LP/IP optimisation

- (i) Identify cut quantities required along the roadway corresponding to each type of soil and fill quantities corresponding to different types of layers or degrees of compaction.
- (ii) Obtain capacity limitations of borrow pits and disposal sites and their setting up costs.
- (iii) Obtain project duration and other constructional constraints.
- (iv) Apply proposed LP/IP model based on the unit costs obtained in the first stage, to obtain optimum material distribution selecting appropriate borrow/disposal sites, optimum plant teams for individual operations from available resources satisfying all constraints.

Stage 3 : Network scheduling

- (i) Apply the results obtained at the end of second stage together with the sequential logic of the construction operations adopted in the LP/IP formulation to obtain a construction schedule.

Each of these stages are further described in the following sections.

4.4 Individual Simulation Stage

The basic aim of any simulation model is to mimic the actual process in the computer usually before the real application to identify the effects of various factors and avoid unfavourable results. The simulation is carried out by identifying various activities of the process and generating the durations for each of these either by a theoretical distribution or a frequency histogram developed from actual data.

The first step in this process is to separate the earthmoving cycle into individual cycle elements. As adopted by some of the past researchers (Willenbrock 1975), this can be broken down as shown in Figure 4.1. Clearly, productive elements; loading, hauling,

unloading and returning can be generated by appropriate theoretical distributions or frequency histograms, and the unproductive elements; queuing at cut or at fill can easily be incorporated into the logic of the simulation model.

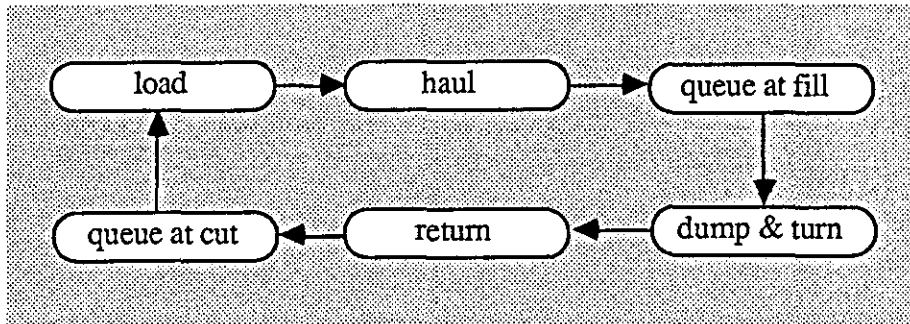


Figure 4.1 - Break down of the earthmoving cycle

The problem now is that there is a large number of variables and factors affecting these cycle elements, for example, loading time can be affected by the size of loader, size of truck, type of soil, site condition etc. A valid simulation model, must therefore, identify the most significant factors affecting these element times and corresponding time generators as done by Clemmens (1978) on scraper operations. However, no one has hitherto, carried out such an analysis for loader-truck operations. This in effect requires collection of field data consisting of cycle element times corresponding to various conditions, analysing them to identify significant factors and categorising them to different conditions. Various types of delays can similarly be identified and quantified. This process is not described here but is systematically explained in Chapters 6 and 7.

Once the element time generators have been developed, earthmoving operations can easily be simulated under specified operating conditions. The anticipated output of the simulation model is the realistic minimum unit earthmoving costs and the appropriate balanced plant teams, operating under various operating conditions, and these unit costs can then be used as input to LP/IP stage.

A detailed development of the simulation model building is carried out in Chapter 8.

4.5 Linear Programming/Integer Programming (LP/IP) Stage

The proposed methodology can easily be explained by considering a typical road construction project as shown in Figure 4.2. However, unlike in the simulation stage, it is difficult to put across the LP/IP methodology in succinct form. Consequently, the LP/IP methodology is fully described in this section.

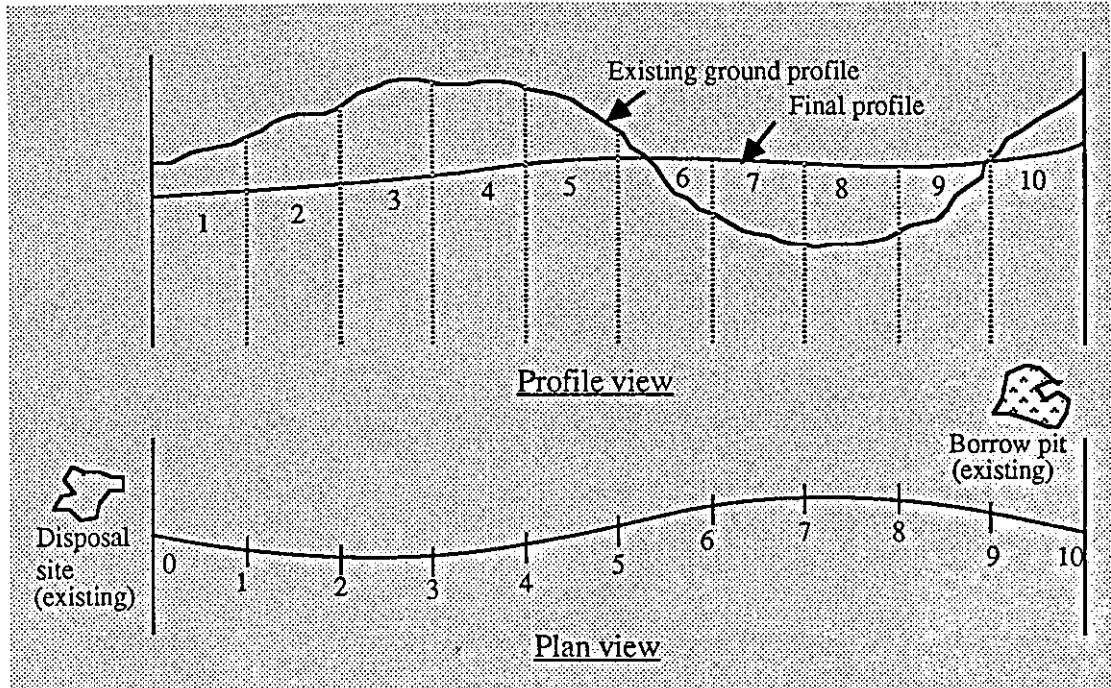


Figure 4.2 - Profile and plan views of a typical road construction project

System definition

Let N be the set of identification numbers ($N=[1,2,3,...M]$) corresponding to all the plant teams available to a contractor and let $N_{i,j}$ (which is essentially a subset of N) be the possible team identification numbers to be used between cut section i and fill section j . Let $X(i,j,n)$ be the volume of cut in metre cubes to be hauled from cut section i to fill section j (in Figure 4.2, i and j can take 7 and 4 values respectively), by team having identification number n which is an element of $N_{i,j}$ (i.e. $n \in N_{i,j}$). It should be noted that the incorporation of different plant teams is necessary in order to compare the speed of production which allows project duration to be accounted for. Furthermore, for each haulage operation there may be several possible plant teams. If sites are available for disposing excess material, let $X_D(i,k,n)$ be the quantity to be disposed from cut section i to disposal site k (in Figure 4.2 $k=1$) using team having identification number n and, in this case, n is an element of $N_{i,k}$ which again is a subset of N (i.e. $n \in N_{i,k} \subset N$).

Similarly, if additional sites are available for borrowing material let $X_B(p,j,n)$ is the quantity of material moved from borrow pit p (in Figure 4.2, $p=1$) to fill section j by team n (where $n \in N_{pj} \subset N$). Also let $C(i,j,n)$ be the total unit cost of haul (including excavation, placement and compaction) from cut section i to fill section j by team n .

$$C(i,j,n) = C_e(i,n) + S_{i,n}^h [C_h(i,n) * d(i,j) + C_c(i,j,n)] \dots\dots\dots (4.1)$$

In Equation (4.1), $C_e(i,n)$, $C_h(i,n)$ and $C_c(i,j,n)$ are the unit costs of excavation, haul and compaction of material cut at section i by team n . The two subscripts are necessary since the cost depends on the cut section (material type) and the team used (mode of excavation). The additional subscript j is included in unit cost of compaction to take into account variation of compaction at different sections (for example, fill sections and disposal sites). If the unit cost of haul and compaction are based on actual volume hauled and compacted, they should be multiplied by appropriate swell (shrinkage) factors. Both of these factors are defined as the ratio of the volume after excavation V_a to the in-place (pre-excavation) volume V_p , i.e.;

$$\text{Swell (shrinkage) factor, } S = V_a/V_p \dots\dots\dots (4.2)$$

For example, suppose that 1m^3 of roadway cut (in place volume) occupies 1.25m^3 of a hauling vehicle and compacts to 0.8m^3 , then the swell factor for hauling is 1.25, while the shrinkage factor for embankment is 0.8. $d(i,j)$ is the haul distance between the centre of masses of cut i and fill j . $S_{i,n}^h$ is the swell factor being hauled for material excavated at section i by team n .

Similarly, $C_D(i,k,n)$ and $C_B(p,j,n)$ can be defined, although these may have an additional component of unit cost of purchasing. To include the production into formulation, also, let $P(i,j,n)$ be the production (m^3/day) in moving earth from cut section i to fill section j by team n based on undisturbed state. This quantity can be calculated by dividing the team hire charge (£/day) by $C(i,j,n)$. $P_D(i,k,n)$ and $P_B(p,j,n)$ can be defined in a similar manner. A complete list of system variable definitions is provided in Appendix A.

4.5.1 Case 1 : Same type of soil throughout and existing borrow/disposal sites

Objective function

The objective function usually is to minimise the total earthmoving cost satisfying the project completion within the specified time. The total cost comprises the cost of moving earth among cut and fill sections (or disposal sites) and borrow pits to fill sections. In symbolic form the objective function can be written as:

$$\begin{aligned} \text{Min } Z = & \sum_i \sum_j \sum_{n \in N_{ij}} C(i,j,n) * X(i,j,n) + \sum_i \sum_k \sum_{n \in N_{ik}} C_D(i,k,n) * X_D(i,k,n) + \\ & \sum_p \sum_j \sum_{n \in N_{pj}} C_B(p,j,n) * X_B(p,j,n) \dots\dots\dots(4.3) \end{aligned}$$

where Z denotes the total cost and $\sum_i \sum_j \sum_{n \in N_{ij}}$ denotes the adding of the products $C(i,j,n) * X(i,j,n)$ for each i,j, and n.

Constraints

1. The total cut required at each section should be equal to the total quantity of material moved from that section to all fill sections and all disposal sites. In symbolic form:

$$\sum_j \sum_{n \in N_{ij}} X(i,j,n) + \sum_k \sum_{n \in N_{ik}} X_D(i,k,n) = Q_C(i) \dots\dots\dots(4.4)$$

where $Q_C(i)$ is the quantity of cut required at section i.

2. The total quantity of fill material required for each fill section should be equal to the quantity of material brought to that section from all cut sections and all borrow pits. In symbolic form:

$$\sum_i \sum_{n \in N_{ij}} S_{i,j}^f * X(i,j,n) + \sum_p \sum_{n \in N_{pj}} S_{p,j}^f * X_B(p,j,n) = Q_F(j) \dots\dots\dots(4.5)$$

where $S_{i,j}^f$ and $S_{p,j}^f$ are the shrinkage factors in fill for material hauled from section i and p respectively, to be compacted in fill j.

$Q_F(j)$ is the quantity of fill required at section j.

The above shrinkage factors do not usually depend upon the plant team used since the specified degree of compaction should somehow be achieved.

3. The total quantity of material brought from each borrow pit should be less than or equal to the capacity of that borrow pit. In symbolic form:

$$\sum_{j \in N_{pj}} \sum X_B(p,j,n) \leq Q_B(p) \dots\dots\dots(4.6)$$

where $Q_B(p)$ is the capacity of borrow pit p.

4. The total quantity of material disposed at each disposal site should be less than or equal to the capacity of that disposal site. In symbolic form:

$$\sum_{i \in N_{ik}} \sum S_{i,k,n}^f * X_D(i,k,n) \leq Q_D(k) \dots\dots\dots(4.7)$$

where $S_{i,k,n}^f$ is the swell factor in fill for material hauled from section i to disposal site k using team number n.

$Q_D(k)$ is the total capacity of disposal site k.

It should be noted that the swell factor may depend on the plant team used since no compaction is usually carried out at disposal sites.

5. The total duration of each plant team utilised for each and every haulage operation should be less than or equal to the total project duration, thereby avoiding any concurrent use of the same plant team. In symbolic form:

$$\sum_i \sum_j [X(i,j,n)/P(i,j,n)] + \sum_p \sum_j [X_B(p,j,n)/P_B(p,j,n)] + \sum_i \sum_k [X_D(i,k,n)/P_D(i,k,n)] \leq D \dots\dots\dots(4.8)$$

where D is the total project duration in days.

It should be noted that in practice some of the equipment items in a particular team may be used in another team. When this happens both the teams cannot be operated concurrently, by grouping such teams as one team group this aspect also can easily be incorporated into the equation (4.8).

The above constraint, however, does not avoid the possibility of concurrent use of more than one team for a particular haulage operation for timely project completion. This may create congestions but can be avoided by ensuring that the total time spent on any particular source and destination, by all possible plant teams is less than or equal to the total project duration, thereby enabling the use of different teams sequentially between source and destination, for project completion as scheduled. In symbolic form:

6. For each haulage operation:

(i) Between cut and fill sections (any combination of i and j);

$$\sum_{n \in N_{ij}} [X(i,j,n)/P(i,j,n)] \leq D \quad \dots\dots\dots(4.9)$$

(ii) Between cut and existing disposal sites (any combination of i and k);

$$\sum_{n \in N_{ik}} [X_D(i,k,n)/P_D(i,k,n)] \leq D \quad \dots\dots\dots(4.10)$$

(iii) Between borrow pits and fill sections (any combination of p and j);

$$\sum_{n \in N_{pj}} [X_B(p,j,n)/P_B(p,j,n)] \leq D \quad \dots\dots\dots(4.11)$$

7. Each variable should have a value equal to or greater than zero. In symbolic form:

$$X(i,j,n) \geq 0, X_D(i,k,n) \geq 0, X_B(p,j,n) \geq 0 \quad \dots\dots\dots(4.12)$$

The formulation now is a LP problem which can easily be solved by a computer and the Z obtained satisfying the constraints is the optimum solution.

4.5.2 Case 2 : Establishing new borrow/disposal sites

Previous formulation assumed the existence of borrow pits and disposal sites. When the borrow/disposal sites are at a considerable distance from the roadway, it may sometimes be economical and even necessary to establish additional sites near the roadway (see Figure 4.3). Deciding how many sites should be established and where should they be located depend upon associated costs such as:

- (a) land acquisition;
- (b) site preparation for excavation and hauling;
- (c) construction and maintenance of access roads; and
- (d) refurbishing and clean up.

These set up costs should be included in the total cost of the project if these sites are used. However, as proposed by Mayer and Stark (1981) this aspect can be incorporated by first defining 0-1 variables $Y_{SB}(1), Y_{SB}(2) \dots Y_{SB}(n_b)$ for each such borrow pit to be set up and $Y_{SD}(1), Y_{SD}(2) \dots Y_{SD}(n_d)$ for each such disposal site to be set up. n_b and n_d represent the number of such borrow pits and disposal sites respectively. The variable $Y_{SB}(b)$ or $Y_{SD}(d)$ has a value of zero if that site is not utilised but has a value of unity otherwise. If the set up cost for a borrow pit b is $K_{SB}(b)$ and disposal site d is $K_{SD}(d)$, then the total cost of utilising the site would be:

- (i) For each borrow pit p to be established;

$$K_{SB}(b)Y_{SB}(b) + \sum_{j \in N_{b,j}} \sum C_{SB}(b,j,n) * X_{SB}(b,j,n) \dots\dots\dots(4.13)$$

- (ii) For each disposal site d to be established;

$$K_{SD}(d)Y_{SD}(d) + \sum_{i \in N_{i,d}} \sum C_{SD}(i,d,n) * X_{SD}(i,d,n) \dots\dots\dots(4.14)$$

where C_{SB} and C_{SD} refer to unit earthmoving costs and X_{SB} and X_{SD} are earthwork quantities.

Finally, the capacity constraints for each new site can be modified as follows.

- (iii) For each borrow pit to be set up;

$$\sum_{j \in N_{bj}} \sum X_{SB}(b,j,n) - Q_{SB}(b)Y_{SB}(b) \leq 0 \dots\dots\dots(4.15)$$

Where $Q_{SB}(b)$ is the capacity of borrow pit b .

(iv) For each disposal site to be set up;

$$\sum_{i \in N_{id}} \sum S_{idn}^f * X_{SD}(i,d,n) - Q_{SD}(d)Y_{SD}(d) \leq 0 \dots\dots\dots(4.16)$$

Where $Q_{SD}(d)$ is the capacity of disposal site d .

These constraints serve a dual role. They ensure that Y_{SB} or $Y_{SD} > 0$ (and equal to unity) whenever any X_S variables are active, so that the set up costs $K_{SB}(b)$ or $K_{SD}(d)$ are included. Secondly, Y_{SB} or $Y_{SD} = 1$ serves as the capacity constraint for the site.

The complete formulation will then be as follows.

Objective function

$$\begin{aligned} \text{Min } Z = & \sum_i \sum_{j \in N_{ij}} \sum C(i,j,n) * X(i,j,n) + \sum_i \sum_{k \in N_{ik}} \sum C_D(i,k,n) * X_D(i,k,n) + \\ & \sum_p \sum_{j \in N_{pj}} \sum C_B(p,j,n) * X_B(p,j,n) + \sum_b K_{SB}(b)Y_{SB}(b) + \\ & \sum_b \sum_{j \in N_{bj}} \sum C_{SB}(b,j,n) * X_{SB}(b,j,n) + \sum_d K_{SD}(d)Y_{SD}(d) + \\ & \sum_i \sum_{d \in N_{id}} \sum C_{SD}(i,d,n) * X_{SD}(i,d,n) \dots\dots\dots(4.17) \end{aligned}$$

Constraints

1. For each value of i (cut section):

$$\sum_{j \in N_{ij}} \sum X(i,j,n) + \sum_{k \in N_{ik}} \sum X_D(i,k,n) + \sum_d \sum X_{SD}(i,d,n) = Q_C(i) \dots\dots\dots(4.18)$$

2. For each value of j (fill section):

$$\sum_i \sum_{n \in N_{ij}} S_{ij}^f * X(i,j,n) + \sum_P \sum_{n \in N_{pj}} S_{pj}^f * X_B(p,j,n) + \sum_b \sum_{n \in N_{bj}} S_{bj}^f * X_{SB}(b,j,n) = Q_F(j) \dots\dots\dots(4.19)$$

where S_{ij}^f , S_{pj}^f and S_{bj}^f are the swell (or shrinkage) factors in fill for material excavated from i, p or b respectively, to be compacted at fill section j.

3. Quantity constraint for existing borrow pit p remains unchanged. (Eq. 4.6)
4. Quantity constraint for existing disposal site k remains unchanged. (Eq. 4.7)
5. For each value of b (borrow pit to be set up):

$$\sum_j \sum_{n \in N_{bj}} X_{SB}(b,j,n) - Q_{SB}(b) Y_{SB}(b) \leq 0 \dots\dots\dots(4.20)$$

where $Q_{SB}(b)$ is the capacity limitation of borrow pit b.

6. For each value of d (disposal site to be set up):

$$\sum_i \sum_{n \in N_{id}} S_{idn}^f * X_{SD}(i,d,n) - Q_{SD}(d) Y_{SD}(d) \leq 0 \dots\dots\dots(4.21)$$

where S_{idn}^f is the swell factor in fill for material excavated from cut section i to be disposed at d by team n and $Q_{SD}(d)$ is the capacity limitation of disposal site d.

7. For each value of n (plant team identification number):

$$\begin{aligned} & \sum_i \sum_j [X(i,j,n)/P(i,j,n)] + \sum_P \sum_j [X_B(p,j,n)/P_B(p,j,n)] + \\ & \sum_i \sum_k [X_D(i,k,n)/P_D(i,k,n)] + \sum_b \sum_j [X_{SB}(b,j,n)/P_{SB}(b,j,n)] \\ & \sum_i \sum_d [X_{SD}(i,d,n)/P_{SD}(i,d,n)] \leq D \dots\dots\dots(4.22) \end{aligned}$$

8. For each haulage operation:

- (i) Constraint for each haulage operation between cut and fill sections remains unchanged. (Eq. 4.9)
- (ii) Constraint for each haulage operation between cut and existing disposal sites remains unchanged. (Eq. 4.10)

- (iii) Constraint for each haulage operation between borrow pits and fill sections remains unchanged. (Eq. 4.11)
- (iv) Constraint for each haulage operation between cut sections and disposal sites to be set up (any combination of i and d);

$$\sum_{n \in N_{i,d}} [X_{SD}(i,d,n)/P_{SD}(i,d,n)] \leq D \dots\dots\dots(4.23)$$

- (v) For each haulage operation between borrow pits to be set up and fill sections (any combination of b and j);

$$\sum_{n \in N_{b,j}} [X_{SB}(b,j,n)/P_{SB}(b,j,n)] \leq D \dots\dots\dots(4.24)$$

9. Non negativity conditions:

$$X(i,j,n) \geq 0, X_D(i,k,n) \geq 0, X_B(p,j,n) \geq 0, X_{SD}(i,d,n) \geq 0, X_{SB}(b,j,n) \geq 0, \\ Y_{SB}(b), Y_{SD}(d) = 0 \text{ or } 1 \dots\dots\dots(4.25)$$

The formulation now is a mixed integer (zero-one) programming problem which can easily be solved by a computer and the Z obtained satisfying these constraints is the optimum solution.

4.5.3 Case 3 : Different degrees of compaction at various layers of a fill and variation of soil strata at cut sections and borrow pits

Since the cross sections of a roadway typically allow for different types of soil or degrees of compaction (for subgrade, subbase sidefill etc.), additional variables or equivalently additional subscripts can be used to distinguish between the quantities required to fill sections (Mayer 1981). For example, $Q_F(j,c)$ represents the quantity of soil required at fill j, while c corresponds to the category of compaction.

Furthermore, borrow sites and cut sections of a roadway often have different soil strata as shown in Figure 4.3. However, some may be unsuitable for any filling while others may be appropriate for certain layers (for example, subgrade). This aspect can also be included into the formulation by incorporating an additional subscript and additional constraint, depending on the suitability of materials to different layers of a fill.

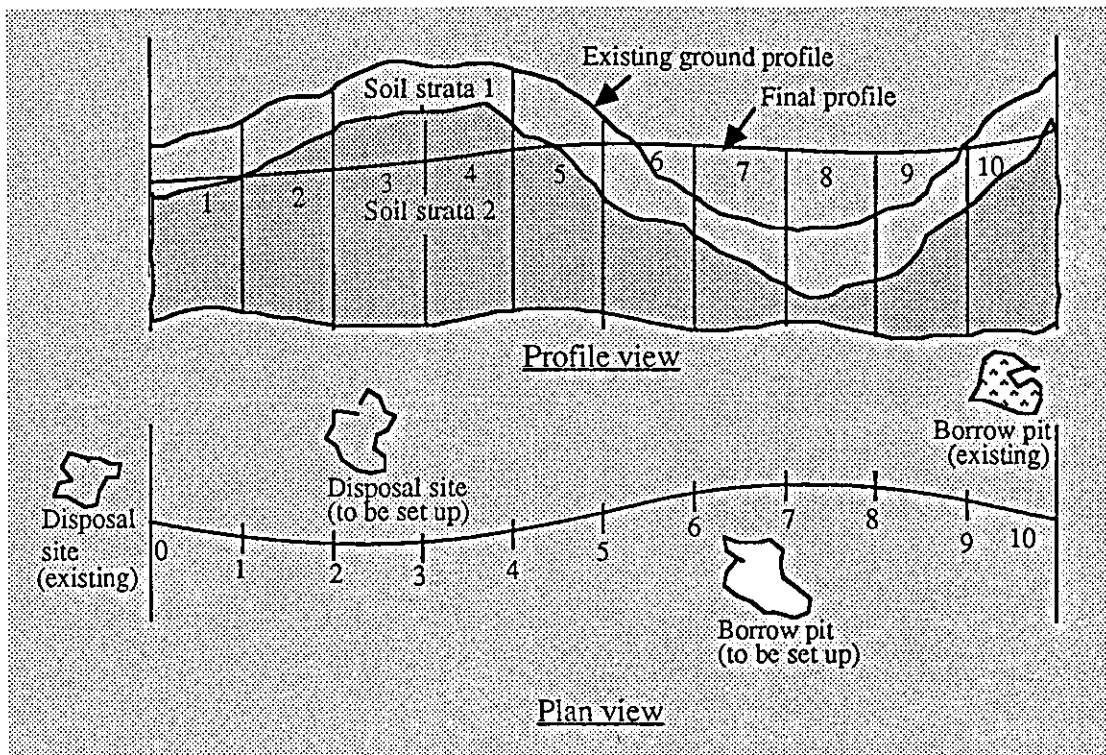


Figure 4.3 - Profile and plan views of a typical road construction project with different soil strata

The formulation extended to accommodate both these features is as follows.

Objective function

$$\begin{aligned}
 \text{Min } Z = & \sum_i \sum_j \sum_s \sum_{c \in N_{i,j,s,c}} C(i,j,s,c,n) * X(i,j,s,c,n) + \\
 & \sum_i \sum_k \sum_s \sum_{n \in N_{i,k,s}} C_D(i,k,s,n) * X_D(i,k,s,n) + \\
 & \sum_p \sum_j \sum_s \sum_{c \in N_{p,j,s,c}} C_B(p,j,s,c,n) * X_B(p,j,s,c,n) + \sum_b K_{SB}(b) Y_{SB}(b) + \\
 & \sum_b \sum_j \sum_s \sum_{c \in N_{b,j,s,c}} C_{SB}(b,j,s,c,n) * X_{SB}(b,j,s,c,n) + \sum_d K_{SD}(d) Y_{SD}(d) + \\
 & \sum_i \sum_d \sum_s \sum_{n \in N_{i,d,s}} C_{SD}(i,d,s,n) * X_{SD}(i,d,s,n) \dots\dots\dots(4.26)
 \end{aligned}$$

Where $X(i,j,s,c,n)$ and $C(i,j,s,c,n)$ are the quantity and the unit cost of hauling material (including placement and compaction) respectively, from strata type s in cut i to layer type c in fill j by plant team number n . All the other variables and constants have similar definitions. Different degrees of compaction are not required at disposal sites and hence the subscript c has been neglected. The appropriate plant team subsets contain three or four subscripts to incorporate any variations of teams depending on the soil type and the degree of compaction.

Constraints

1. For each value of s and i (each strata in each cut):

$$\sum_j \sum_c \sum_{n \in N_{i,j,s,c}} X(i,j,s,c,n) + \sum_k \sum_{n \in N_{i,k,s}} X_D(i,k,s,n) + \sum_d \sum_{n \in N_{i,d,s}} X_{SD}(i,d,s,n) = Q_C(i,s) \dots\dots\dots(4.27)$$

where $Q_C(i,s)$ is the quantity of material available at cut section i corresponding to strata type s . This quantity can be calculated by cross sectional drawings and bore hole data.

2. For each value of c and j (each layer in each fill):

$$\sum_i \sum_s \sum_{n \in N_{i,j,s,c}} S_{i,j,s,c}^f * X(i,j,s,c,n) + \sum_p \sum_s \sum_{n \in N_{p,j,s,c}} S_{p,j,s,c}^f * X_B(p,j,s,c,n) + \sum_b \sum_s \sum_{n \in N_{b,j,s,c}} S_{b,j,s,c}^f * X_{SB}(b,j,s,c,n) = Q_F(j,c) \dots\dots\dots(4.28)$$

where $Q_F(j,c)$ is the quantity of fill material required to layer c in fill section j and this can be calculated from drawings.

3. For each value of s and p (each strata in each borrow pit):

$$\sum_j \sum_c \sum_{n \in N_{p,j,s,c}} X_B(p,j,s,c,n) \leq Q_B(p,s) \dots\dots\dots(4.29)$$

where $Q_B(p,s)$ is the capacity limitation of strata type s in borrow pit p .

4. For each value of k (each disposal site):

$$\sum_i \sum_s \sum_{n \in N_{i,k,s}} S_{i,k,s,n}^f * X_D(i,k,s,n) \leq Q_D(k) \dots\dots\dots(4.30)$$

5. For each value of s and b (each strata in each borrow pit to be set up):

$$\sum_j \sum_c \sum_{n \in N_{bj,s,c}} X_{SB}(b,j,s,c,n) - Q_{SB}(b,s) Y_{SB}(b) \leq 0 \dots\dots\dots(4.31)$$

where $Q_{SB}(b,s)$ is the capacity limitation of strata type s in borrow pit b .

6. For each value of d (disposal site to be set up):

$$\sum_i \sum_s \sum_{n \in N_{i,d,s}} S_{i,d,s,n}^f * X_{SD}(i,d,s,n) - Q_{SD}(d) Y_{SD}(d) \leq 0 \dots\dots\dots(4.32)$$

7. For each value of n (plant team):

$$\begin{aligned} & \sum_i \sum_j \sum_s \sum_c [X(i,j,s,c,n)/P(i,j,s,c,n)] + \\ & \sum_p \sum_j \sum_s \sum_c [X_B(p,j,s,c,n)/P_B(p,j,s,c,n)] + \\ & \sum_i \sum_k \sum_s [X_D(i,k,s,n)/P_D(i,k,s,n)] + \\ & \sum_b \sum_j \sum_s \sum_c [X_{SB}(b,j,s,c,n)/P_{SB}(b,j,s,c,n)] + \\ & \sum_i \sum_d \sum_s [X_{SD}(i,d,s,n)/P_{SD}(i,d,s,n)] \leq D \dots\dots\dots(4.33) \end{aligned}$$

8. For each haulage operation corresponding to a road section, borrow pit or a disposal site:

- (i) For any combination of i and j ;

$$\sum_s \sum_c \sum_{n \in N_{i,j,s,c}} [X(i,j,s,c,n)/P(i,j,s,c,n)] \leq D \dots\dots\dots(4.34)$$

- (ii) For any combination of i and k ;

$$\sum_s \sum_{n \in N_{i,k,s}} [X_D(i,k,s,n)/P_D(i,k,s,n)] \leq D \dots\dots\dots(4.35)$$

- (iii) For any combination of p and j ;

$$\sum_s \sum_c \sum_{n \in N_{p,j,s,c}} [X_B(p,j,s,c,n)/P_B(p,j,s,c,n)] \leq D \dots\dots\dots(4.36)$$

(iv) For any combination of i and d;

$$\sum_s \sum_{n \in N_{i,d,s}} [X_{SD}(i,d,s,n)/P_{SD}(i,d,s,n)] \leq D \quad \dots\dots\dots(4.37)$$

(v) For any combination of b and j;

$$\sum_s \sum_c \sum_{n \in N_{b,j,s,c}} [X_{SB}(b,j,s,c,n)/P_{SB}(b,j,s,c,n)] \leq D \quad \dots\dots\dots(4.38)$$

9. Non negativity conditions:

$$X(i,j,s,c,n) \geq 0, X_D(i,k,s,n) \geq 0, X_B(p,j,s,c,n) \geq 0, X_{SD}(i,d,s,n) \geq 0, \\ X_{SB}(b,j,s,c,n) \geq 0, \text{ and } Y_{SB}(b), Y_{SD}(d) = 0 \text{ or } 1. \quad \dots\dots\dots(4.39)$$

Situations where certain material types are unsuitable for certain layers can be incorporated by omitting variables for unsuitable materials. For example, if soil type 1 (S1) in cut section 1 (i=1) is not suitable for the subgrade (SG), then $X(1,j,S1,SG,n)$ is not used as a variable.

The formulation again is a mixed integer (zero-one) programming problem and can be solved in a similar manner.

4.5.4 Model extensions

4.5.4.1 Equipment sharing among teams

The team utilisation constraints of the above formulations (Eqs. 4.8, 4.22 and 4.33) assume that plant items in a particular team are not utilised for another. In practice, however, a particular item of equipment may be used in several teams. In such situations, the above equations can be modified as follows.

Let N_T be a subset of plant teams (or a team group) which share plant items. Then, for each such team group;

$$\sum_i \sum_j \sum_s \sum_c \sum_{n \in N_T} [X(i,j,s,c,n)/P(i,j,s,c,n)] + \\ \sum_p \sum_j \sum_s \sum_c \sum_{n \in N_T} [X_B(p,j,s,c,n)/P_B(p,j,s,c,n)] +$$

$$\begin{aligned}
& \sum_i \sum_k \sum_s \sum_{n \in N_T} [X_D(i,k,s,n)/P_D(i,k,s,n)] + \\
& \sum_b \sum_j \sum_s \sum_c \sum_{n \in N_T} [X_{SB}(b,j,s,c,n)/P_{SB}(b,j,s,c,n)] + \\
& \sum_i \sum_d \sum_s \sum_{n \in N_T} [X_{SD}(i,d,s,n)/P_{SD}(i,d,s,n)] \leq D \dots\dots\dots(4.40)
\end{aligned}$$

4.5.4.2 Equipment congestion

There may be situations where the use of several plant teams at a particular cut section or a fill section is impossible. For example, if the work area at cut section i is limited to one team at a time then instead of constraints (4.34), (4.35) and (4.37) the following constraint can be substituted.

$$\begin{aligned}
& \sum_j \sum_s \sum_c \sum_{n \in N_{i,j,s,c}} [X(i,j,s,c,n)/P(i,j,s,c,n)] + \\
& \sum_k \sum_s \sum_{n \in N_{i,k,s}} [X_D(i,k,s,n)/P_D(i,k,s,n)] + \\
& \sum_d \sum_s \sum_{n \in N_{i,d,s}} [X_{SD}(i,d,s,n)/P_{SD}(i,d,s,n)] \leq D \dots\dots\dots(4.41)
\end{aligned}$$

Depending on the area limitation only some of the terms of this equation may be applicable to a particular cut section.

4.5.4.3 Sequence of operation

Although, the above formulation takes the project duration into account, it ignores the sequence of operations at a cut or fill section, particularly when different soil strata are available and different degrees of compaction are required. For example, in a cut section the top strata should be moved before starting working in subsequent strata, or in a fill section unsuitable material (if present) should be removed before subgrade filling. In such situations, equations (4.34) to (4.38) can be replaced by following constraints, which limit the summation of all team utilisation times corresponding to one roadway section to the project duration.

- (i) For any roadway section m where only cutting is required (Figure 4.4[a]):

$$\begin{aligned} & \sum_j \sum_s \sum_{c \in N_{m,j,s,c}} [X(m,j,s,c,n)/P(m,j,s,c,n)] + \\ & \sum_k \sum_s \sum_{n \in N_{m,k,s}} [X_D(m,k,s,n)/P_D(m,k,s,n)] + \\ & \sum_d \sum_s \sum_{n \in N_{m,d,s}} [X_{SD}(m,d,s,n)/P_{SD}(m,d,s,n)] \leq D \dots\dots\dots(4.42) \end{aligned}$$

In fact, this equation is the same as (4.41)

- (ii) For any roadway section m where only filling is required (Figure 4.4[b]):

$$\begin{aligned} & \sum_i \sum_s \sum_{c \in N_{i,m,s,c}} [X(i,m,s,c,n)/P(i,m,s,c,n)] + \\ & \sum_p \sum_s \sum_{c \in N_{p,m,s,c}} [X_B(p,m,s,c,n)/P_B(p,m,s,c,n)] + \\ & \sum_b \sum_s \sum_{c \in N_{b,m,s,c}} [X_{SB}(b,m,s,c,n)/P_{SB}(b,m,s,c,n)] \leq D \dots\dots\dots(4.43) \end{aligned}$$

- (iii) For any roadway section m where unsuitable soil should be disposed before any filling (Figure 4.4[c]):

$$\text{last two terms in equation (4.42) + all terms in (4.43) } \leq D \dots\dots\dots(4.44)$$

- (iv) For any roadway section where both cut and fill are required:

- (a) *Case 1 (Figure 4.4[d])*: The greater of, duration required to move top strata (suitable for only certain layers, for example subgrade) and the duration required to fill those layers (subgrade) together with the greater of, duration required to move other cut material (for example strata 2) and duration required to fill remaining layers $\leq D \dots\dots\dots(4.45)$

- (b) *Case 2 (Figure 4.5[e])*: Duration required to move top strata together with the greater of, time required to fill remaining layers and time required to remove remaining cutting $\leq D \dots\dots\dots(4.46)$

In all four cases, subjective judgement is necessary to treat different situations and the above formulae can easily be modified, with similar arguments, in such situations as one section should be completed before start working in another section.

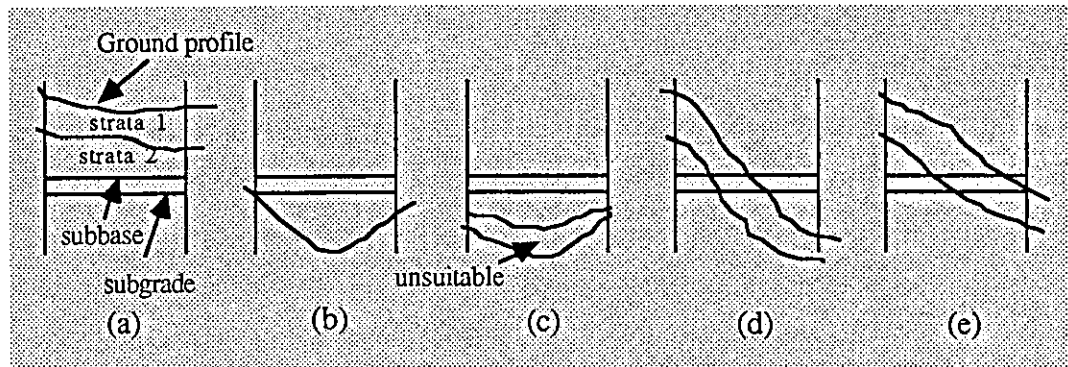


Figure 4.4 - Possible shapes of cut and fill sections of a roadway

4.5.4.4 Obstructions due to other structures

There may be situations where the construction of a bridge, culvert or any other structure prevents material movement across it during its construction. This aspect can be incorporated into equations (4.42) to (4.46) by including any delay times occurred because of such construction activities.

This delay in fact occurs if and only if such material movements are present in the optimum solution which is unknown in advance. However, this can be overcome by first defining 0-1 variables $\lambda(m)$ for each roadway section m . The constraint is again the total time spent removing and/or borrowing material from/to a roadway section, together with any delays incurred, should be less than or equal to the total project duration. In symbolic form:

For any roadway section (m) ;

$$T_{ND}(m) + T_D(m) + \lambda(m) [d_s - T_{ND}(m)] \leq D \dots\dots\dots(4.47)$$

This equation is in general form. $T_{ND}(m)$ and $T_D(m)$ indicate the total time spent for material movements corresponding to roadway section m without using the bridge and using the bridge respectively. d_s is the time required for bridge construction. It is clear that if $T_{ND}(m) > d_s$ then the bridge can be completed before it is used for material movements and hence no overall delays occur. To make $\lambda(m)$ behave as expected two additional constraints are necessary:

$$(i) \quad \lambda(m) [d_s - T_{ND}(m)] \geq 0 \quad \dots\dots\dots(4.48)$$

This ensures that whenever $d_s < T_{ND}(m)$, $\lambda(m) = 0$

$$(ii) \quad T_D(m) - \lambda(m)D \leq 0 \quad \dots\dots\dots(4.49)$$

This ensures that when $T_D(m)$ is positive, $\lambda(m) = 1$.

To make sure that $\lambda(m)$ is zero when the bridge is not used the term $\lambda(m)\epsilon$ (ϵ is a very small value) should be added to the objective function. This formulation now is a quadratic formulation which will be difficult to solve and the benefit obtained may not justify the difficulty. However, a conservative solution can be obtained by replacing the term $[d_s - T_{ND}(m)]$ by d_s and omitting the constraint (4.48). This requires only one binary variable per structure for all sections. That is, instead of constraints (4.47), (4.48) and (4.49) the following two can be applied:

$$T_{ND}(m) + T_D(m) + \lambda(s) d_s \leq D \quad \dots\dots\dots(4.50)$$

$$T_D(m) - \lambda(s)D \leq 0 \quad \dots\dots\dots(4.51)$$

If the structure to be constructed is small, then it is unlikely that this will take more time than that required to haul materials among sections corresponding to haulage operations without using the structure. In this case, there is little interference to haulage operations and the effect of that can be neglected in the formulation. This is analogous to situations where unsuitable material should be removed before starting any filling in that section. In cases where it is likely that the construction of a structure interfere with haulage operations it is recommended to apply the constraints set out in equation (4.50) and (4.51). Whatever the case, in all the above situations, the duration required to construct such a structure in a particular section must be added to the appropriate constraint equation corresponding to that section.

All the models developed above, except those that contain quadratic constraints, can be solved by any LP/IP package and it is the author's view that if appropriate constraints relevant to a particular situation are applied, the above model satisfactorily provides answers to all the objectives listed earlier in this chapter.

4.6 Network Scheduling Stage

Essentially, about 95% of the model is developed during the first two stages of the model but the solution process is not complete until the contractor is provided with a network schedule presenting the sequence of activities. As mentioned earlier, most information required to draw up a network is presented at the end of LP/IP stage in the forms of quantities involved and the resources which can easily be manipulated to obtain durations required for the each activity. The user has only to enter the logic of the network as expected during LP/IP formulation, so that any network analysis software package can be used to obtain the anticipated construction schedule.

It is interesting to note that at any stage of construction, the model can be rerun to reoptimise and reschedule the future activities, incorporating new constraints which were not foreseen earlier.

4.7 Summary

The objectives of the model were identified and the proposed methodology was systematically developed.

It was shown that, for a typical road construction project, computer simulation combined with LP/IP can be applied to obtain an optimum material distribution satisfying real life constraints like project completion time and plant limitations. In this way, the proposed model consists of three basic stages; individual simulation stage, LP/IP stage and network scheduling stage. After a brief description of the simulation stage, the appropriate LP/IP formulations were fully developed with detailed explanations. The results obtained from the LP/IP stage can then be used to draw up a construction schedule.

A simple schematic representation of the model, together with the expected input and output at all three stages (individual simulation, LP/IP optimisation and network scheduling) is depicted in Figure 4.5.

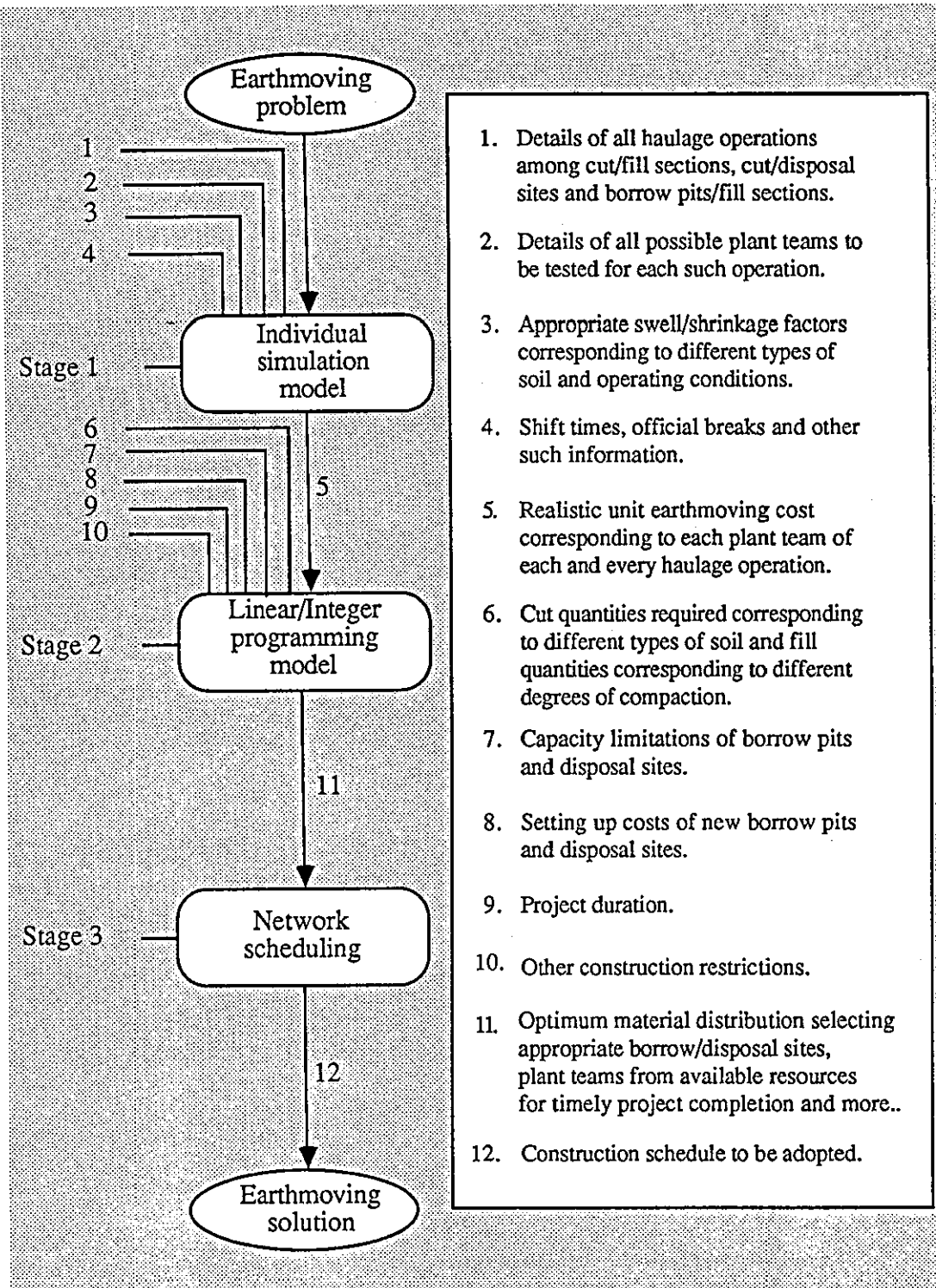


Figure 4.5 - A simple schematic representation of the proposed model

CHAPTER FIVE

THEORY OF SIMULATION AND DEVELOPMENT OF MODELLING APPROACH FOR EARTHMOVING OPERATIONS

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5.2 Functions of a Model

5.3 Different Types of Models

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5.6.5 What sampling method ?

5.7 Conclusions

5.1 Introduction

Robert E. Shannon, in his book *Systems Simulation : the art and science* (Shannon 1975) identifies simulation as;

" The process of designing a model of a real system and conducting experiments with this model for the purpose of either of understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system"

According to this definition, simulation emphasises both facets, the *art* which is the development and the *science* which is the experimentation with the model. Simulation received its original impetus from the aerospace programs. Today it has been successfully applied to many other areas due to its simplicity of the fundamental approach and vast potential in all disciplines. For example, it has already been applied to Business (Meir 1969, Gershefski 1970, Naylor 1970), Economics (Naylor 1971, Pacher 1972), Marketing (Amstutz 1967, Meadows 1970), Education (Armstrong 1970), Politics (Cherryholmes 1969), Social Science (Guetzkow 1962, Dutton 1971), Behavioural Science (Hogatt 1963, Siegal 1969), Transportation (Kresge 1971), Construction Management (Douglas 1964, Gaarslev 1969, Willenbrock 1975, Clemmens 1978) and many others.

To successfully and efficiently simulate complex problems one must adopt comparatively detailed and specific approaches. This, together with considerable research attracted to simulation, has helped to create a variety of modelling methods.

Before starting to build a complete simulation model for earthwork operations, a clear understanding of available modelling methods is thus required.

Firstly, this chapter describes the theory of modelling in general, with particular reference to computer simulation, and compares different approaches. Secondly, these methods are evaluated and the most suitable techniques for earthwork simulation are selected.

5.2 Functions of a Model

A model is basically a representation of an object, system, or an idea in some form other than the entity itself (Shannon 1975), and is built with a view to explaining, understanding and improving the system. The concept of modelling is so general that it is difficult to classify all the functions of a model. However, Elmaghraby (1968) recognises five common uses as:

- (i) an aid to thought;
- (ii) an aid to communication;
- (iii) for training and instruction;
- (iv) a tool for prediction; and
- (v) an aid to experimentation.

A network representation of a complex project can be considered an obvious example of a model's usefulness as an aid to thought. This assists management to organise and sort out hazy concepts, understand what steps are necessary and in what sequence, to help develop inter-relationships, and determine what resources are required.

As an aid to communication, a properly conceived model can help reduce ambiguity, created by verbal descriptions of the system, by providing more efficient and effective mode of communication such as histograms, graphs, piecharts etc.

Clearly, models have been and continue to be widely used as training and instruction aids. This type of training is very common in situations where learning with a prototype model is both expensive and dangerous.

One of the most important uses of model building in almost any discipline is to predict the behaviour of the system modelled in situations where it is economically infeasible to build the full scale object or system. This is very common in testing the behaviour of space vehicles.

From the Civil Engineering point of view, experimentation with a model can be regarded as the most important and common objective. This is usually carried out by varying certain parameters of the system whilst holding all the others constant and observing the results. In most practical situations experimentation with the reality is both dangerous and economically prohibitive. By experimentation, the most suitable combination of parameters can be achieved with relative ease with low cost.

5.3 Different Types of Models

Models, in particular simulation models, can be considered as a continuous spectrum, starting with exact models or mock-ups of reality and proceeding to completely abstract mathematical models as shown in Figure 5.1 (Rowe 1963).

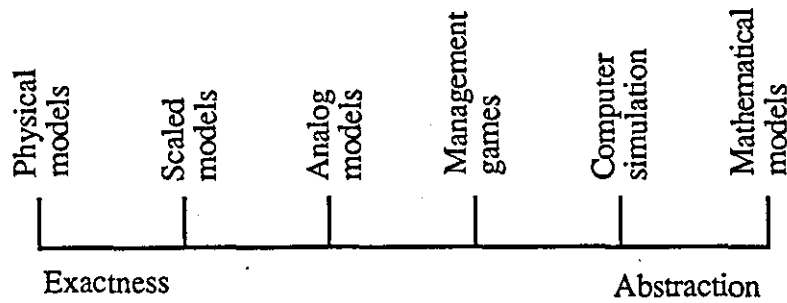


Figure 5.1 - Model spectrum

Models towards the beginning of the spectrum are called physical (or iconic) models and they may be full scale mock-ups or scaled models resembling the system being modelled. They may be three dimensional like a scale model airplane tested in a wind tunnel or two dimensional like a scaled layout of a construction site.

Sometimes, a property of the real object is represented by a substituted property that often behaves in a similar manner. These models are called analog models and the problem is usually solved in the substituted state and the results transferred into original state. A very simple example is a graph where distance along axis represents a certain property like time, volume, cost, production etc. Any kind of flow diagrams can also be thought of as analog models.

Models around the middle of the spectrum can be regarded as games where individuals and computers interact. Such models are difficult to fully model and the individual interacts, with the computer output (which simulates all the other aspects of the model) and feeds data back into the computer according to the output received. Proceeding a bit further along the spectrum, complete computerised simulation is encountered, which most people generally visualise when the term computer simulation is used.

At the other extreme, there are symbolic or mathematical models which use symbols (such as t , v , for time and volume) rather than a physical device in representing an entity. Mathematical models are the most abstract, most general and most popular. Queuing theory is a good example of a mathematical model. However, application of

these models is limited in complex situations where several assumptions have to be made to obtain a solvable model, in which case the results obtained may not be realistic. Mathematical models may use results produced by other models and in real situations more than one type of model may be required to successfully model a real problem.

One obvious example is the problem at hand where earthmoving in road construction is simulated to obtain realistic unit costs (computer simulation model), which are then used by the linear optimisation model (mathematical model) followed by presentation of results in a network schedule (analog model). The mathematical model applicable to the problem was fully developed in the previous chapter and the analog section, being comparatively simple, what is required now is to try and understand the computer simulation part which is discussed in the following sections.

5.4 Fundamentals of Computer Simulation

5.4.1 Simulation approach

5.4.1.1 The basics

Computer simulation methods have developed since early 1960's and are usually the most commonly used of all the analytical tools of management science and are becoming popular in construction management. The basic idea is that the analyst builds a model of the system (in this case earthwork simulation) and writes a computer program embodying the model and imitates the systems behaviour, subjecting to variety of operating policies to select the most desirable approach. Computer simulation thus involves experimentation on a computer based model using the model as the vehicle of experimentation, often in a *trial and error* basis to demonstrate the effects of the various policies. This means that all simulation models are input/output models as shown in Figure 5.2.

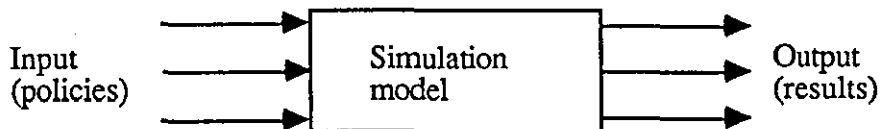


Figure 5.2 - Simulation as experimentation (source - Pidd 1984)

Simulation models are, therefore, *run* rather than *solved* in order to obtain desired results. They can only serve as a tool for experimentation under conditions specified

by the experimenter. Thus simulation is not a theory but a methodology of problem solving.

The most difficult part of simulation is usually the actual model development by understanding logical relationships, interactions between various sub-systems or entities. This process is eased by the use of logical models. The simplest way of thinking about logical models is to consider flow diagrams. One example is the use of flow process charts for method studies in the construction industry (Harris 1983) to display the various processes through which the product or object passes through during construction. These flow charts provide clear and unambiguous logical relationships thereby providing the framework for simulation model building. They are often very helpful in the early stage of model building and one such flow diagram used by the author in his model building is described later in this chapter.

5.4.1.2 Why simulate?

Essentially, computer simulation is no panacea. Valid simulations require long computer programs with considerable complexity. Despite this, it is surprising how such an approach is needed in real life.

The reasons for adopting computer simulation for earthmoving operations were discussed in the previous chapter. However, it is worthwhile to consider the following advantages of simulation compared to direct experimentation and mathematical modelling.

- (i) Usually real life experimentation is more expensive than simulation experimentation in understanding the systems' behaviour.
- (ii) A valid simulation model is capable of simulating weeks, months or even years in few minutes enabling to compare a whole range of policies very quickly.
- (iii) Direct experimentation is not usually repeatable or repetition is quite expensive, simulation on the other hand, is perfectly repeatable.
- (iv) Unlike simulation, testing of extreme policies or conditions in real experimentation could be dangerous.
- (v) A complete mathematical formulation of the problem may not exist or analytical methods of solving them have not yet been developed.
- (vi) Even if analytical methods are available they may be quite complicated and simulation provides simpler solutions.

- (vii) Analytical solutions may exist but they are beyond the ability of the available personnel.
- (viii) Simulation facilitates the observation of the simulated history of the process over a period of time in addition to other requirements.

5.4.1.3 The simulation process

Once it has been decided to use simulation to investigate behaviour of a real system, the steps to be followed and their relationships can be depicted as shown in Figure 5.3 and are briefly described as follows.

1. System definition : Defining the system to be modelled after determining the boundaries, restrictions and the extent of results expected.
2. Model formulation : Identification of logical relationships and interactions between sub-systems and development of logical flow diagrams.
3. Data preparation : Identification of data required by the model, and their reduction to appropriate form (input parameters).
4. Model translation : Translation of the logical relationships to a computer program.
5. Validation : Increasing to an acceptable level of confidence that an inference drawn from the model about the real system be correct.
6. Strategic planning : Design of an experiment that will yield the desired information.
7. Tactical planning : Determination of how each of the test designed is to be executed.
8. Experimentation : Execution of simulation with varying input parameters to generate desired results and to perform sensitivity analysis.
9. Interpretation : Drawing inferences from the results generated by simulation.
10. Implementation : Application of the results to use.
11. Documentation : Recording the activities, results, together with model and its use.

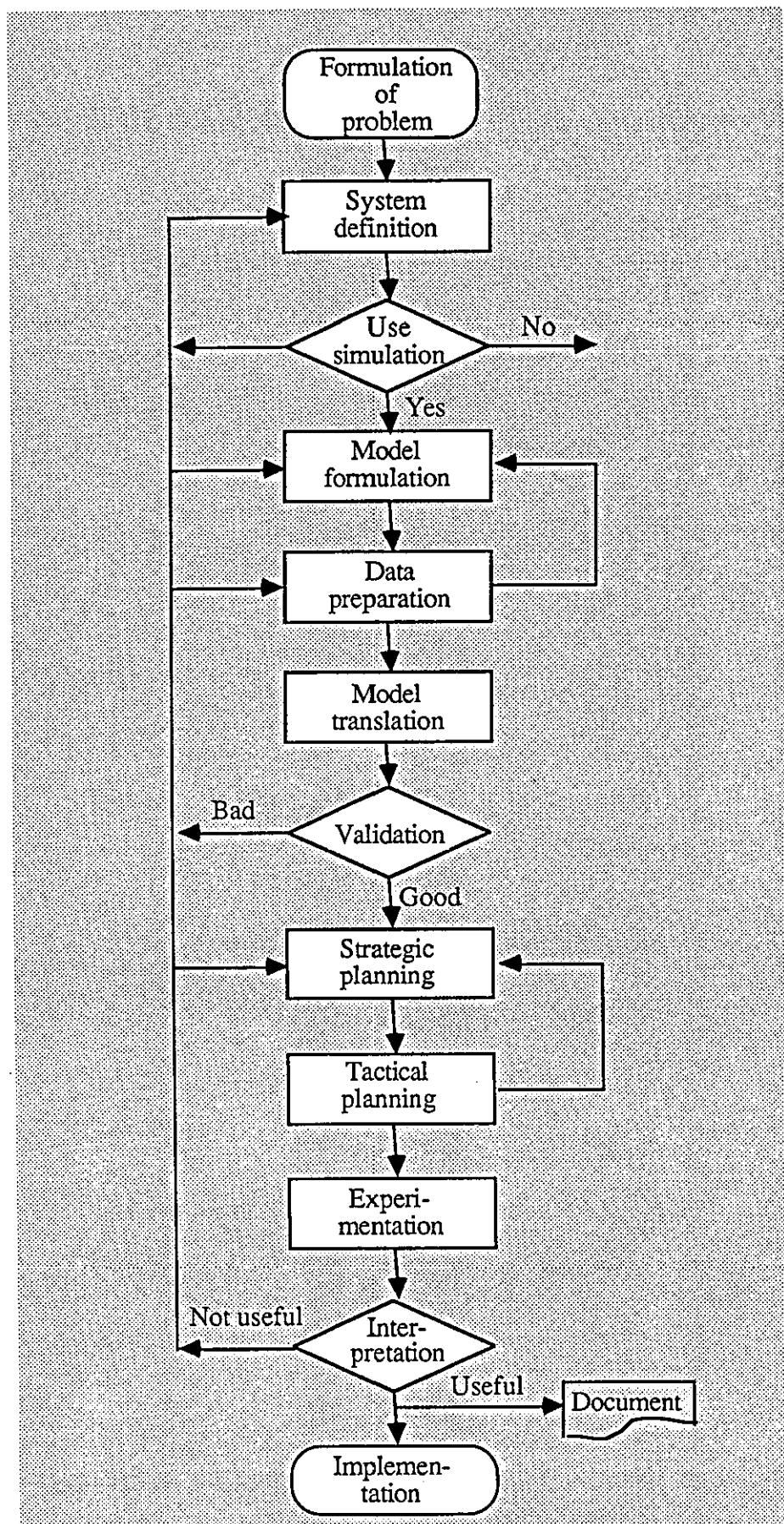


Figure 5.3 - The simulation process (source - Shannon 1975)

5.4.2 Different modelling approaches

Some modelling approaches are more suited to certain problems than to others. Therefore, before arriving at a particular method for earthmoving simulation, it is worthwhile to consider different approaches available, in particular, for the following aspects of simulation.

1. Time handling
2. Behaviour of the system (stochastic or deterministic)
3. Type of the system (discrete or continuous)

5.4.2.1 Time handling

One of the advantages of computer simulation is its ability to simulate several weeks or months in few minutes of computer time. Since simulation involves mimicking of changes in the system through time, it requires a considerable thought to decide how the time flow may be handled within simulation. Basically, there are two techniques for this purpose, namely, 'Time slicing' and 'Next event'.

Time slicing

'Time slicing' can be regarded as the simplest way of controlling the time flow within simulation and it involves forwarding the simulation clock in equal time intervals as the simulation proceeds. The problem with this approach is that the simulationist must decide on a suitable time interval before simulation is carried out. If this interval is too large, the behaviour of the model is much coarser and the state changes occurred between intervals cannot be modelled, on the other hand, if the interval is too small the model is frequently examined unnecessarily (when no state changes are possible) leading to excess computer time. However, in situations where state changes occur at regular intervals it is quite adequate to adopt this technique.

Next event technique

In this case, the model is examined and updated at variable time intervals, only when it is known that a state change is due. These state changes are usually called events and, because time is moved from event to event, this approach is called the next event technique, and is preferred in many real life applications.

5.4.2.2 Behaviour of the system

Behaviour of a system being modelled can basically be considered as either stochastic or deterministic. A deterministic model is one whose behaviour is entirely predictable, in other words, it is capable of predicting precisely what will happen next. A cycle of operations of an automatic machine can be considered as deterministic since each repeated identical cycle will take the same length of time.

Behaviour of a stochastic model, on the other hand, cannot entirely be predicted though some statement may be made about how likely certain events can occur. For example, travel time of a truck from A to B may not always be the same even under the same operating conditions. Statistically, it can be considered that the travel time is normally distributed, for example, with mean of twenty minutes and standard deviation of three minutes. This means that probability distributions are used in stochastic models. As the simulation proceeds the required system times are sampled from appropriate probability distributions to introduce probabilistic nature into models.

5.4.2.3 Type of system

Generally, the variables included in a simulation model can be thought of as changing state in four ways (Pidd 1984).

- (i) Continuous at any point of time. Thus values change smoothly and are accessible at any time point within the simulation.
- (ii) Continuously but only at discrete time points. In this case, values change continuously but can only be accessed at pre-defined times.
- (iii) Discretely at any point of time. Thus, state changes are easily identifiable and can occur at any point of time.
- (iv) Discretely, but only at discrete point of time. In these situations, the state changes can only occur at specified points of time.

By considering these, computer simulation applications can be divided into those employing discrete change and those allow the variables to change continuously through time.

Discrete change

As an example of a discrete event simulation, consider a truck transporting soil from a cut section to a fill section. Viewed from the perspective of discrete change the following change of events may be considered:

- (a) truck arrives at cut and queues (if a queue exists);
- (b) truck starts loading;
- (c) truck ends loading and starts hauling;
- (d) truck ends hauling and starts unloading; and
- (e) truck ends unloading and starts returning.

The time taken between adjacent events can either be calculated deterministically or could be sampled from appropriate probability distributions. Thus, for example, when a truck starts to be loaded its end of loading time can be scheduled by referring to the 'known' loading time. Therefore, in discrete simulation, state changes always occur at discrete time intervals and the variables are only of interest when they point to a change in state of the system.

Continuous change

In continuous simulation, variables change their values continuously through time. For example, consider the travel time of a truck given in the previous example. Clearly, the speed of a truck varies continuously starting from zero at cut section and changing thereafter. If speed is to be considered as a variable in the model to describe travel time, then it cannot be simulated discretely. Hence, in these simulations a continuous change model should be employed. These continuous changes can be represented by differential equations which would, in theory, allow the variables to be computed at any point of time. It should be noted that this example is actually a mixed discrete/continuous problem since other event times can be modelled discretely.

Most problems in the construction industry, including earthmoving, can be successfully modelled in the perspective of discrete change. Hence, the subsequent sections are devoted to explore only the discrete event simulation methods.

5.5 Discrete Event Simulation

5.5.1 Discrete event modelling

Many applications of discrete event simulation involve queuing systems of some kind or other. Since state changes of queuing systems almost always occur discretely, they lend themselves well to discrete event simulation. Earthmoving in road construction is a clear example where muck shifting trucks wait at the loading phase to be served by a loader. Before proceeding, it would be convenient to understand the terminology used in discrete event simulation.

5.5.1.1 Terminology

Terminology can be divided into two parts, namely, the objects of the system and operations of the entities.

Objects of the system

1. *Entities* : These are the elements of the system being simulated and can be individually identified and processed. For example, equipment items in an earthmoving team, people waiting in a queue to be served, machines in a factory can be regarded as entities. The system, thus, can be considered as a set of related entities and their interactions produce the distinctive behaviour of the system. The entities remaining throughout simulation (for example, trucks in an earthmoving team) are permanent entities and those pass by after service (for example, people waiting in a retail shop) are temporary entities.
2. *Classes* : Although entities are individually identifiable, similar entities can be grouped into classes. For example, all scrapers and all pushers in an equipment team can be considered as two different classes of entity.
3. *Attributes* : Attributes convey additional information about entities. For example, capacity of scraper, loading method (pushed, push-pull or elevating), number of engines, all are attributes of scraper entity. These attributes are helpful in many ways in simulation. They can be used to subdivide different classes (push-pull scrapers, self loading scrapers etc.) and may also be used to control the behaviour of an entity. For example, the method of loading, affects the loading time of scrapers and hence will be used to categorise the process of generating loading times.

4. *Sets* : Entities may be permanently divided into classes but during simulation entities change states and those states may be represented as sets. For example, all scrapers and trucks waiting at the cut area to be served can be considered as a set.

Operations of the entities

During simulation, entities co-operate and change their state. The following are thus needed to explain these operations and also to describe the time flow.

1. *Event* : An event is an instant in time at which a significant state change occurs in the system. For example, start loading of a scraper, end loading, end hauling etc. all are events. It is the responsibility of the simulationist to identify only the significant events according to his objective of simulation.
2. *Activity* : Operations initiated at each event are called activities. Thus activities are what transform the state of entities. Clearly, loading, hauling, dumping and turning etc. are all activities in earthmoving simulation.
3. *Process* : A sequence of events grouped together in the chronological order can be regarded as a process. For example, arrive at cut, start loading, end loading, start hauling, end hauling, start unloading, end unloading, start returning grouped together can be considered as a process.
4. *Simulation clock* : Simulation clock is the simulated time reached in the simulation and is used to check whether any event is due at different set times.

The relationship between above definitions can be depicted as shown in Figure 5.4.

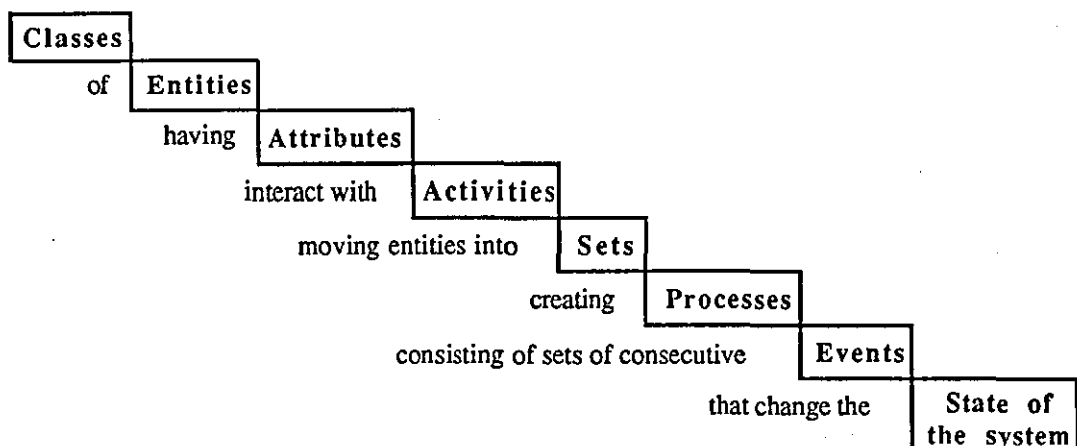


Figure 5.4 - Relationship of simulation terminology

5.5.1.2 Activity cycle diagrams

It was identified earlier that simulation modelling requires some kind of flow diagrams, representing relationships and interactions between entities to start with. Activity cycle diagrams are one way of modelling these interactions and are particularly useful for systems with strong queuing structures. The use of activity cycle diagrams was popularised by Hills (1971) and are normally associated with 'Activity' and 'Three phase approach' of modelling (to be described later). However, Matthewson (1974) argues that they are useful in any other approaches of discrete event modelling and are of general use.

Activity cycle diagrams consist of only two symbols shown in Figure 5.5. A flow diagram developed by these symbols displays graphically the life history of each class of entity and their interactions. Each class of entity is considered to have a life cycle consisting a series of states which are changed as its life proceeds.

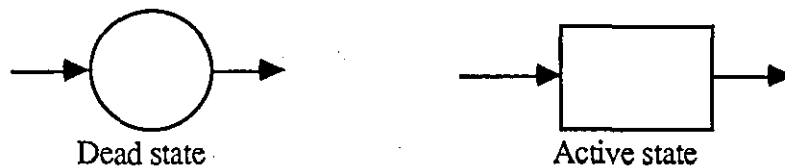


Figure 5.5 - Symbols for activity cycle diagrams (source - Pidd 1984)

An active state usually, but not necessarily, involves a co-operation of two classes of entity and whose duration can always be determined in advance by taking a sample from an appropriate probability distribution (if the model is stochastic). For example, loading of a truck or a scraper is an active state.

On the other hand, a dead state represents idling and involves no co-operation between different classes of entity. Queuing time of hauling units in earthmoving is an example of a dead state. Activity cycle diagrams are usually drawn as alternate dead and active states, and the complete diagram of a system can be obtained by combining the diagrams drawn for each class of entity.

Activity cycle diagram : An example

The following simple example was taken to illustrate the principles behind in drawing activity cycle diagrams (Pidd 1984).

Consider a simple engineering jobshop consisting of several identical machines capable of processing a certain kind of a job. Jobs are allocated to the first available machine and the processing time is a variable independent of the particular machine being used. The job shop is staffed by a single operator who has to perform two tasks:

1. reset machines between jobs if the cutting edges are still satisfactory; and
2. retool those machines whose cutting edges are too worn to be reset.

Thus, the two classes of entity are:

1. the operator; and
2. the machines.

The operative is responsible for two major tasks 'retool' and 'reset' as described above and in addition he may be unavailable (away) whilst attending to personal needs. This means that there are three active states as shown in Figure 5.6.

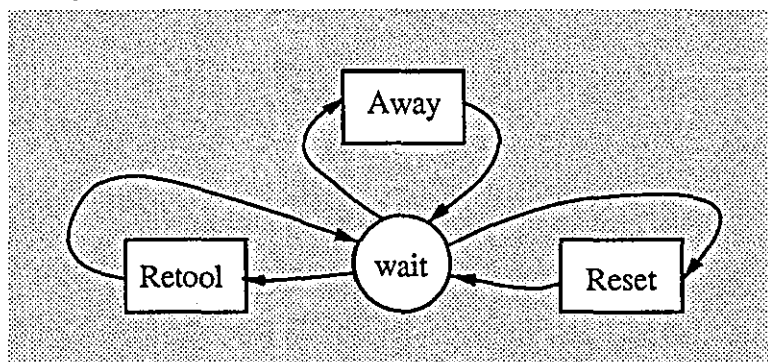


Figure 5.6 - The operative's activity cycle

Retool and *reset* are carried out in co-operation with the machines (the other class of entity) and are therefore active states. The durations of these activities can be obtained by appropriate probability distributions, which themselves can be developed by actually observing the time taken for these activities. The duration of activity *away* can also be generated by a probability distribution and hence it is an active state being satisfied one requirement of active states. In addition to all these states, the operative may be idling between active operations in a dead state *wait*. In practice he may stay in the dead state quite some time or instantly pass it between two adjacent active states. Therefore, the diagram consists of alternate active and dead states according to the usual convention.

With similar arguments, the three active states of the machines are *retool*, *reset*, *running* and the appropriate activity cycle diagram can be represented as shown in Figure 5.7.

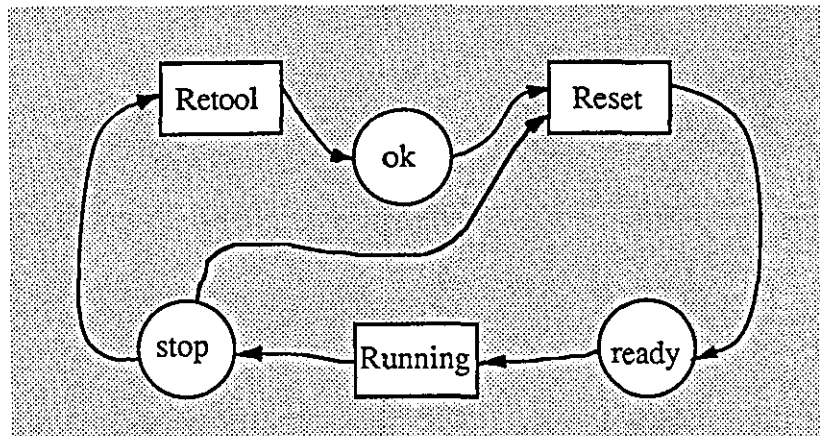


Figure 5.7 - The machines' activity cycle

There are three dead states, *ok*, *stop* and *ready*. The dead states *ok* and *ready* may not exist in real life but have been added for two reasons. Firstly, to maintain the convention of activity cycle diagrams (alternate active and dead states) and secondly, to allow the model to be enhanced later, when there are two operators, one of whom is responsible for *retool* and the other is responsible for *reset*.

An attribute may be used during simulation to decide whether a machine moves to *reset* or *retool* on each occasion.

Now, to represent the entire system, the two activity cycle diagrams can be combined as shown in Figure 5.8.

Note that the dead states are unique for each class of entity and some active states involve co-operation between two classes of entity.

Clearly, the activity cycle diagrams provide a graphical representation of the interactions or the logic of the system which must be built into the skeleton of the simulation model. Thus, they allow precise specification of the conditions that must hold before state changes can occur. It should also be noted that the activity cycle diagrams cannot embody all the possibilities in real life but once the skeleton model is developed incorporating obvious inter-relationships and interactions, the model can easily be enhanced without further referring to an activity cycle diagram. The use of activity

cycle diagram in model building is further described in Chapter 8 during the development of the *proper* earthmoving simulation model.

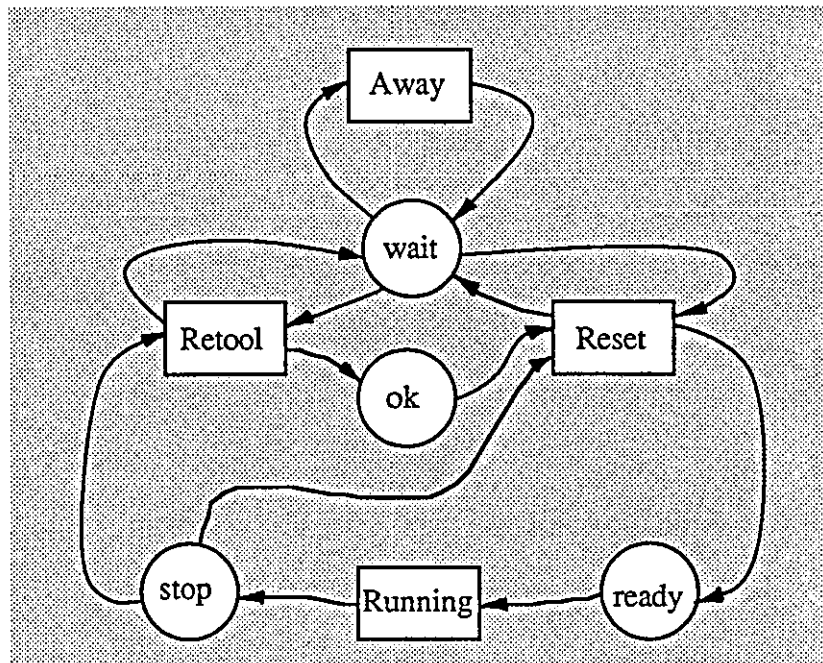


Figure 5.8 - Combined activity cycle diagram

5.5.2 Different approaches of discrete event modelling

Activity cycle diagrams do provide a clear and unambiguous interactions between different entities of a model. Once this stage is passed the problem arises as to how these interactions are embodied effectively in a computer program. Basically there are four widely used approaches to achieve this task and each of those embodies a distinctive world view. These approaches are:

1. The Event approach;
2. The Activity approach;
3. The Process interaction approach; and
4. The Three phase approach.

According to Fishman (1973), all these four methods have a common feature that they produce programs with a three level hierarchical structure as follows:

Level 1 - the executive (control program);

- Level 2 - operations; and
- Level 3 - detailed routines.

The executive controls level two and is responsible for sequencing the operations which occur as the simulation proceeds. Thus, the executive identifies when the next event is due and ensures that the correct operations occur at that time. Each of the above four approaches have different styles of executives.

The second level describes the operations that make up the model and provides explicit instructions to the computer about the interactions of the entities. This level constitutes the simulation program *proper* and is the main concern of the simulationist in model building. Each of these four main approaches adopts its own structure in level two requiring the analyst to divide the operations of the system into its basic building blocks. These are event routines, activities, or processes in the case of event approach, activity approach or process interaction approach respectively. Execution of these segments and interaction between segments are also controlled by the executive.

The third level of the program consists of routines to generate random variates, collect statistics, and to generate reports etc. and are called by the second level.

Each of these approaches is briefly described in the following sections.

5.5.3 The Event approach

In the event based approach, the second level, the simulation program *proper* is made up of a set of event routines each of which describes the operations in which entities engage when the system changes state. The event based executive performs the following tasks in order to control the simulation.

- (i) *Time scan* : Determining the next event time and moving the simulation clock to then.
- (ii) *Event identification* : Identifying which events are due at that time.
- (iii) *Event execution* : Properly executing those events identified as due now.

The executive manages these tasks by the use of an event list which can be thought of as a diary into which future event notices are added and from which old notices are removed as the simulation proceeds.

In short, the event based executive executes the following two face cycle continuously until simulation is over.

1. Time scan:
 - (a) determining the next event by scanning the event list;
 - (b) moving the simulation clock time to then; and
 - (c) producing a current event list consisting of event notices of all the events identified as due now.
2. Event execution
Executing each event of the current event list and updating event list accordingly.

5.5.4 The Activity approach

Unlike an event based approach, where concentration is on mapping out the possible operations which might follow from a state change, the activity approach focuses on the interactions of various classes of entity. The basic building block of the activity approach is the *activity* and when coded into the program segments each activity will have a two part structure.

Test head : Tests the conditions which must be satisfied if the activity is to be executed. For example, in earthmoving, existence of a free loader must be true if the activity *loading a truck* is to be started.

Actions : The operations consisting the activity, and can only be performed if the test head is passed.

Level two of an activity based program thus consists of a set of independent routines each of which has the above two part structure. Each of these routines is called by the executive and executed only if the test head is passed, otherwise the control is directly returned to the executive. The system moves from event to event as in the event based approach and at each event, each activity is attempted in turn.

The only major task performed by an activity based executive is the time scan which involves identification of when the next event is due. Unlike an event approach where a dynamic event list is used to achieve this, time cells are used in the activity approach.

The time cell can be regarded as an attribute of each permanent entity and indicates when each entity is due to change state next.

In the executive, the time cells may be held as a list which is not ordered by value. During the time scan no attempt is made either to identify which of the entities will change state or which activity is due next, but after time scan simulation clock is moved to the minimum time cell and executive makes repeated activity scan attempting each activity in turn until no more action is possible.

Thus, an activity based executive has two repetitive steps as follows.

- (i) Time scan.
- (ii) Repeated activity scan.

One disadvantage of activity approach when compared to event approach is its run time inefficiency, due to its repetitive activity scan, even though the conditions within simulation may mean that only one activity is possible. On the other hand, event based approach involves execution of only pre-identified activities in the current event list. However, the activity approach has two important advantages. Firstly, it tends to provide smaller program segments for activities than would be the case for events. Secondly, the analyst need not be too concerned about the sequence of activities since it is sorted out by the executive in the activity scan.

5.5.5 The Process interaction approach

This method has been developed in an attempt to combine features of both event and activity based approaches. The second level of the simulation program consists of separate program segments of processes rather than event routines or activities as in event or activity based approaches. As defined earlier, a process can be described as the sequence of operations through which an entity passes during its life within the system. Compared to activity and event approaches, the executive and the routines in the second level of the program are complicated. Typically, this approach views each entity as moving through various operations which constitute its process.

5.5.6 The Three phase approach

5.5.6.1 'B' and 'C' activities

Three phase approach to discrete event simulation was first developed by Tocher (1963) and is a successful attempt in combining the simplicity of the activity approach with the efficient execution of the event based approach. Essentially, the basic building block is the activity which in this case is categorised into 'B' and 'C' activities. 'B' activities are bound or book keeping activities which are executed directly by the executive program whenever their scheduled time is reached. As with the activity approach there are no test heads at the beginning of each 'B' activity routine. For example, in earthmoving, once the loading of a truck is started, its *end loading* is bound to occur when the service time has elapsed. No other condition should be satisfied. Hence it is a 'B' activity. 'C' activities are conditional or co-operative activities whose execution depends either on the co-operation of different classes of entity or on the satisfaction of specific conditions within the simulation. For example, if *begin loading* is to be started two conditions should be met. Firstly, there should be a truck waiting in the queue and secondly, the loader should be free. Thus, it is conditional and co-operative indicating *begin loading* as a 'C' activity.

5.5.6.2 A Three phase executive

The three phase executive basically has three phases called A, B, and C as follows.

- A phase (time scan) : Determines when the next event is due and which 'B' activities are due at that time. Moves the simulation clock time to next event time.
- B phase (B calls) : Executes all 'B' activities identified in the 'A' phase as being due now.
- C phase (C scan) : Attempts each 'C' activity in turn and executes those whose conditions are satisfied. Repeats 'C' scan until no more 'C' activities are possible. (This is similar to activity scan in activity approach).

A three phase executive usually carries out these three phases by assigning a three part record to each entity as shown in Figure 5.9. The first part is the time cell indicating the simulation time at which this entity is next due to change state. The second part indicates which 'B' activity is due. If the entity is waiting for a 'C' activity, then some indication is given (usually by assigning a negative value) that the next activity is

undetermined. The third part (not essential) indicates the activity in which the entity was last engaged.

Time cell	Next 'B' activity	Previous activity
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Figure 5.9 - The three part record

During the time scan the executive scans time cells of entities whose next activity is a 'B' activity and selects the minimum time cell. Then it keeps a list of all those entities having this minimum time cell. These entities are the entities involved in the next event change. After moving the simulation clock to this time cell the executive carries out all those 'B' activities due now. Subsequently, the executive enters the 'C' phase as in the typical activity approach. This process is repeated until simulation is over.

5.6 Development of Simulation Approach for Earthmoving Operations

The previous sections reviewed modelling in general with particular reference to computer simulation and evaluated possible approaches. Based on this knowledge the following sections select the most appropriate simulation techniques to be adopted for earthmoving operations.

5.6.1 Time slicing or Next event ?

As described earlier, time slicing involves advancing the simulation clock in a pre-defined time interval, whereas the next event technique involves moving the clock forward to the next event time, during simulation. For earthwork simulation, next event technique was selected in preference to time slicing due to following reasons.

- (i) Earthwork state changes occur at variable length of time and intermediate state changes may not be accounted for if time slicing is used.
- (ii) Next event technique is clearer and simpler.
- (iii) Time slicing involves more computer time due to extra scanning.
- (iv) Next event technique is more suitable for discrete event simulation like earthmoving.

5.6.2 Stochastic or deterministic ?

One of the objectives of this research is to incorporate the stochastic nature of real life situations into production estimates in an attempt to optimise earthmoving operations. Thus, simulation of earthmoving operations should be carried out in a stochastic environment.

5.6.3 What simulation language ?

Essentially, a highly disciplined and structured programming approach should be adopted in simulation modelling of comparatively complex problems like earthmoving. This enables successive enhancements, easy verification and debugging. In achieving this, selection of the language to be adopted also plays an important role. This is not an easy job, mainly due to the availability of large number of simulation languages. Some of these have been developed for proprietary applications while others can be used for any purpose. Different simulation languages adopt different world views. For example, SIMSCRIPT (Markowitz 1963) adopts event based approach, ECSL (Clementson 1982) adopts activity based approach, and GPSS (Greenberg 1972) and SIMULA (Hills 1973) follows the process interaction approach. Earthmoving operations can be simulated either by any of these languages or by a general purpose language like Fortran, Basic or Pascal.

In order to select a suitable language for earthmoving simulation according to author's requirements, a survey on simulation languages was performed and the following selection criteria were considered.

- (i) Type of language (continuous or discrete).
- (ii) Ease of use including programming and debugging.
- (iii) Suitability for the purpose.
- (iv) Output facilities.
- (v) Portability.
- (vi) Availability.
- (vii) Support.
- (viii) Capability.

By applying these selection criteria, the available simulation languages, at the time of the research, were reduced to the following eight candidates.

- (i) GPSS/H
- (ii) GPSS/Fortran
- (iii) SIMSCRIPT II.5
- (iv) SIMAN
- (v) SLAM
- (vi) SIMULA
- (vii) ECSL
- (viii) General purpose languages (Fortran, Basic, Pascal)

Each of these languages was carefully reviewed and the list was reduced to three, SIMAN (Pegden 1985), SIMSCRIPT (Markowitz 1963) and Pascal. After considerable thought, it was decided to adopt the general purpose language, Pascal, for the following reasons.

- (a) A major part of research work was to be carried out in Sri Lanka where the software support would be considerably less in a problematic situation.
- (b) The author has not used SIMAN or SIMSCRIPT II.5 and it would be necessary to spend a lot of time in developing the required skill in using the language.
- (c) The use of SIMAN or SIMSCRIPT II.5 may create problems in developing the overall framework to incorporate properties of all the haulage operations and several plant teams to each haulage operation.
- (d) The use of a simulation language may restrict the access to the model by potential users due to their limited computer facilities.
- (e) Large quantities of data will have to be processed at any time and this may create difficulties when using a simulation language.
- (f) The Pascal language has its own inherent text processing, self documenting and complex numeric handling facilities which lend themselves suitable for simulation modelling.
- (g) Some of past researches (Bratley 1987, Jennergren 1984, Davies 1989) have recommended Pascal as a suitable language for discrete event modelling.

5.6.4 Event, Activity, Process or Three phase approach ?

The Three phase approach was selected in preference to other methods for the following reasons.

- (a) Although the event approach provides efficient execution, it is comparatively difficult to program and debug.
- (b) Activity approach is easy to program, adopts well structured approach, and is particularly suitable for complex problems thereby enabling the gradual enhancement of the model. However, it is very inefficient in execution.
- (c) Three phase approach succeeds in providing all the advantages present in activity approach together with efficient execution.

5.6.5 What sampling method ?

Clearly, earthwork simulation being stochastic, requires some sort of a random number generation for various cycle element times involved in earthmoving. This is usually achieved by taking samples from probability distributions corresponding to each such cycle element. These probability distributions are usually derived by actual field data collected on each of these cycle elements under various operating conditions. The unavailability of reliable probability distributions to generate these cycle times, made it necessary to collect data in the form of various cycle element times of earthmoving operations. This data collection and analysis to develop these appropriate distributions are discussed in Chapters 6 and 7 respectively.

5.7 Conclusions

In model building, different approaches of modelling and languages were reviewed, with particular reference to simulation, and the following conclusions were derived as an aid to proceed with simulation model building for earthwork operations.

1. The next event technique is the most suitable time handling method for earthwork simulation.
2. Simulation should be carried out in a stochastic environment.
3. The Three phase approach is the most suitable simulation approach.

4. Activity cycle diagrams are a very good representation of relationships and interactions between entities and are useful particularly during the initial stage of model building.
5. The general purpose language Pascal was selected as the most suitable language.
6. The random variates providing cycle element times should be generated from appropriate probability distributions developed from field data.

CHAPTER SIX

DATA COLLECTION FOR MODEL BUILDING AND VALIDATION

6.1 Introduction

6.2 Identification of Required Information

6.2.1 Questionnaire survey

6.2.2 Identification of important factors affecting cycle element times

6.2.2.1 Factors affecting scraper cycle element times

6.2.2.2 Factors affecting pusher cycle element times

6.2.2.3 Factors affecting truck cycle element times

6.2.2.4 Factors affecting loader cycle time

6.2.2.5 Factors affecting dozer cycle element times

6.2.3 Categorisation of delays

6.2.4 Points to ponder in developing the data collection programme

6.3 Development of the Data Collection Programme

6.3.1 Study method

6.3.2 Development of observation forms

6.4 Data Collection

6.4.1 A brief description of projects used

6.4.2 Data collection procedure

6.5 Summary

6.1 Introduction

During the development of a research methodology, the need for field data collection for both simulation model building and validation of overall model was identified. This need was further explained in the previous chapter. Clearly, any data collection task should be carried out after pre-planning the project as far ahead as possible by identifying its objectives.

The three main objectives of data collection were:

1. to identify various types of probability distributions representing different cycle element times;
2. to calculate input parameters for the above distributions under various operating conditions; and
3. to find out overall equipment utilisation, quantifying various types of delays and to gather other relevant information for model validation.

In effect, to achieve the above objectives, it was first necessary to identify important factors affecting various cycle element times and to categorise the numerous types of delays so that the extent of field information required could be established in advance. Subsequently, this information could be used to develop the actual data collection programme.

This chapter presents the entire data collection process, including background information and is described under three major parts:

1. identification of required information;
2. development of data collection programme; and
3. data collection.

6.2 Identification of Required Information

6.2.1 Questionnaire survey

Clearly, validity of the model depends on successful incorporation of important variables affecting team production. Since the simulation model is based on generating cycle element times, identification of the most effective variables on individual cycle elements is necessary to develop a valid model. Consequently, the questionnaire presented in Appendix B was sent to 35 construction engineers involving eight

earthmoving contractors in Sri Lanka, of which 24 favourably responded. The results of this survey, together with already acquired knowledge from a literature review and discussions with experts in the industry, were used to identify the most important variables which are listed in the next section. However, in deriving conclusions from the survey, a statistical analysis technique was not adopted as the results were used only to supplement the knowledge on cycle element variables.

6.2.2 Identification of important factors affecting cycle element times

In this investigation, the basic items of plant studied were, scrapers, pushers, dump trucks, loaders, dozers, graders and compactors. The productive cycle of each of these units is made up of number of elements each of which is repeated in a very similar fashion on successive cycles. Factors affecting a productive cycle can basically be categorised into classification and experimental (Clemmens 1978). Classification factors are uncontrollable and include characteristics of equipment, operator skill etc., whilst experimental factors can further be divided into qualitative and quantitative. It has been recognised that classification factors do have a significant effect on cycle time. However, enormous amount of data are required to appropriately classify their individual effects and hence it was decided to incorporate them stochastically. Consequently, only experimental factors were considered during data collection.

The cycle elements, together with the most important experimental factors thought to have an effect on element times, are described under separate headings. Qualitative factors are further subdivided into different treatment levels and are listed against the appropriate factor when it appears for the first time in the thesis. All those factors will be tested for significance during data analysis and significant ones can then be used in categorising various operating conditions based on which appropriate cycle element times are generated during simulation.

6.2.2.1 Factors affecting scraper cycle element times

Past researchers have broken down the earthmoving cycle of a hauling unit into varying degrees of detail depending on their objectives (Parsons 1977, Clemmens 1978). In this investigation some of these elements can be combined with others to reduce complexity during simulation runs. For example, manoeuvring of hauling units at cut or fill sections can be incorporated into loading and unloading elements respectively. Consequently, the same breakdown given in Figure 4.1 can be used and it is reproduced in Figure 6.1 for convenience. Queuing at cut or fill areas are delay

elements which may or may not be present and can be incorporated into the logic of the simulation model.

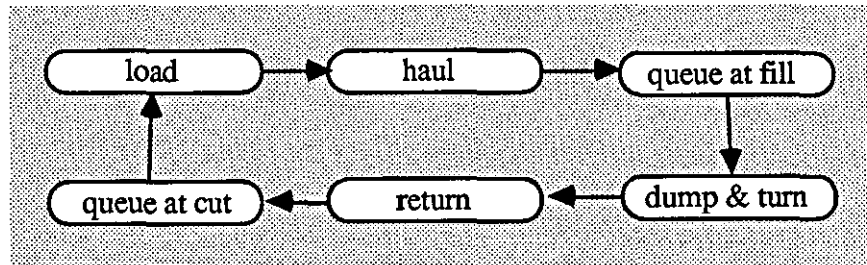


Figure 6.1 - Break down of earthmoving cycle

The factors which probably have an effect on scraper cycle element times are:

1. Scraper loading time:
 - (a) loading method (1-single pusher, 2-two pushers, 3-push-pull, 4-elevating);
 - (b) type of scraper (1-single engine, 2-twin engine);
 - (c) type of soil * (1-common earth, 2-weathered rock, 3-hard rock);
 - (d) size and condition at cut site ** (1-favourable, 2-average, 3-unfavourable);
 - (e) size of scraper (1-capacity < 18m³, 2- 18 < capacity < 25m³, 3- 25 < capacity < 32m³, 4- capacity > 32m³); and
 - (f) the relative size of pusher and the scraper unit (1-under balanced, 2-balanced, 3-over balanced).
2. Scraper dump and turn time:
 - (a) size and condition at fill site *** (1-favourable, 2-average, 3-unfavourable).
3. Scraper hauling or returning time:
 - (a) haul or return distance;
 - (b) type of scraper;
 - (c) haul road condition (1-good, 2-average, 3-poor);
 - (d) grade of haul road (1-favourable, 2-negligible, 3-unfavourable); and
 - (e) size of scraper.

6.2.2.2 Factors affecting pusher cycle element times

Pusher cycle in this case means the pushing operation incorporated with scraper loading and consists of two elements as shown in Figure 6.2.

- * Common earth - clayey sand, sand, sand & gravel, gravel, loose earth.
Weathered rock - decomposed rock (rock particles and common earth).
- Hard rock - any kind of ripable rock.
- ** Favourable - easy manoeuvring of hauling & loading units and clean work area.
Average - occasional restrictions for hauling and loading units with clean work area.
Unfavourable - restricted cut site with manoeuvring delays and soft ground conditions.
- *** Favourable - easy manoeuvring of hauling units, no queue at fill and no obstruction by other eqt.
Average - easy manoeuvring of hauling units with occasional queuing at dump site and occasional external delays due to other eqt.
Unfavourable - restricted fill site with occasional unloading queues, occasional external delays due to interaction and frequent assistance for trucks to pull out from the dump area.

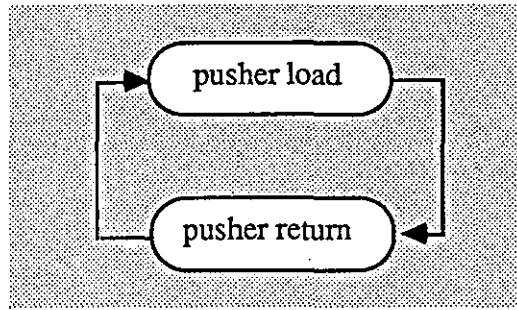


Figure 6.2 - Break down of pusher cycle

1. Pusher loading (similar to scraper loading time):
 - (a) number of pushers involved in loading;
 - (b) type of associated scraper;
 - (c) type of soil;
 - (d) size and condition at site; and
 - (e) the relative size of pusher and the scraper unit.
2. Pusher return time (boosting, reversing and contact manoeuvring time):
 - (a) pushing method (1-backtrack, 2-chain, 3-shuttle) (Peurifoy 1985); and
 - (b) size and condition at site.

6.2.2.3 Factors affecting truck cycle element times

The cycle elements considered in a truck earthmoving cycle are the same as in Figure 6.1 described for scraper operations and a similar breakdown has previously been adopted by Willenbrock and Lee (Willenbrock 1975) in their truck simulation model. However, in this case the loading element consists of the positioning time of a truck together with the number of complete loader cycles which is considered separately, since the loading time cannot be generated without knowing the behaviour of a loader cycle itself.

1. Truck loading time:
 - (a) number of buckets (relative capacity of truck and loader bucket); and
 - (b) loader cycle time.
2. Truck dump and turn time:
 - (a) size and condition at fill site;
 - (b) type of truck (1-rear dump, 2-bottom dump, 3-side dump); and
 - (c) size of truck (1-capacity < 5m³, 2- 5 < capacity < 10m³, 3- 10 < capacity < 15m³, 4- capacity > 15m³).

3. Truck hauling or returning time:

- (a) haul distance;
- (b) haul road condition;
- (c) grade of haul road;
- (d) type of truck; and
- (e) size of truck.

6.2.2.4 Factors affecting loader cycle time

The loaders considered in this case are front end loaders and backhoes. Unlike pushers in scraper loading, the loader cycle time need not be broken down into individual elements since it does not have a preparation time for loading another truck. Hence, only the total cycle time can be considered. The factors affecting are:

- (a) type of soil;
- (b) type of loader (1-front end loader, 2-backhoe loader); and
- (c) size and condition at cut site.

6.2.2.5 Factors affecting dozer cycle element times

Dozer cycle element times are usually very short and sometimes it is very difficult to differentiate cycle elements. In this investigation it is sufficient to consider the entire dozer cycle. The factors affecting are:

- (a) type of soil;
- (b) size and condition at site;
- (c) type and size of blade;
- (d) size of dozer (drawbar pull);
- (e) pushing distance; and
- (f) grade.

All these factors identified above are summarised in Table 6.1

Table 6.1 - Factors to be tested for significance on different cycle element times

		Quantitative			Qualitative												
Equipment category	Cycle element	Variable/Factor			haul/return distance	loader cycle time	no. of buckets	loading method ¹	type of equipment ²	size of equipment ³	type of soil	size & cond. at cut	size & cond. at fill	relative size of eqt.	haul/return road cond	grade of road	pushing method
scraper	load dump and turn haul/return	*			*			*	*	*	*	*	*	*	*	*	
pusher	load return							*	*		*	*		*			*
truck	load dump and turn haul/return	*		*	*	*			*	*			*		*	*	
loader	total cycle								*		*	*					
dozer	total cycle	*							*	*	*	*				*	

- 1 - scraper operations: represent single pusher, 2 pushers, push-pull and elevating
 - pusher operations: single pusher or two pushers

- 2 - scraper operations: represent single engine and twin engine
 - truck operations : represent bottom dump, rear dump and side dump
 - loader operations : represent front end loader or backhoe
 - dozer operations : represent type and size of blade

- 3 - dozer operations : represent drawbar pull and others as explained earlier

6.2.3 Categorisation of delays

Delays are unavoidable in any construction operation and earthmoving is no exception. In this case, delays can occur between or within cycle elements. Some of these delays are predictable while others are not. For example, weather effects, breakdowns of equipment, management policy changes cannot easily be predicted while routine maintenance, personal needs are predictable to acceptable accuracy. As far as the model building is concerned, all predictable delays should be incorporated. This required a systematic identification of delays.

After careful consideration of similar work carried out in the past (Clemmens 1978) these delays can be categorised as:

- (i) *major delays* - delays lasting more than 15 minutes caused by weather, breakdowns, management policy changes;
- (ii) *minor delays* - delays lasting less than 15 minutes caused by operational delays, refuelling, routine maintenance, personal delays, other operations external to plant team etc.; and
- (iii) *wait delays* - interaction delays caused by waiting at cut for loader assistance or waiting at fill for dumping.

Unlike major delays, minor delays are predictable and can be represented by theoretical distributions or frequency histograms in simulation models. However, it is required to identify the exact causes of these minor delays so that it could be incorporated into appropriate cycle element during simulation. For example, minor delays caused by a particular truck during hauling should be separately identified so that it can be applied to hauling element during truck hauling in simulation model. The wait delays can simply be incorporated into the logic of the model.

6.2.4 Points to ponder in developing the data collection programme

The following important points were drawn from the above discussion and were used in designing the field observation sheets and in collecting actual field data to achieve the objectives set out in Section 6.1.

1. Separate studies should be carried out on front-end loaders and backhoe loaders since loading element of a truck consists of several loader cycles. Then a loader cycle time and the number of buckets for a particular truck can be used to generate the truck loading time.
2. Separate pusher studies should also be done to quantify pusher element times, in particular, the pusher return time.
3. In all cases, qualitative or quantitative values of all the factors listed in Table 6.1, should be recorded.
4. Any delay occurred either within or between elements should be quantified as far as possible and causes listed thereby enabling to categorise them into appropriate classes and elements during analysis.

5. General descriptions, special features, overall equipment utilisation, project drawings, extracts of BOQs, planning methods adopted, any restrictions etc, should be collected for model validation purposes.

6.3 Development of the Data Collection Programme

6.3.1 Study method

It was identified, in the previous section, that the primary data consist of various cycle element times of earthmoving equipment. Essentially, this requires a time study. From the two probable time study methods, the *cumulative* and *flyback*, the former was adopted for the following reasons.

- (i) It is very difficult, if not impossible to use the flyback timing method when more than one entity is to be observed at the same time as in this case.
- (ii) Only one stop watch can be used to observe event times of all entities under study.
- (iii) Observers need not be specifically trained to follow this method.
- (iv) Most of past researchers have adopted this technique for similar work.

As mentioned in Chapter 2, Clemmens (1978) has used two basic methods for data collection, namely, random study period method and all day study period method. Although both of these methods provide a true sample (Clemmens 1978), the author feels that the second method provides a better sample providing a continuous picture of what happens at site. It was, therefore, decided to adopt the all day study period as much as possible during data collection.

6.3.2 Development of observation forms

Considering the important points derived in Section 6.2.4, field data collection observation forms were designed to accommodate all the important event times and other relevant information for the following cases.

1. Scraper and truck hauling operations.
2. Dozer hauling operations.
3. Loader operations.
4. Compactor/grader operations.
5. Overall equipment utilisation.

Completed specimen observation forms and definitions of event times adopted are provided in Appendix C.

6.4 Data Collection

6.4.1 A brief description of projects used

Most of the required data were collected from Sri Lankan road construction sites during author's one and half year intermediate stay in Sri Lanka (April 87 to October 88). Essentially, the idea was to observe as many sites as possible covering wide variety of constraints, operating conditions and plant team configurations to obtain representative samples of different populations. It should be appreciated that being a small country and with the political unrest in Sri Lanka during observation period, only five road construction sites were possible to be studied. However, all attempts were taken to include as many variations as possible by observing available sites for longer periods.

Scrapers were not used in any of the above sites and all attempts were failed to find road construction involving scrapers, however, one other site involving scrapers for overburden removal was observed as a sample study. Clearly, it is not advisable to use one site as a representative sample, therefore, it was decided to adopt results of a similar scraper study carried out in the past, in developing the concept of the model (Clemmens 1978).

However, in addition to above sites, data from two other road projects consisting of both scraper-pusher and loader-truck operations were obtained from the UK to supplement the data to be used for model validation and experimentation purposes.

General description of all projects used, data collected, study durations etc. are summarised in Table 6.2.

6.4.2 Data collection procedure

Data collection procedure described in this section is only applicable to projects one to six (see Table 6.2). Before starting the actual data collection, the observers were given clear instructions on the procedure to be adopted during the study. The number of observers at one time was varied from two to eight depending on the complexity of the operation.

The observer gang was basically divided into three groups to observe: hauling units; loading units; and grading and compacting units, each of these is described below.

Table 6.2 - Details of sites used for data collection

Purpose	Project site	Description	Data collected	Study period (days)
Model development	1. Anamaduwa Gam Udawa road network (stage 1)	Contractor = RCDC Contract value = Rs. 30 mill. Earthwork qty. = 116900m ³	1738 cycles of truck cycle element times, overall equipment utilisation	15
	2. Randenigala Giranduru-Kotte road project	Contractor = SD&CC Contract value = Rs. 5 mill. Earthwork qty. = 51000m ³	420 cycles of truck cycle element times, overall equipment utilisation	15
	3. Nilwala Ganga project site 1 Bandattara	Contractor = BEC(french) Contract value = Rs. 1315 mill. Earthwork qty. = 2061140m ³	966 cycles of truck cycle element times and 1457 cycles of loader cycle time	10
	4. Nilwala Ganga project site 2 Wallatota		1604 cycles of truck cycle element times and 3071 cycles of loader cycle time	11
Validation	5. Anamaduwa Gam Udawa road network (stage 2)	Included in stage 1	705 cycles of truck cycle element times, overall equipment utilisation	7
	6. Puttalam Cement Factory Quarry site	-	295 cycles of scraper cycle element times	2
	7. A42 Measham and Ashby By-pass	Contractor = BUDGE Earthwork qty. = 5 million m ³	Project details, material distribution, equipment utilisation, production achieved	-
Experimentation	8. M40 Motorway Banbury By-pass	Contractor = WIMPEY Contract value = £25 million Earthwork qty. = 670000m ³ (tendered only)	Project details, selected material distribution, equipment teams, construction schedules etc.	-

(a) Study of hauling units

This was the most crucial operation since the hauling units cannot usually be observed throughout its complete cycle by one observer, requiring strict control on data recording. All the observers engaged in one haulage operation were instructed to synchronise stop-watches before any study thereby enabling to combine observation sheets to determine hauling and returning times. One observer was located at cut area, one at fill area (one observer at each fill area if more than one destination) and another observer along the haul road to record any haul or return delays. All equipment event times, quantities moved, delays occurred and other special features were systematically recorded. After each study, observation sheets were carefully amalgamated to represent all event times and other details in one sheet.

In addition to loader-truck operations, dozer operations used for short hauls were also studied with a view to simulating their behaviour. However, the study was limited to one site and was decided to abandon it for the following reasons.

- (i) It was observed that there usually were no interactions on dozer operations due to other equipment thereby diminishing the requirement of dozer simulation.
- (ii) The cycle time varies tremendously due to variation in quantitative variables like haul distance during its operation thereby making it difficult to predict them in a simulation model.
- (iii) Due to above reasoning, a production estimate comparable to or better than that obtained by simulation can be obtained by other methods. These estimates can then be adopted in linear optimisation stage in the proposed model without breaking the integrity of the optimisation model.

(b) Study of loading units

Only one loading unit was involved in all the sites at one time and one observer was assigned to record all the event times, delay times, and other special features.

(c) Grading and compaction operations

One observer was located at each destination to observe event times, production and other special features of grading and compacting units. This study was implemented to determine the effect of these operations on hauling units and also to find the resources required to achieve a given production under various operating conditions. However, after some time, the observation of grading and compaction operations was abandoned for the following reasons.

- (i) There was very little effect of grading and compaction on hauling units and it can safely be neglected.
- (ii) The production rates of grading and compaction units are governed by large number of unquantifiable variables thereby making it very difficult to categorise cycle times and time required to achieve a certain production.

6.5 Summary

Important factors which have considerable effect on various earthmoving cycle element times were identified with the aid of a questionnaire survey and the author's already acquired knowledge from other sources. These results were used to establish the data required for model building and validation purposes.

Cumulative time studies proved to be the most suitable technique for data collection. Observation forms were designed to accommodate required event times and other relevant information on scraper, truck, loader, dozer, grader/compactor operations as well as to record overall equipment utilisation.

Six large construction sites were observed in Sri Lanka mainly on loader-truck operations. Study duration varied from about two to three weeks (except study six) and the number of observers for each site varied from two to eight depending on the complexity of the job. Data from two additional sites were obtained from the UK for model validation and experimentation purposes.

Data collection was carried out in three main groups: for hauling units; for loading units; and for grading and compaction units. However, data collection on grading and compaction operations was halfway abandoned since it was found that there was no significant effect of those on hauling operations and also the large number of variables involved and unsystematic compaction operations made it difficult to quantify the production.

Data collected from first six sites (see Table 6.2) were carefully compiled in dBASE III files to be retrieved partly during data analysis which is described in the next chapter and partly during model validation.

CHAPTER SEVEN

DEVELOPMENT OF MODEL INPUT PARAMETERS

7.1 Introduction

7.2 Systematic Factor Analysis

7.2.1 Break down of earthmoving cycle revisited

7.2.2 Procedure adopted in factor analysis

7.2.2.1 Factor analysis : Loader cycle time

7.2.2.2 Factor analysis : Positioning delay time

7.2.2.3 Factor analysis : Hauling delay time

7.2.2.4 Factor analysis : Dump and turn time

7.2.2.5 Factor analysis : Returning delay time

7.2.2.6 Factor analysis : Hauling time

7.2.2.7 Factor analysis : Returning time

7.2.2.8 Cycle element times of other equipment items

7.2.2.9 Summary results of factor analysis

7.3 Distribution Fitting and Parameter Evaluation

7.3.1 Important distributions

7.3.1.1 Erlang distribution

7.3.1.2 Weibull distribution

7.3.2 Procedure adopted in distribution fitting

7.3.2.1 Distribution fitting : Loading time

7.3.2.2 Distribution fitting : Positioning delay time

7.3.2.3 Distribution fitting : Hauling delay time

7.3.2.4 Distribution fitting : Dump and turn time

7.3.2.5 Distribution fitting : Returning delay time

7.3.2.6 Distribution fitting : Hauling/returning time

7.4 Summary

7.4.1 Loader-truck operations

7.4.2 Scraper-pusher operations

7.1 Introduction

Among other things, the previous chapter identified the probable factors affecting cycle element times of various earthmoving equipment, and stressed the necessity of testing their significance in simulation modelling. During the development of methodology, Chapter 4 also described the need for detecting the types of distributions representing those cycle element times and evaluating their input parameters corresponding to different treatment levels.

This chapter achieves the aforementioned objectives by systematically analysing the data collected for loader-truck operations and is carried out in two main stages as follows.

1. Identification of significant factors affecting different cycle element times of earthmoving equipment by systematic statistical techniques.
2. Identification of the types of theoretical distributions representing those cycle element times to a significant accuracy and evaluation of input parameters corresponding to various element times and operating conditions.

Over 7000 loader cycle times observed from 8 loaders and 4700 cycle times observed from 43 trucks were used in the following analysis.

7.2 Systematic Factor Analysis

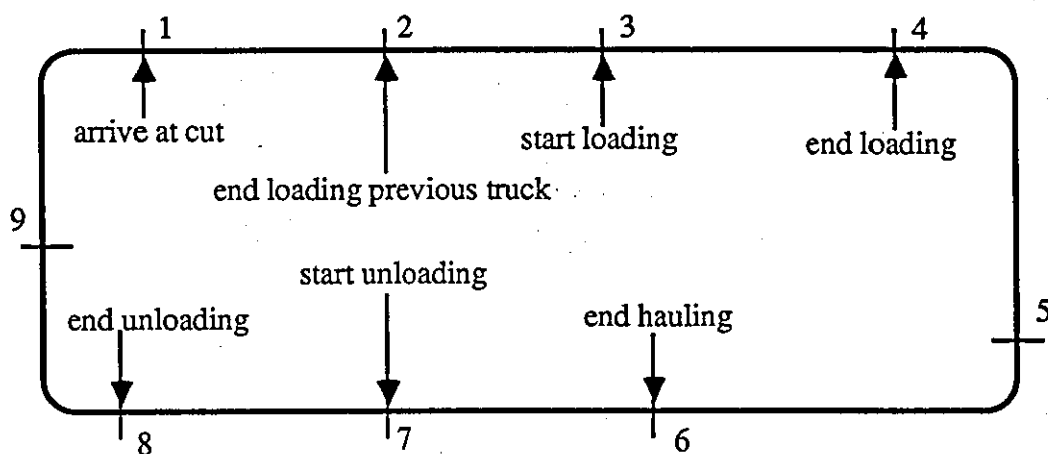
7.2.1 Break down of earthmoving cycle revisited

It was noticed during field observations that the previous break down of an earthmoving cycle would be greatly improved by incorporating certain unforeseen delays. For example, the observed loader idling time between two trucks, when there exists a queue at cut, was longer than the time difference between start loading and end returning of a truck when there is no queue. In other words, the positioning delay is longer when a queue exists in the cut area. The difference between the positioning time and the positioning delay should be clearly noted. The former may contain a part of loader cycle if the loader has already started loading during the positioning process, but the latter is purely a delay and does not include any overlapping of positioning time and loading time. In this way:

positioning time equals end positioning time of a truck minus the greater of end returning time to cut area and end loading time of previous truck; and

positioning delay equals start loading time of a truck minus the greater of end returning time to cut area and end loading time of previous truck.

Start loading can commence before end of positioning, since the loader can move to take the first bucket during this time. The longer positioning delay observed when there is a queue at cut may be due to late pulling out of the previous truck or no room to position until the previous truck is fully out. The positioning delay may also include, delays caused by loader during external work, routine maintenance, personal delays etc. To include all these, the earthmoving cycle was re-divided as shown in Figure 7.1, where numbers along the cycle indicate event times.



- | | |
|---------------------|---|
| 1 - 2 (logic) | queuing time due to loader engaged in loading another truck. |
| 2 - 3 (predictable) | positioning delay or queuing time due to loader delay involving refuelling, routine maintenance, personal delays, previous truck not pulling out etc. |
| 3 - 4 (predictable) | loading time. |
| 4 - 5 (predictable) | pulling out delay at cut + delay during hauling (minor delay). |
| 5 - 6 (predictable) | hauling time without delay. |
| 6 - 7 (logic) | queuing time at fill. |
| 7 - 8 (predictable) | dump and turn time. |
| 8 - 9 (predictable) | pulling out delay at fill + delay during returning (minor delay). |
| 9 - 1 (predictable) | returning time without delay. |

Figure 7.1 - Modified break down of earthmoving cycle

All predictable element times can be generated during simulation, whilst others are incorporated logically. The above breakdown of cycle elements is adhered to during the data analysis and model building.

7.2.2 Procedure adopted in factor analysis

The availability of MINITAB statistical package (Ryan 1985) at Loughborough University of Technology and its powerful, variance analysis, regression analysis and plotting facilities together with ease of use clearly indicated its suitability for factor analysis.

Before starting the actual analysis, the first step was to calculate all element times according to the above breakdown and include identification for qualitative factors against each observation. This was done in the dBASE environment. Subsequently, all the data collected were combined (stacked) and transferred into MINITAB work sheets for further analysis.

Loader and truck cycle times were treated separately in two different worksheets. In this way, loader cycle time, truck positioning delay, hauling time, hauling delay, dump and turn, return time and returning delay were carefully analysed and examined by isolating the factors to be tested and treating them at different treatment levels. Clearly, the principle behind the significant factor identification is a comparison between the random variability within the sample and variability due to the particular factor under consideration. If the random variability is greater than that due to the factor, then it is insignificant and can be discarded or vice versa.

The techniques used for these inferences are listed below.

- (i) Dot plots and other plots.
- (ii) Histograms.
- (iii) Regression analysis.
- (iv) Residual examination.
- (v) Variance analysis.

In addition, the insignificant factors obtained from above statistical methods were partially discarded with the following idea in mind.

" A simulation model need not be a completely realistic representation of the real system. In fact, most simulation models err on the side of being overly

realistic rather than overly idealised. With the former approach, the model easily degenerates into a mass of trivia and meandering details, so that a great deal of programming and computer time is required to obtain a small amount of information. Furthermore, failing to strip away trivial factors to get down to the core of the system may obscure the significance of these results that are obtained " (Hillier 1974).

The factor analysis for each of the element times is briefly described in the following discussion, and a sample output is provided in Appendix D.

7.2.2.1 Factor analysis : Loader cycle time

It was clearly observed at one of the sites that all the operations in the cut area took a longer time than actually required due to the poor methods adopted. For example, the inappropriate positioning of the backhoe loader increased the loader cycle time considerably. Behind this case, there were lots of other reasons like bad supervision, poor motivation of operators etc. Although in all the other cases, these variations were taken stochastically, due to obvious evidence in this case, it was decided to include an additional factor called *operational factor** which takes 1, 2 and 3 for *good, average* and *poor* operating conditions respectively.

With this, the experimental factors against which the loader cycle time was tested were: type of loader; soil type; operational factor; condition at site; among loaders; and among sites.

When grouped and analysed according to type of loader (wheel loader and backhoe) and after separating other factors, it was found that there was a significant difference between the cycle time for the two loader types. Clearly, the reason would be the actual travelling involved by the wheel loader during loading, compared to backhoe loader.

The effect of soil types could only be tested for backhoe loaders and was found to be considerable, perhaps due to the varying effort required to get a bucket full of soil. The operational factor was also found to be significant. The condition at cut site was trivial, and small difference between site conditions would have been the reason for this result. In addition, among loader variation and among site variation were also found insignificant.

Table 7.1 provides a summary of loader cycle time by significant factors.

* Good - Efficient and skilled work team, correct method of operation.
Average - Skilled work team but inaccurate method of operation or vice versa.
Poor - Inefficient work team and incorrect method of operation.

Table 7.1 - Summary of loader cycle time by type of loader, type of soil and operational factor

Loader type	Soil type	Operational factor	Number of observations	Average cycle time (sec.)	Std.dev. (sec.)
wheel loader	com. earth	poor	369	44.7	7.5
backhoe	com.earth	average	4528	22.7	6.5
backhoe	com.earth	poor	1778	39.6	10.0
backhoe	wea. rock	poor	320	46.0	14.9

7.2.2.2 Factor analysis : Positioning delay time

The positioning delay time was tested against five factors: queue condition; operational factor; size of truck; size and condition at site; and among sites. The additional factor, queue condition which takes 1 and 2 corresponds to no queue and existence of a queue at cut respectively, was added based on the discussion in Section 7.2.1.

When grouped and analysed positioning delay time corresponding to different factors, it was clearly observed that queue condition at cut is a significant factor. The probable reason for this increased positioning delay was also discussed in Section 7.2.1.

The only other influential factor was the operational factor. Although the size of truck seems to be a reasonable significant factor, it was observed negligible during analysis. Size and condition at cut site and between site variability were also found immaterial.

A summary of positioning delay time by significant factors is presented in Table 7.2.

Table 7.2 - Summary of positioning delay time by queue condition and operational factor

Queue condition	Operational factor	Number of observations	Average time (sec.)	Std. deviation (sec.)
no queue	average	2212	30.7	93.4
queue exists	average	2095	37.4	66.9
no queue	poor	228	67.1	105.8
queue exists	poor	193	91.2	139.8

7.2.2.3 Factor analysis : Hauling delay time

Hauling delay time was tested with three factors: haul distance; operational factor; and among sites.

It was grouped and analysed corresponding to these factors and found none of them is significant statistically. The mean hauling delay and the standard deviation were found to be 27 seconds and 101 seconds respectively.

7.2.2.4 Factor analysis : Dump and turn time

The factors considered were: size of truck; condition at fill site; operational factor; and among sites.

Dump and turn times were grouped and analysed, and it was interesting to find that the size of truck as a significant factor. Clearly, this is due to longer time required to manoeuvre large trucks. However, truck sizes 1 and 2 resulted in similar dump times enabling them to group together and this may be due to the small difference between these two sizes. In addition, the condition at site was also found considerable. The remaining factors, between site variability and operational factor were immaterial.

Dump and turn times by significant factors are summarised in Table 7.3.

Table 7.3 - Summary of dump and turn time by fill site condition and truck size

Fill site condition	Truck size	Number of observations	Average time (sec.)	Std.deviation (sec.)
good	1 and 2	547	33.0	12.4
average	1 and 2	1630	42.3	19.5
poor	1 and 2	1523	67.3	37.3
poor	4	158	74.3	34.9

7.2.2.5 Factor analysis : Returning delay time

Similar to hauling delay, returning delay time was tested with: return distance; operational factor; and between sites, and found that none of them are significant. The resulted mean time and standard deviation were 133 seconds and 331 seconds respectively.

It is quite interesting to note the large difference in delay during hauling and returning. The reason for longer returning delay was that the operators tended to spend time on refreshments, personal needs, refuelling, routine maintenance etc. during returning rather than during hauling.

7.2.2.6 Factor analysis : Hauling time

The hauling and returning times are the most critical in loader-truck operations and considerable variations were observed from project to project and even from cycle to cycle of the same project. Explanation of these variations involves a great deal of complexity. Clemmens (1978) in his scraper studies, combined hauling and returning time to avoid some of these complexities by neglecting factors like haul road condition and grade. In this case, this was impossible as it was observed that in some occasions different routes were used during hauling and returning and also if combined the queuing at fill site cannot realistically be accounted for during simulation. Consequently, it was decided to consider hauling and returning time separately.

The factors tested against hauling time were: haul distance; size of truck; grade of haul road; road condition; operational factor; and among sites.

Unlike earlier cases, where all the tested factors were qualitative, analysis of hauling time required a different treatment due to one factor, haul distance, being quantitative. Consequently, variance analysis tests like ANOVA could not be directly applied. Essentially, this required, regression analysis, examination of variance tables associated with regression, residual examination and also visual inferences made from various plots.

The 'Anamaduwa Gam Udawa' site had a good representation of different truck sizes and all the other qualitative factors being constant, it was selected to test the significance of truck size on hauling time. Separating data for each truck size graphs were plotted considering haul distance as the independent variable and the hauling time as the dependent variable (see Appendix D). Clearly, as expected, a linear relationship was apparent and simple linear regression was carried out for each case by avoiding the constant term for easy comparison. These graphs are superimposed in Figure 7.2. To further investigate the effect, a combined regression analysis for all four truck sizes was carried out by adopting the 'dummy variable' principle (Draper 1966). After careful examination of the fitted equation, variance tables and the plotted graphs, it was considered that there is no significant effect due to size of truck and it was discarded

from further analysis. This can be confirmed by referring to plant manufacturers' handbooks (Caterpillar 1987). Clemmens (1978) also has arrived at the same conclusion for scraper operations.

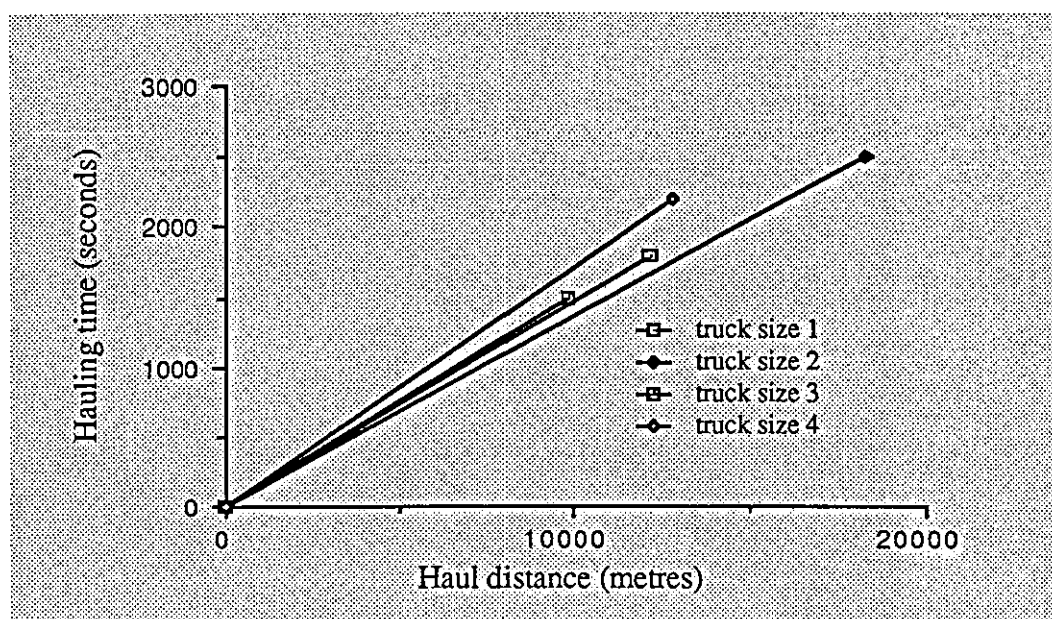


Figure 7.2 - Graphs of hauling time and haul distance for different truck sizes

The only site having a varying degree of road condition was 'Randenigala' and all the others factors being constant, it was selected for testing haul road condition. The results of the combined regression analysis were sufficient to identify the insignificance of the road condition and hence discontinued from further analysis. However, one should be careful not to stick onto these inferences when extreme road conditions are involved but for most practical cases involving road construction, condition of haul road can be safely neglected.

Having disregarded the truck size and road condition, between site variability was tested using three sites; 'Anamaduwa', 'Bandattara' and 'Wallatota'. The same procedure in testing the effect of truck size was followed and the combined plot for different sites is shown in Figure 7.3. The narrow range of haul distances observed at 'Bandattara' was the reason for its deviation from other sites and should not be misinterpreted. After examining the plots and the results of the regression analysis it was concluded that the variability among sites is insignificant and hence disregarded.

It is interesting to note the insignificance of operational factor and grade of road. The former seems to be significant only for operations at cutting site. Regarding the latter, it should be noted that the observed grades were either favourable or flat. In favourable grades, although it is theoretically possible to attain higher hauling speeds, operators tend to follow the same speed when the truck is fully loaded. However, had the grade been unfavourable, there would have been a slowing effect.

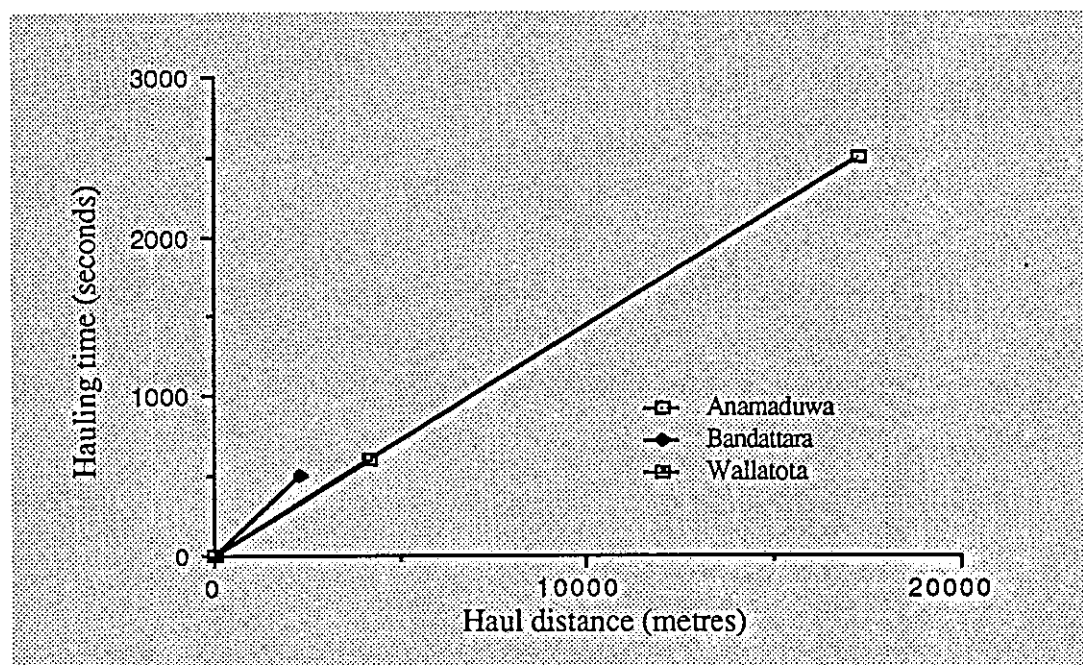


Figure 7.3 - Graphs of hauling time and haul distance for different sites

Ultimately, the only significant factor affecting hauling time was found to be the haul distance. This is reinforced by the fact that the increase in the coefficient of determination in the regression equation was only 2.25, being 91.96 when only the haul distance was involved and 94.21 when all the other factors were also incorporated.

The regression equation obtained was;

$$\text{Hauling time (seconds)} = 44.80 + 0.139 \times \text{Haul distance (metres)}$$

7.2.2.7 Factor analysis : Returning time

Analogous to hauling time, the factors by which the returning time was tested were: return distance; size of truck; grade; road condition; operational factor; and among sites. The procedure adopted was identical to that described under hauling time. With similar

arguments, it was found that only the return distance is significant in evaluating return time.

The regression equation was;

$$\text{Return time (seconds)} = 31.83 + 0.121 \times \text{Return distance (metres)}$$

7.2.2.8 Cycle element times of other equipment items

For the reasons given in Chapter 6, data collection on grading and compaction operations was halfway abandoned. Furthermore, times taken for these operations vary considerably from site to site, hence data collected from one site may not be representative to another. However, this variation is not a serious problem since the effect of this on hauling operations was insignificant. The author recommends that such times and choice of appropriate compacting and grading equipment to suit the hauling team are better selected by past experience.

7.2.2.9 Summary results of factor analysis

All factors tested and significant factors identified corresponding to all cycle element times are summarised in Table 7.4.

7.3 Distribution Fitting and Parameter Evaluation

As mentioned in Section 7.1, the main objective of this section is to fit theoretical distributions or frequency histograms to different cycle element times, after categorising them into various treatment levels corresponding to significant factors identified in the previous section. The fitted distributions, together with appropriate parameters can then be used in the simulation model in generating cycle element times under various operating conditions.

Clearly, the reliability of simulation results depends on the accuracy of random distributions used in generating cycle element times. These distributions can either be theoretical distributions fitted onto actual data or frequency histograms of actual data themselves.

Table 7.4 - Summary results of factor analysis

Element	Factors tested	Significant factors
1. loader cycle time	<ol style="list-style-type: none"> 1. type of loader 2. soil type 3. operational factor 4. size and condition at site 5. loader number 6. site number 	<ol style="list-style-type: none"> 1. type of loader 2. soil type 3. operational factor
2. positioning delay	<ol style="list-style-type: none"> 1. size and condition at site 2. truck size 3. queue condition 4. operational factor 5. site number 	<ol style="list-style-type: none"> 1. queue condition 2. operational factor
3. hauling time	<ol style="list-style-type: none"> 1. haul distance 2. truck size 3. grade of haul road 4. road condition 5. operational factor 6. site number 	<ol style="list-style-type: none"> 1. haul distance
4. hauling delay	<ol style="list-style-type: none"> 1. haul distance 2. operational factor 3. site number 	none
5. dump and turn	<ol style="list-style-type: none"> 1. truck size 2. size and condition at site 3. operational factor 4. site number 	<ol style="list-style-type: none"> 1. size and condition at site 2. truck size
6. return time	<ol style="list-style-type: none"> 1. return distance 2. truck size 3. grade of return road 4. road condition 5. operational factor 6. site number 	<ol style="list-style-type: none"> 1. return distance
7. returning delay	<ol style="list-style-type: none"> 1. return distance 2. operational factor 3. site number 	none

Averill (1982) and Hillier (1974) recommend the former approach for two reasons: firstly, the data collected at two different instances on the same system can produce dissimilar distributions, secondly, the random values produced by an empirical method will always be within the range of the actual sample and not necessarily represent the whole system. Consequently, in this study priority was given to fit a theoretical distribution for all element times.

7.3.1 Important distributions

Before describing the actual fitting process, a brief explanation of important distributions is presented in this section for easier understanding of the following discussion.

7.3.1.1 Erlang distribution

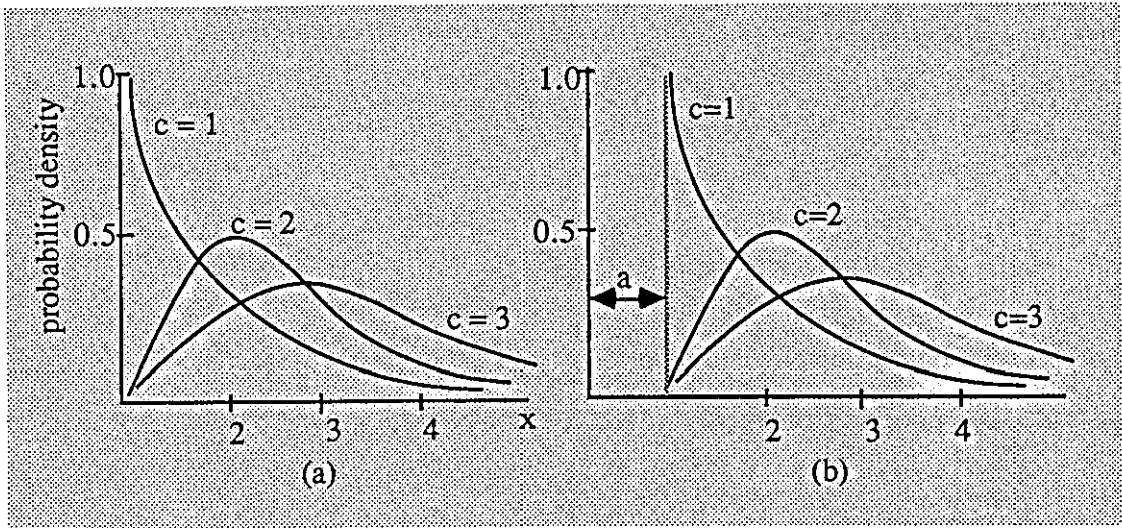
The ability to acquire a wide range of shapes (Figure 7.4[a]) together with its relative simplicity particularly in generating random variates has made the Erlang distribution very popular among simulation analysts.

Erlang distribution is nonnegative and can be defined by two parameters: the scale parameter 'b' and the shape parameter 'c' (an alternative parameter is $\lambda = 1/b$) (Shannon 1975, Hastings 1975). The Erlang distribution belongs to the Gamma distribution family taking only integer shape parameters which when unity and ten the Erlang distribution represents the Exponential distribution and Normal distribution respectively.

In practice however, most random variates tend to follow shifted Erlang distribution (Figure 7.4[b]), in which case an additional parameter, the minimum value 'a', should be added to the erlang variates to generate their element times.

7.3.1.2 Weibull distribution

Weibull distribution also is popular among simulation analysts due to its flexibility to get a range of shapes (Figure 7.5) and similar to Erlang distribution, it can be defined by two parameters; the scale parameter 'b' and the shape parameter 'c' (Hastings 1975). For the same reasoning given above, an additional parameter 'a', minimum value may also be used to generate random variates for real life applications.



$$\text{probability density function, } f(x) = \frac{\left[(x/b)^{c-1} \exp(-x/b) \right]}{b[(c-1)!]}$$

scale parameter, $b > 0$

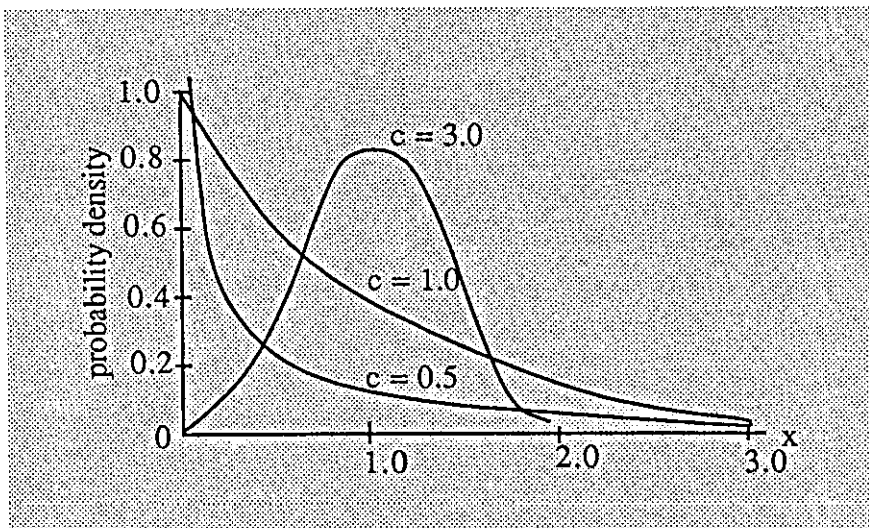
shape parameter, $c > 0$, c is an integer

range $0 \leq x \leq +\infty$

mean = bc

std. deviation = $b\sqrt{c}$

Figure 7.4 - Erlang distribution



$$\text{probability density function, } f(x) = \frac{(cx^{c-1})}{b^c} \exp \left[-(x/b)^c \right]$$

scale parameter $b > 0$

shape parameter $c > 0$

range $0 \leq x \leq +\infty$

Figure 7.5 - Weibull distribution

7.3.2 Procedure adopted in distribution fitting

Extended Control and Simulation Language (ECSL) was selected for distribution fitting particularly due to its capability to fit a theoretical distribution from fifteen different types; Normal, Log-normal, Binomial, Poisson, Erlang, Gamma, Beta, Extreme value, Weibull, Geometric, Negative binomial, Negative exponential, Pareto, Logistic, and Uniform (Clementson 1982).

The first step in distribution fitting was to plot frequency histograms of different cycle element times corresponding to various treatment levels. For each treatment level several histograms were drawn using MINITAB statistical package by changing the width of the histogram and tested using ECSL with a view to identifying the best fitted theoretical distribution.

ECSL compares the given histogram with above theoretical distributions and those which fit reasonably well are reported in detail. It calculates the distribution parameters from the given data and carries out two goodness of fit tests: the Kolmogorov-Smirnov (K-S) and Chi Squared (C-S) tests to examine the hypothesis that the distribution fits the actual data. Subsequently, it provides a pictorial representation of observed and expected frequency distributions for visual examination.

Some actual frequency histograms seemed to be near normal and others skewed to left. In all cases, distribution fitting was also attempted after transforming the actual data into various transformations. Transformation is a technique by which skewed data can be shifted either to the left or right to obtain a frequency histogram with reduced skewness.

From the results of the ECSL analysis the best fitted distributions were selected and the results obtained for each element time corresponding to various treatment levels are briefly described in the following discussion. A sample analysis together with observed and fitted frequency histograms are also provided in Appendix D.

7.3.2.1 Distribution fitting : Loading time

The shifted Erlang distribution was found to be the best fitted distribution for loader cycle times. Out of the four treatment levels tested, two cases satisfied both K-S and C-S goodness of fit tests, one case satisfied only the K-S test and the other failed both

tests. However, it was decided to adopt the Erlang distribution for all treatment levels of the loader cycle for the following reasons.

- (i) It fully satisfied two cases and partially satisfied another case.
- (ii) Past researchers have concluded that Erlang distribution is a good representation of earthmoving operations (Clemmens 1978, Gaarslev 1969).

The summary results are presented in Table 7.5. In all cases, *yes* and *no* under the K-S or C-S test indicate *satisfactory* and *unsatisfactory* respectively. The fitted distributions are represented in a short form, for example, 4+Erlang(7, 2.5,S) means minimum value = 4 seconds, shape parameter = 7 and the scale parameter = 2.5.

Table 7.5 - Summary of distribution fitting for loader cycle time

Treatment level	Number of observations	K-S test result	C-S test result	Fitted distribution (sec.)
front end loader, common earth with poor operational factor	369	yes	yes	20+Erlang(10, 2.4,S)
backhoe, common earth with average operational factor	4528	no	no	4 +Erlang(7, 2.5,S)
backhoe, common earth with poor operational factor	1778	yes	no	13+Erlang(6, 4.1,S)
backhoe, weathered rock with poor operational factor	320	yes	yes	23+Erlang(2,10.5,S)

7.3.2.2 Distribution fitting : Positioning delay time

The Weibull distribution was found to be the best fitted distribution for positioning delay times. Four treatment levels were tested and in all cases but one both K-S and C-S tests were satisfied. In the remaining case K-S test was satisfied and C-S test was very nearly failed. Consequently, the positioning delay was assumed to be Weibull distributed and the summary results are given in Table 7.6. The conventions adopted in the previous table are unchanged.

Table 7.6 - Summary of distribution fitting for positioning delay time

Treatment level	Number of observations	K-S test result	C-S test result	Fitted distribution (sec.)
no queue at cut with average operational factor	2212	yes	yes	10+Weibull(0.4, 7.0,S)
queue exists at cut with average operational factor	2095	yes	yes	20 +Weibull(0.5, 14.3,S)
no queue at cut with poor operational factor	228	yes	yes	10+Weibull(0.6, 40.2,S)
queue exists at cut with poor operational factor	193	yes	no	40+Weibull(0.5,30.1,S)

7.3.2.3 Distribution fitting : Hauling delay time

There is only one treatment level for hauling delay time and the following Weibull distribution was found to be the best fitted distribution after passing both goodness of fit tests.

$$\text{Distribution} = 0.0 + \text{Weibull}(0.4, 9.2, S)$$

7.3.2.4 Distribution fitting : Dump and turn time

Distribution fitting for dump and turn time was not obvious as in other cases and considerable testing had to be done before arriving at any conclusions. However, after careful consideration it was decided to adopt Weibull distribution for all four treatment levels tested for the following reasons.

- (i) Both goodness of fit tests were satisfied for one case.
- (ii) K-S test was satisfied for another case.
- (iii) Although the other two did not satisfy the tests they were very close to Weibull distribution both by tests carried out and by visual examination.

Although these results are in contrast to past findings (Clemmens 1978) where Erlang distribution has been suggested as the best representation, the decision taken was unavoidable since in no occasions it was more close to the Erlang distribution.

The fitted distributions are summarised in Table 7.7.

Table 7.7 - Summary of distribution fitting for dump and turn time

Treatment level	Number of observations	K-S test result	C-S test result	Fitted distribution (sec.)
good site condition with truck size 1 and 2	547	no	no	8.0+Weibull(1.9, 28.5,S)
average site condition with truck size 1 and 2	1630	no	no	13.2+Weibull(1.6,34.1,S)
poor site condition with truck size 1 and 2	1523	yes	no	8.6+Weibull(1.7, 66.1,S)
poor site condition with truck size 4	158	yes	yes	1.0+Weibull(2.3,83.9,S)

Note : Definitions of size of truck are as given in Section 6.2.2.3

7.3.2.5 Distribution fitting : Returning delay time

The fitted Weibull distribution satisfied the K-S test but failed to satisfy the C-S test. However, it was assumed to follow the Weibull distribution since it fully satisfied, for a similar case, hauling delay time and also the fitted histogram was very close to the actual histogram.

Distribution = 0.0+Weibull(0.6, 63.0,S)

7.3.2.6 Distribution fitting : Hauling/returning time

The procedure adopted to fit a distribution to hauling/returning time was rather different particularly due to their relationships with the only significant quantitative variable, travel distance.

These relationships have already been established in Sections 7.2.2.6 and 7.2.2.7 by forming a simple regression model with hauling/returning time as the dependent variable and the travel distance as the independent variable. The least square principle was used to develop the equation which took the following general form: (Draper 1966)

$$Y = \beta_0 + \beta_1 X + \epsilon \dots\dots\dots(7.1)$$

where Y = the mean value of haul/return time (in seconds) corresponding to a particular value of X in metres.

β_0, β_1 = parameters obtained from regression analysis.

X = the haul/return distance in metres.

ϵ = random error term by which any Y value may fall off the regression line and frequently represents the effects of many factors considered insignificant.

Frequently, the distribution of the random error term 'e' is assumed to be normal and this decision is usually based on the experimenters prior knowledge rather than the extensive experiments of the problem at hand (Acton 1966). However, to examine the behaviour of 'e' more clearly, several histograms of hauling/returning times were plotted for given values of haul/return distances and observed the normality shape with a relatively constant standard deviation. Consequently, by considering this observation and past research work carried out (Clemmens 1978) this error term 'e' was taken to be normally distributed with mean = 0 and standard deviation = σ . For a given haul/return distance (X), therefore, the possible values of hauling/returning times are normally distributed with mean = $(\beta_0 + \beta_1 X)$ and standard deviation of σ as shown in Figure 7.6.

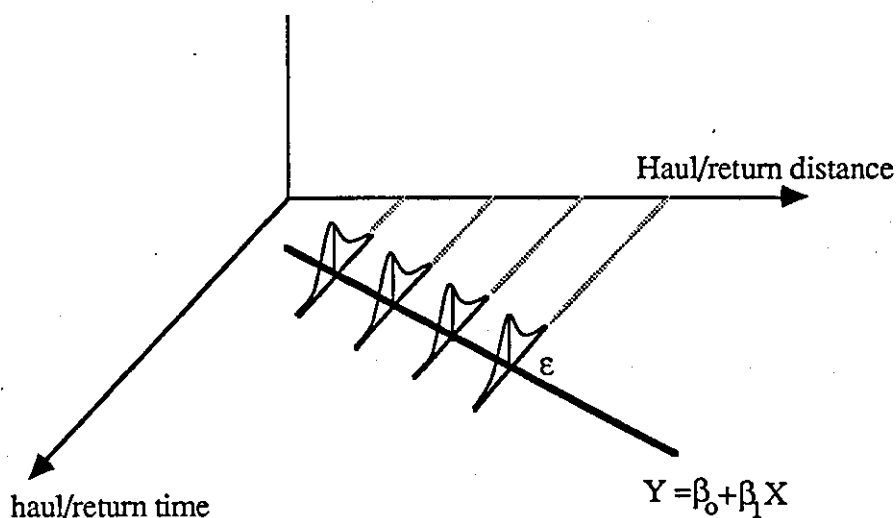


Figure 7.6 - Relationship between haul/return time and haul/return distance

The values of β_0 , β_1 , σ and other important statistics obtained by MINITAB statistical analysis for both hauling and returning times are shown in Table 7.8

The constants 44.8 and 31.8 seconds can be used to describe the acceleration and deceleration of trucks usually occurring near cut and fill sections.

Table 7.8 - Summary of distribution fitting for haul/return time

Element	Parameter	95% confidence interval	% described by regression
hauling	$\beta_0 = 44.80$ (sec.) $\beta_1 = 0.139$ (sec./m) $\sigma = 137.8$ sec.	38.75 - 50.85 0.138 - 0.140	92
returning	$\beta_0 = 31.83$ (sec.) $\beta_1 = 0.121$ (sec./m) $\sigma = 109.9$ sec.	26.71 - 36.94 0.120 - 0.122	93

The above parameters can now be used to find a realistic haul/return time for a given haul/return distance. For example, if the haul distance is 8 km the expected (mean) value of hauling time becomes: $44.80 + 0.139 \times 8000 = 1157$ seconds. Then the Normal distribution with mean value 1157 seconds and standard deviation of 137.8 seconds can then be used to select a value for hauling time during simulation.

7.4 Summary

7.4.1 Loader-truck operations

Over 7000 loader cycle times observed from eight loaders and 4700 cycle times observed from 43 trucks, corresponding to wide variety of operating conditions, team configurations were used in the data analysis.

With the aid of the information discovered during field data collection the earthmoving cycle was re-divided into different cycle elements and all significant factors affecting each of these element times were identified statistically. MINITAB software package was used for this purpose and the summary findings are shown in Table 7.4.

The cycle element times were then grouped into different treatment levels according to the significant factors identified, and the most suitable theoretical distributions representing them were developed systematically. ECSL simulation package was used for all cases except for hauling and returning time and the Erlang, Weibull and Normal distributions were found to be the most representative for different cases. The summary findings are shown in Table 7.9 where the fitted distributions are represented in a short form, for example, 20+Erlang(10, 2.4, S) represents the Erlang distribution

with a minimum value = 20 seconds, shape parameter = 10 and the scale parameter = 2.4. The same convention is applicable to Weibull distribution.

Table 7.9 - Fitted distributions for loader-truck cycle element times

Cycle element	Treatment level	Fitted distribution (sec.)
1. loader cycle	1. wheel loader, common earth with poor o.f. 2. backhoe, common earth with average o.f. 3. backhoe, common earth with poor o.f. 4. backhoe, weathered rock with poor o.f.	20+Erlang(10, 2.4,S) 4+Erlang(7, 2.5,S) 13+Erlang(6, 4.1,S) 23+Erlang(2, 10.5,S)
2. positioning delay of truck	1. no queue at cut with average oper. factor 2. queue exists at cut with average oper. factor 3. no queue at cut with poor oper. factor 4. queue exists at cut with poor oper. factor	10.0+Weibull(0.4, 7.0,S) 20.0+Weibull(0.5,14.3,S) 10.0+Weibull(0.6,40.2,S) 40.0+Weibull(0.5,30.1,S)
3. Hauling delay	For all cases	0.0+Weibull(0.4,9.2,S)
4. Dump & turn	1. good site condition with truck size 1 & 2 2. average site condition with truck size 1 & 2 3. poor site condition with truck size 1 & 2 4. poor site condition with truck size 4	8.0+Weibull(1.9, 28.5,S) 13.2+Weibull(1.6,34.1,S) 8.6+Weibull(1.7,66.1,S) 1.0+Weibull(2.3,83.9,S)
5. Return Delay	For all cases	0.0+Weibull(0.6,63.0,S)
6. Hauling	For all cases	Normal with mean = 44.8+0.139xHaul distance and std. dev. = 137.8
7. Returning	For all cases	Normal with mean = 31.8+0.121xReturn distance and std. dev. = 109.9

Clearly, it is impossible to observe the entire population of operating conditions in a practicable study, thus developed distributions should be used with care. For example,

if a very steep haul road is present in a particular road site, use of above distributions are not recommended.

7.4.2 Scraper-pusher operations

As stated in Chapter 6, scraper-pusher operations were not studied and the distributions representing various cycle element times were obtained from a similar study carried out by Clemmens (1978) for scraper-pusher operations. The fitted distributions for various cycle elements and treatment levels are summarised in Table 7.10. Surprisingly though Clemmens' loading cycle time does not depend on the type of material when tested with common earth, ripped or blasted rock. However, the author believes that further field observations and tests are needed to justify this conclusion and is not recommended for extreme situations.

All these distributions, together with input parameters representing them for both loader-truck operations and scraper-pusher operations, will be used to generate realistic cycle element times corresponding to various operating conditions during the simulation model building as described in the next chapter.

Table 7.10 - Fitted distributions for scraper-pusher cycle element times

Cycle element	Treatment level	Fitted distribution
1. loading cycle (scraper)	1. loading with one pusher 2. loading with two pushers 3. loading, push-pull 4. loading, elevating	15+Erlang(4, 9.2,S) 15+Erlang(7, 4.4,S) 57+Erlang(5, 10.0,S) 56+Erlang(7, 7.7,S)
2. dump & turn (scraper)	For all cases	21+Erlang(6, 5.5,S)
3. Travelling delay (scraper)	For all cases	0+Erlang(1,114,S)
4. Travelling (scraper)	1. single Engine 2. twin engine	Normal with mean = 82+0.093*distance and std.dev. = 76 Normal with mean = 94+0.0558*distance and std. dev.= 60
5. loading cycle (pusher)	1. loading with one pusher 2. loading with two pushers	15+Erlang(4, 9.3,S) 15+Erlang(7,4.4,S)
6. Return time (pusher)	For all cases	20+Erlang(4,5.7,S)
7. External delay (pusher)	For all cases	0+Erlang(1,52,S)

CHAPTER EIGHT

DEVELOPMENT OF THE 'RESOM' MODEL

8.1 Introduction

8.2 Hardware Selection

8.3 Simulation Model Building

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8.3.1.2 Activity cycle diagrams

8.3.1.3 Identification of important events and categorising them to 'B' and 'C' activities

8.3.1.4 Flow diagrams for loader-truck operations

8.3.1.5 Three phase loader-truck executive

8.3.1.6 An overview of loader-truck executive

8.3.2 Simulation model building for scraper-pusher operations

8.3.2.1 Assumptions made

8.3.2.2 Activity cycle diagrams

8.3.2.3 Identification of important events and categorising them to 'B' and 'C' activities

8.3.3 A description of the simulation model

8.4 Linear/Integer Programming Model

8.4.1 Software used for LP/IP model solution

8.4.2 General description of LINDO

8.5 Network Model

8.6 Summary

8.1 Introduction

Before stepping through the actual model development in detail, let us recapitulate what has already been established in some of the previous chapters. Chapter 4 presented the detailed methodology to be adopted in the model development, explaining in particular the LP/IP model; whereas Chapter 5 provided a broad and succinct explanation of simulation modelling techniques, introduced the required terminology, and selected appropriate techniques and the language (Pascal) to be used in simulation model building. After identifying the requirement of data collection, Chapter 6 provided the data collection process in detail. Finally, the systematic data analysis to identify the significant parameters affecting various cycle element times of earthmoving operations, and also to recognise the appropriate probability distributions representing them together with the evaluation of their input parameters were presented in Chapter 7. In effect now, the necessary information for actual model development has already been established.

This chapter systematically develops the overall model which has been named RESOM: an acronym for Roadwork Earthmoving System Optimisation Model and it basically consists of 3 major parts, simulation modelling being the largest, as follows.

1. Development of simulation model.
2. Development of LP/IP model.
3. Development of network model.

8.2 Hardware Selection

Up until recently, most complex models were developed on Mainframes which were the only solution at one time. However, with the continuous development of powerful microcomputers, the trend gradually changed towards the personal computers. This is clearly seen, particularly in the construction industry since most, if not all contractors adopt personal computers for their problem solving.

The choice therefore was clear, and it was decided to use an IBM PS/2 computer with 1024kb RAM and 30Mb hard disk storage together with a colour monitor for increased visual impact. The IBM PS/2 was a better choice than the other competitors like Apple Macintosh and selected for the following reasons.

- (i) Easy availability with a lot of compatibles.

- (ii) Popularity among scientists, Engineers and also in the construction industry.
- (iii) Wide availability of software packages thus making it easier to solve LP/IP formulation and network scheduling stage.
- (iv) The popularity of the Apple Macintosh (although is a capable machine) has not yet been fully established in the industry and the appropriate software, either not available or difficult to access.

8.3 Simulation Model Building

As mentioned in Chapter 5, due to its wide popularity and unique potential, computer simulation has evolved number of possible approaches, some of which have been developed for special purposes while others can be used generally for any simulation model. After reviewing some of those widely used approaches, Chapter 5 also identified the most appropriate techniques to be used for simulation of earthmoving operations. Those selected were:

- | | |
|----------------------------------|---|
| (i) Time handling | - Next event technique; |
| (ii) Stochastic or deterministic | - Stochastic; |
| (iii) Simulation language | - Pascal; |
| (iv) Modelling approach | - Three phase approach; and |
| (v) Sampling method | - Probability distributions developed from actual data. |

After data analysis in Chapter 7, it was also established that all the scraper and pusher cycle element times except scraper travel time can be represented by an Erlang distribution. Scraper travel time can be taken as normally distributed. Furthermore, all loader and truck cycle element times except truck hauling time, returning time and loading time were found to be Weibull distributed. Loader cycle time can be best represented as an Erlang distribution whereas truck hauling and returning times were again normally distributed. All these fitted distributions and parameters are shown in Tables 7.9 and 7.10 in Chapter 7.

Furthermore, objectives of the overall model building have already been identified in Chapter 1, however, at this stage, it is quite crucial to recognise the detailed objectives to be achieved from simulation stage. These can be perceived as follows.

- (i) To find out realistic unit cost (£/m³) and production (m³/day) given the; type of material; source and destination; plant team and operating conditions.
- (ii) To determine production efficiency, idle times, delay times, queuing time histograms, queue length histograms corresponding to the above given conditions.
- (iii) To experiment with the simulation model by varying simulating conditions, plant items etc. with a view to achieving a minimum realistic cost, and corresponding production to be used during LP/IP stage.
- (iv) To carry out the above three steps for the entire project under consideration covering all feasible haulage operations to obtain input data for the LP/IP stage.

8.3.1 Simulation model building for loader-truck operations

8.3.1.1 Assumptions made

In modelling any system, only some elements or features of the system are modelled and others are assumed to be unimportant and irrelevant in the context of the objectives. These assumptions should be clearly stated as they may have to be questioned at a later stage in modelling process. Those assumed in loader-truck operations are:

- (i) no priority queues are present at the loading phase and always served on FIFO basis;
- (ii) in cases where there is more than one server, hauling units are served by the first available server;
- (iii) all equipment items used at the beginning of simulation remain unchanged unless altered during simulation by interacting the model;
- (iv) hauling units and the servers entertain official breaks only at the loading area; and
- (v) the swell factor in hauling depends on the type of material and the shrinkage factor in compaction on the specifications at the destination.

8.3.1.2 Activity cycle diagrams

As mentioned in Chapter 5, simulation modelling, at least initially, requires some kind of flow diagrams to represent interactions between different classes of entity. Activity cycle diagram method is the one decided to be used and its development basically involves three main steps: identification of different classes of entity; identification of activities in which they involve; and linking these activities to form activity cycle diagrams.

Important classes of entity

Clearly, there are two important classes of entity to be considered in loader-truck operations:

- (i) Dump trucks; and
- (ii) Loaders.

Consideration of other equipment like compactors, dozers or sprinklers is unnecessary since it was found that the effects of these on hauling operations were insignificant.

Activities involved

Activities involved with each of these entity classes have already been identified during data collection and analysis. They are:

- Dump trucks;
- (a) truck - loading
 - (b) truck - hauling
 - (c) truck - dump & turn
 - (d) truck - returning
 - (e) truck - positioning delay

- Loaders;
- (a) loader - loading
 - (b) loader - positioning delay

Development of activity cycle diagrams

The activities identified for truck operations can now be linked as shown in Figure 8.1 to form activity cycle diagram for trucks.

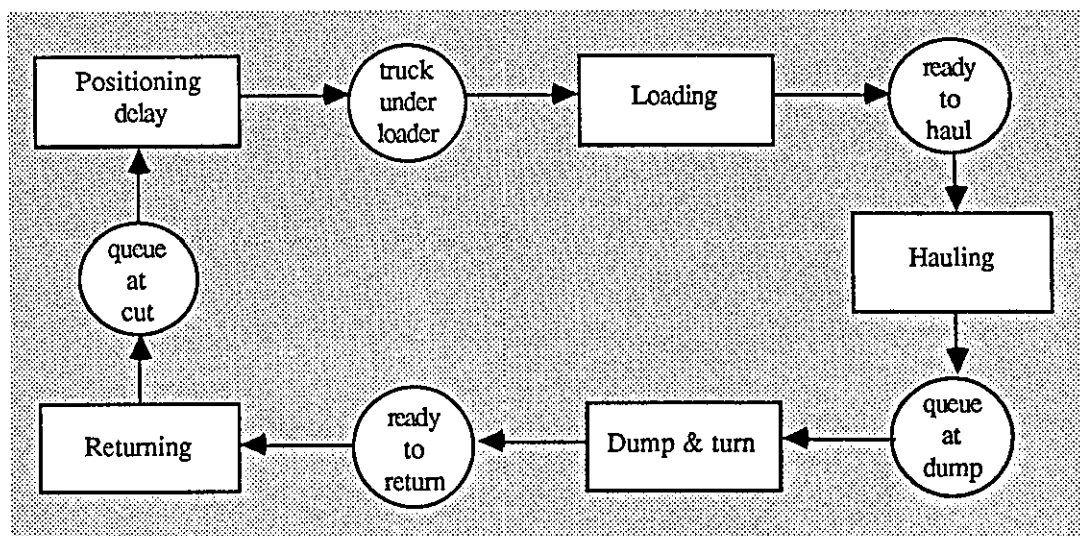


Figure 8.1 - Activity cycle diagram for trucks

Figure 8.1 has been deliberately simplified to provide a simpler representation of activity relationships, but in actual practice the process will be much more complex. For example, the positioning delay depends on the queuing condition at the loading phase (existence of a loading queue or not) or dump and turn time depends on the size and condition at site. All these factors have already been categorised into different operating levels and are incorporated into the simulation program code.

As argued during the development of model input parameters, the positioning delay time is the time between start loading and end returning of a particular truck if there is no loading queue, or time between start loading of a particular truck and end loading of the previous truck otherwise. This delay may be due to loader external delays like routine maintenance, refuelling, operator's personal needs etc. or manoeuvring delay of trucks. Therefore, before loading is commenced a truck should always undergo this *positioning delay* activity. At the end of this phase, a truck is in the dead state *truck under loader* followed by another active state *loading*. Truck loading may consist of number of loader cycles and at the end of it there is another dead state *ready to haul* and then the *hauling* activity begins. A truck encounters another dead state *queue at dump* at the end of hauling followed by the next active state *dump & turn*. The active state *returning* begins after passing the dead state *ready to return* and ultimately at the end of returning, truck queues at the loading phase until the conditions are satisfied to be loaded, thus initiating another cycle. In actual practice, the dead states, *ready to haul*, *ready to return*, may not exist and instantly pass from one active state to another. However, these were included to maintain the convention of activity cycle diagrams (Pidd 1984).

Similarly, the activity cycle diagram for loaders can be drawn as shown in Figure 8.2.

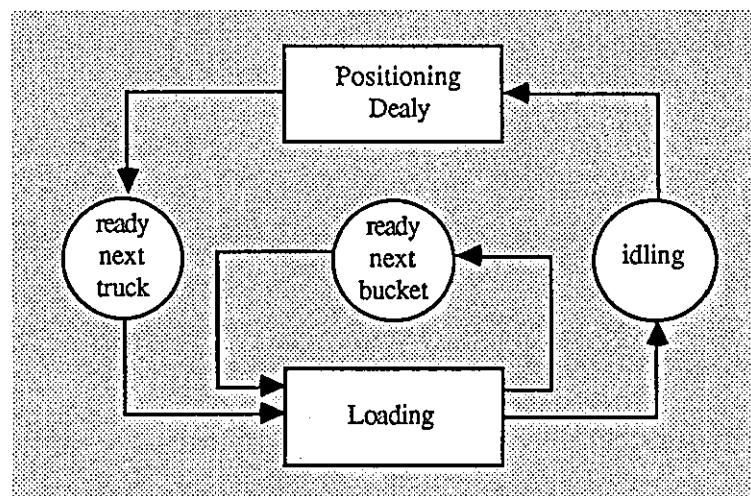


Figure 8.2 - Activity cycle diagram for loaders

At the end of each loader cycle used to load a particular truck, the loader may instantly pass the dead state *ready next bucket*. The process is repeated until the truck is full and then undergoes another dead state *idling*. What dead state is due after each loader cycle is determined by two attributes, the truck capacity and the bucket capacity of loader. The loader idles until another truck is at the loading phase and the truck and the loader together, undergo the active state the *positioning delay*. During this, the loader may be stationary and at the end of positioning delay the loader may instantly pass the dead state *ready next truck* and loading begins thus initiating loading of another truck.

The combined activity cycle diagram representing entity interactions can now be drawn as shown in Figure 8.3.

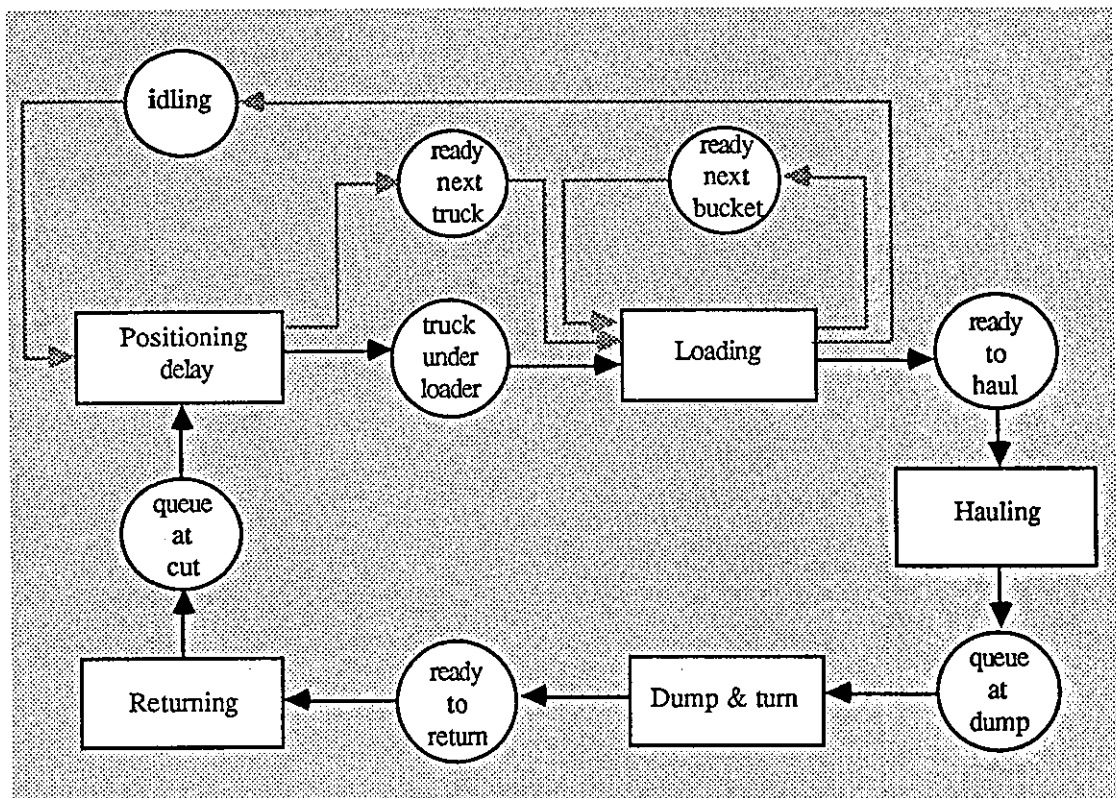


Figure 8.3 - Combined activity cycle diagram for loader-truck operations

8.3.1.3 Identification of important events and categorising them to 'B' and 'C' activities

Identification of important events

To proceed with simulation model building it is required at this stage to identify important events which subsequently can be categorised into 'B' and 'C' activities. The

simplest way to do this is to consider the beginning and end of each active state as events. However, since some events always coincide, it is sufficient to consider only distinctive ones. For example, *end loading* and *start hauling* events of a truck always coincide and hence can be considered together. With similar arguments, the important events of loader-truck operations can be identified as:

- (i) truck - end loading and start hauling;
- (ii) truck - end hauling and start dump & turn;
- (iii) truck - end dump & turn and start returning;
- (iv) truck - end of return;
- (v) loader - end loading; and
- (vi) truck & loader - start positioning delay.

Quite correctly, one may argue that end hauling and begin dump & turn of a truck cannot occur at the same time if there is a queue at the unloading site. However, it has been observed that in most practical situations, truck queuing at unloading site is not present, or can be avoided, or in worse situations can be incorporated by adopting appropriate fill site condition thus enabling to combine these two events.

It may also be noted that *end positioning delay* and *start loading* events have not been considered. This is because, once the positioning delay is started with a set of a truck and a loader they co-operate each other until the end of loading is encountered, without requiring any other condition to be satisfied. Thus these two events are unimportant.

Categorising into 'B' and 'C' activities

As explained in Chapter 5, the three phase approach uses two distinct kinds of activity 'B' and 'C' to improve simulation efficiency. Just to recapitulate, 'B' activities are bound or book keeping activities, executed directly by the executive whenever there scheduled time is reached. A 'C' activity on the other hand, is conditional and co-operative requiring co-operation of another class of entity or satisfaction of specific conditions within simulation before starting its execution. Thus, the above identified events can now be categorised into 'B' and 'C' activities as follows.

(i) *Truck - end loading and start hauling*

Once the positioning delay is commenced for a set of a truck and a loader, truck end loading is bound to occur when the positioning delay time and the loading time is elapsed. These times can be generated from appropriate probability distributions

developed earlier. No other condition should be satisfied, hence this is a 'B' activity.

(ii) *Truck - end hauling and start dump & turn*

Once hauling of a truck is commenced its end hauling and start dump & turn can be obtained by another two probability distributions which are used to generate hauling time and the external delay in hauling. Once this time is reached end hauling is bound to occur thus making this an another 'B' activity.

(iii) *Truck - end dump & turn and start returning*

With similar arguments this again is a 'B' activity.

(iv) *Truck - end of return*

With similar arguments this again is a 'B' activity.

(v) *Loader - end loading*

Similar to truck end loading, this is bound to occur when the positioning delay time and truck loading time is elapsed. Hence this is a 'B' activity.

(vi) *Truck and loader - start positioning delay*

According to the definition of positioning delay time, at least two conditions must be satisfied before starting this activity. Firstly, there should be a truck waiting to be loaded and secondly, a free loader should be available for assistance. This activity is, therefore, conditional and co-operative thus it is a 'C' activity.

The above activities identified for loader-truck operations can be designated as:

- B1 = Truck - end loading and start hauling;
- B2 = Truck - end hauling and start dump & turn;
- B3 = Truck - end dump & turn and start returning;
- B4 = Truck - end of return;
- B5 = Loader - end loading; and

C1 = Truck and loader - start positioning delay.

Clearly, statistics should be collected during simulation if at all to use the results in actual practice. This can easily be achieved by adding another 'B' activity (B6) called *statistics collection*. Any activity is triggered from an entity class and in this case, the

corresponding entity can be designated as *observer*. At a given instance simulation statistics can be collected by this activity and at the same time rescheduling the next collection time. Since it does not need co-operation of any other class of entity or satisfaction of any other condition, it is a 'B' activity. According to the Three phase approach all these 'B' and 'C' activities can be programmed as separate segments whose execution is controlled by a three phase executive.

8.3.1.4 Flow diagrams for loader-truck operations

Development of program segments for each of the above 'B' and 'C' activities requires identification of what should be carried out under each of these routines. The simplest way to achieve this, is to draw flow diagrams and those for the above 6 activities are shown in Figures 8.4 to 8.9.

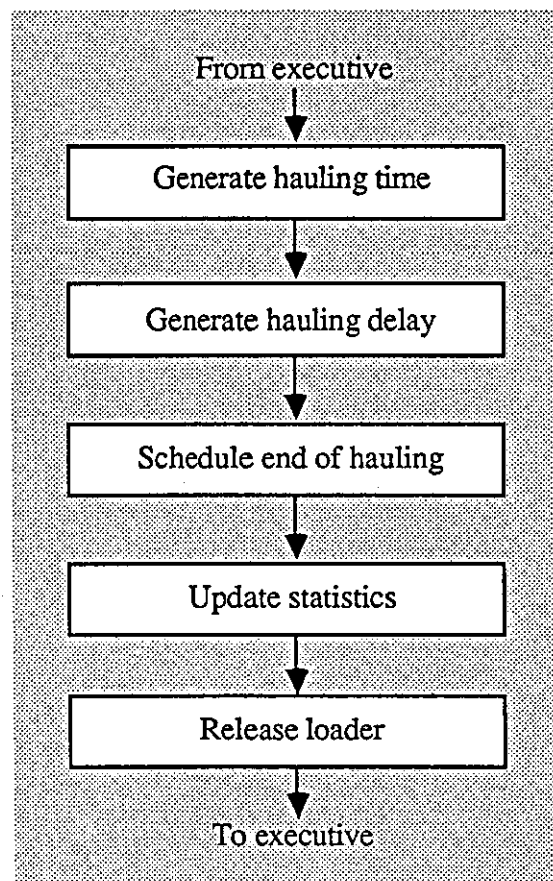


Figure 8.4 - Truck - end loading and start hauling activity routine

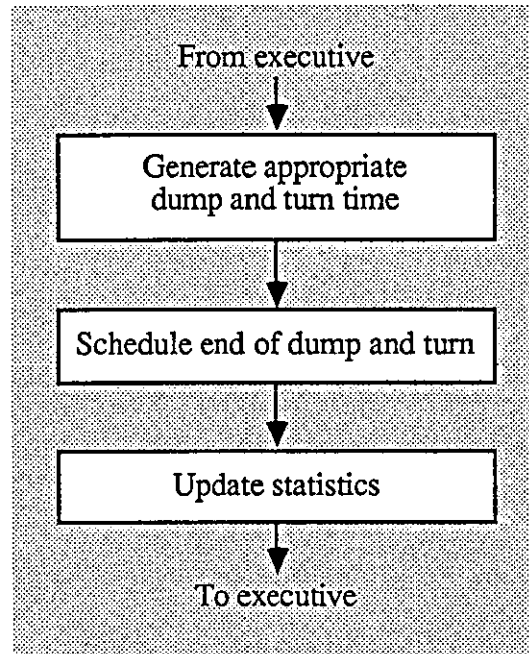


Figure 8.5 - Truck - end hauling and start dump & turn activity routine

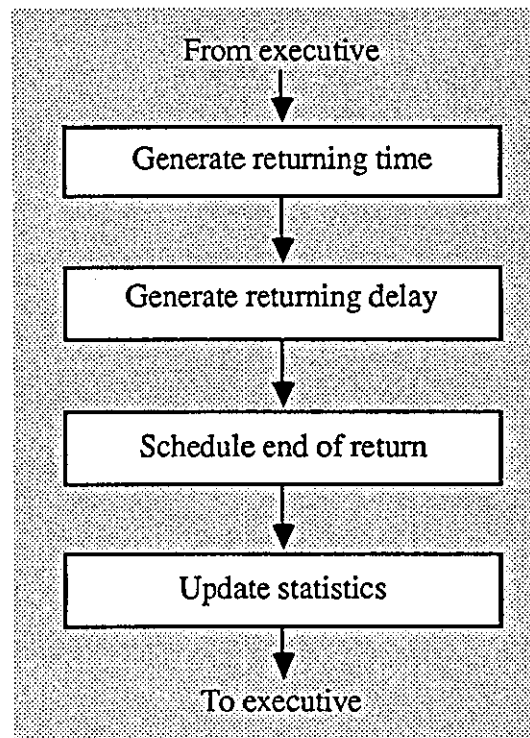


Figure 8.6 - Truck - end dump & turn and start returning activity routine

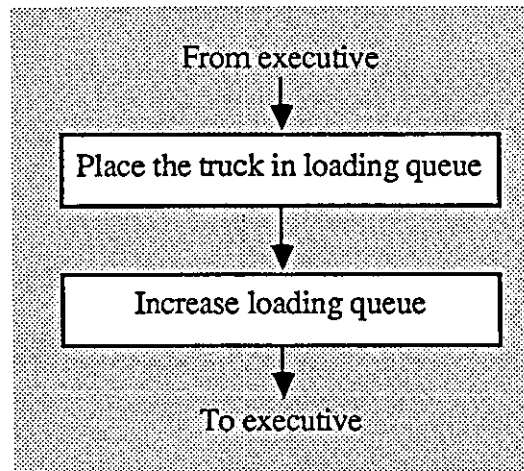


Figure 8.7 - Truck - end return activity routine

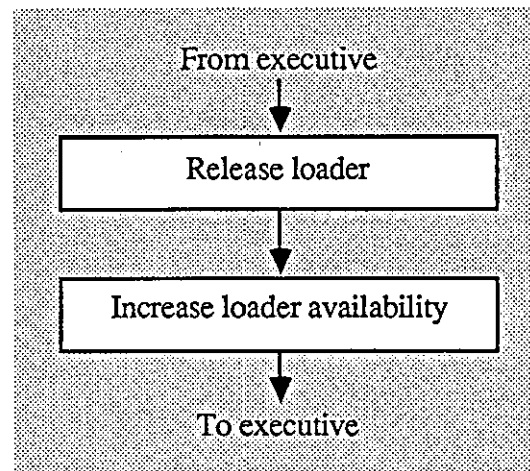


Figure 8.8 - Loader - end loading activity routine

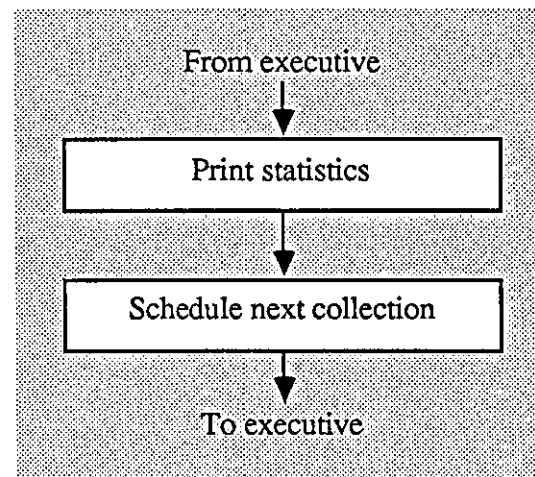


Figure 8.9 - Observer - Statistics collection activity routine

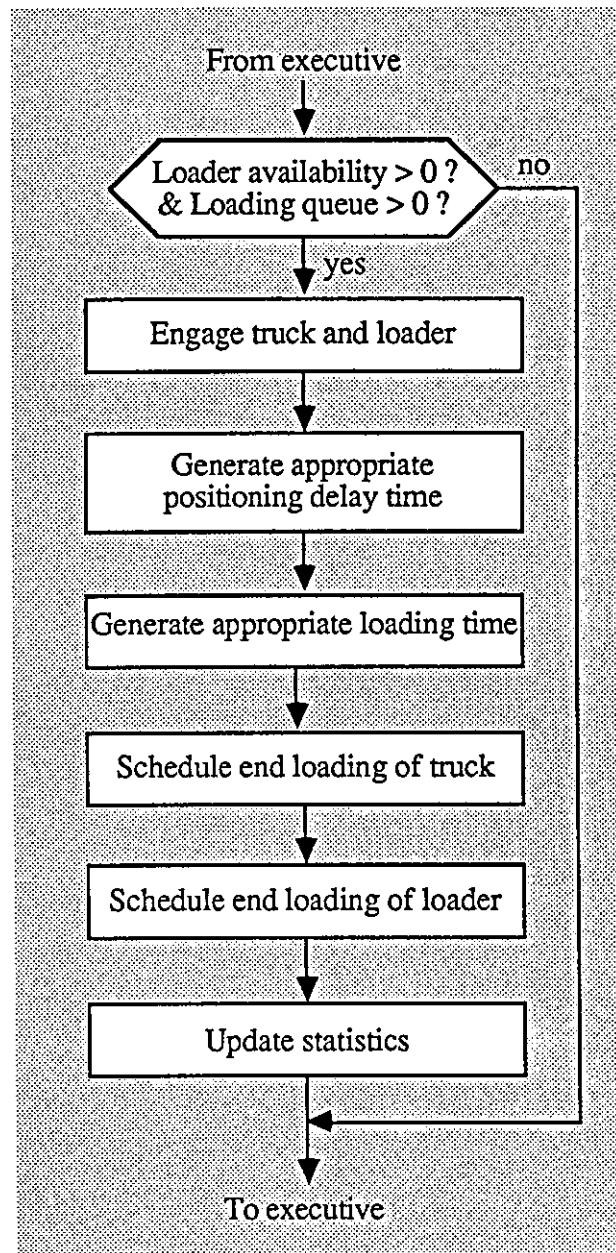


Figure 8.10 - Truck and loader - start positioning delay activity routine

These flow diagrams have been oversimplified for clear depiction of the underlying concept but the actual program routines are much more complicated. All the 'B' activity routines are directly executed by the executive at the appropriate time but a 'C' activity being co-operative and conditional, is always tested for execution and is executed only if the test head at the beginning of the routine is satisfied. Otherwise no action will be taken and the control is passed back to the executive.

8.3.1.5 Three phase loader-truck executive

The RESOM executive is the overall administrator of the entire simulation model. When the appropriate times comes, or in other words, when loader-trucks are simulated the control is passed to the Three phase loader-truck executive.

As explained in Chapter 5, a three phase executive has three main phases: A; B; and C for time scan, B calls and C scan respectively, and the executive cycles through these phases as the simulation proceeds. A simplified version of the loader-truck executive is shown in Figure 8.11, and more details about the programming aspects are provided under programmer's manual in Appendix E.

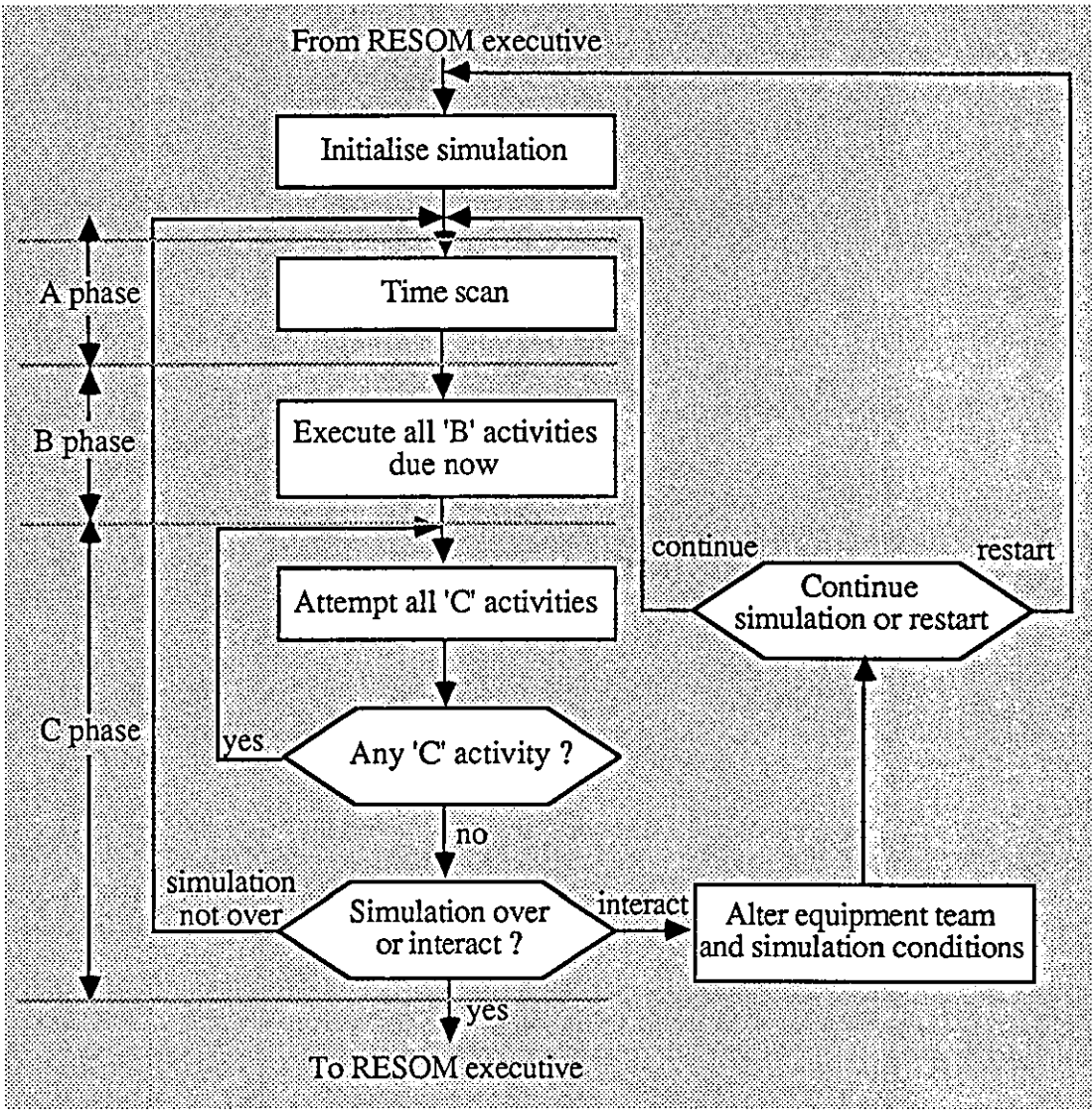


Figure 8.11 - Simplified Three phase loader-truck executive

8.3.1.6 An overview of loader-truck executive

The actual simulation process of loader-truck operations involves considerable details and complexity, due to the incorporation of features like interaction to change equipment items or to change simulation conditions etc., but the underlying concept of driving the simulation (or in other words, functions of the loader-truck executive) can be explained with a simple example.

Consider a loader-truck team consisting of four dump trucks and one loader to be used in hauling material from source A to destination B. The activity cycle diagram shown in Figure 8.3 indicates two main classes of entity, *loader* and *trucks*. In addition, a dummy entity class *observer* was included for statistics collection. As identified earlier, the activities involved with these entity classes are; B1 to B6, and C1.

At the heart of the loader-truck executive is a table of records representing the status of each entity as shown in Table 8.1.

Table 8.1- Entity status at stage 1

1	2	3	4	5	6...
Entity	Time-cell (seconds)	Next activity	Previous activity	Attribute 1	
1. loader 1	50	5	-1		
2. observer	900	6	6		
3. truck 1	50	1	-1		
4. truck 2	0	-1	4		
5. truck 3	0	-1	4		
6. truck 4	0	-1	4		

Suppose, Table 8.1 shows the entity status just a little after beginning of simulation. Column one shows the entity name ordered alphabetically and column two represents the simulation time at which the next change of state is due. Column three provides the next activity due at the time cell whereas column four represents the last activity engaged. A positive value in column three or four corresponds to a particular 'B' activity (for example, 6 means B6) and a negative value represents a particular 'C' activity. Beyond column five are attributes corresponding to each entity class and are used to guide simulation in appropriate directions when a decision is to be taken particularly in generating cycle element times.

The 'A' phase

Supposing that the simulation clock is 0, the following observations can be made from Table 8.1.

- (a) Loader 1 is serving the truck 1 and the end of loading is scheduled at time = 50 seconds.
- (b) Clock = 0.
- (c) Loader availability = 0.
- (d) Number of trucks waiting to be loaded = 3.

The 'A' phase now proceeds as follows.

- (i) Scans each entity in the table to find out the minimum time cell of these entities whose next activity is a 'B' activity. ('C' activities are not considered since they are co-operative).
- (ii) Store all these entity locations having this minimum time cell.
- (iii) Now move the simulation clock to this minimum time cell.

Entities one, two and three have a 'B' activity scheduled but only one and three have the minimum time cell indicating that loader is due to engage in activity B5 (end loading) and truck 1 is due to end loading and start hauling. No changes are made to the table but at the end of 'A' phase entity one and three are noted and simulation clock moved to 50.

The 'B' phase

During this phase the executive directly executes the 'B' activity routines identified as next due corresponding to each entity selected in the 'A' phase. In the example, routines B5 and B1 are executed for loader 1 and truck 1 respectively. As shown in flow diagrams (Figures 8.4 and 8.8), B1 generates the hauling time and schedules end of hauling whilst B5 releases the loader. Supposing that the generated hauling time and hauling delay for truck 1 is 400 seconds, the entity states at the end of the 'B' phase are shown in Table 8.2.

The 'C' phase

At the 'C' phase the executive attempts each 'C' activity until no changes occur during the 'C' scan. In the example, there is only one 'C' activity, C1-start positioning delay. Executive starts with the first entity, loader 1 and checks the test head of activity routine C1 (Figure 8.10). In this case loader is waiting to serve another truck and three trucks

are waiting to be loaded, thus the test head is satisfied and the loader starts serving truck 2. After executing the routine C1 assuming the loading time of truck 2 is 60 seconds the entity states are shown in Table 8.3.

Table 8.2 - Entity status at stage 2

1	2	3	4	5	6...
Entity	Time-cell (seconds)	Next activity	Previous activity	Attribute 1	
1. loader 1	50	-1	5		
2. observer	900	6	6		
3. truck 1	450	2	-1		
4. truck 2	0	-1	4		
5. truck 3	0	-1	4		
6. truck 4	0	-1	4		

Clock = 50, loader availability = 1, loading queue = 3

Table 8.3 - Entity status at stage 3

1	2	3	4	5	6...
Entity	Time-cell (seconds)	Next activity	Previous activity	Attribute 1	
1. loader 1	110	5	-1		
2. observer	900	6	6		
3. truck 1	450	2	-1		
4. truck 2	60	1	-1		
5. truck 3	0	-1	4		
6. truck 4	0	-1	4		

Clock = 50, loader availability = 0, loading queue = 2

The 'C' scan continues to check each of the proceeding entities for state changes but no execution is possible since the loader availability is zero. At the end of last entity (truck 4), 'C' scan is reinitialised from entity one since there was a state change during the last scan. Clearly, re-execution of routine C1 is not possible due to unavailability of a free loader. Note that the clock is still at 50 seconds and the loader is free only at 110 seconds. After failing to execute C1 routine for any of the entities the control is passed

back to time scan thus initiating another cycle. This process is repeated until simulation is over or interrupted.

8.3.2 Simulation model building for scraper-pusher operations

8.3.2.1 Assumptions made

Assumptions made for scraper-pusher operations are the same as those assumed for loader-truck operations.

8.3.2.2 Activity cycle diagrams

Similar to loader-truck operations, activity cycle diagrams for scraper-pusher operations can be developed as follows.

Important classes of entity

In this case also there are two important classes of entity to be considered:

- (i) Scrapers; and
- (ii) Pushers.

In situations where separate pushers are not used for scraper loading, pusher entity class can be ignored.

Activities involved

Activities involved with these classes of entity are:

- | | |
|-----------|---------------------------|
| Scrapers; | (a) scraper - loading |
| | (b) scraper - hauling |
| | (c) scraper - dump & turn |
| | (d) scraper - returning |
| Pushers; | (a) pusher - loading |
| | (b) pusher - returning |

Development of activity cycle diagrams

Figure 8.12 shows a simplified version of an activity cycle diagram for scrapers. Essentially push loading requires co-operation of one or two pushers depending on the requirement whilst push-pull loading requires the assistance of another push-pull scraper. What loading method is to be adopted for a particular scraper is determined by

the attribute called *method of loading*. Beyond that, descriptions of other dead and active states are similar to loader-truck operations.

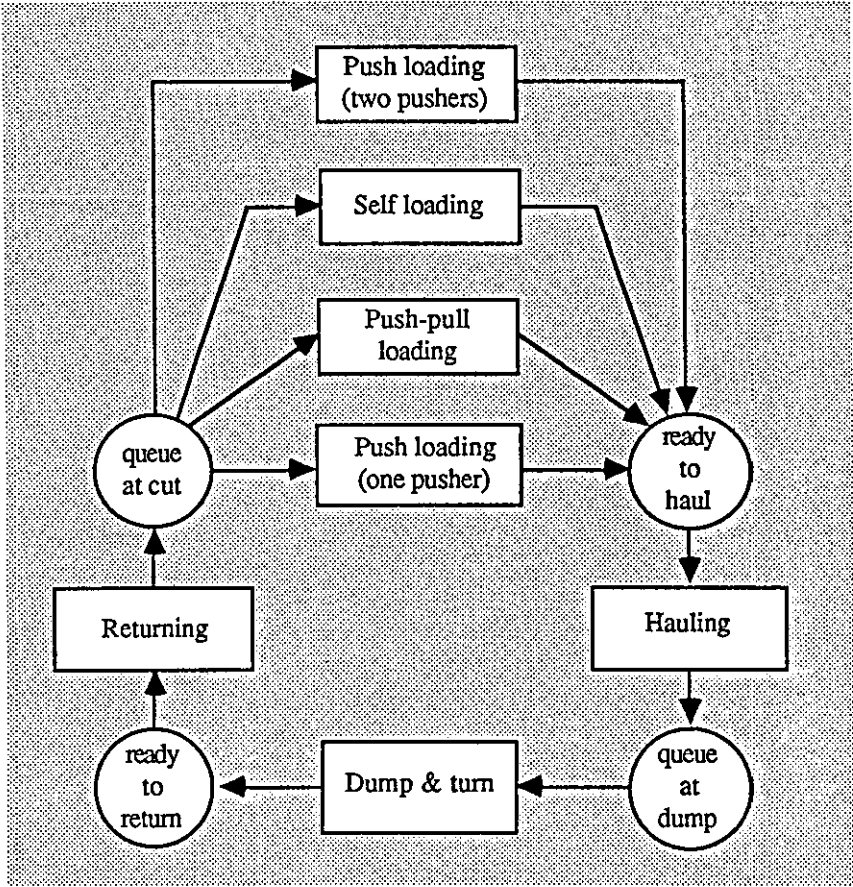


Figure 8.12 - Activity cycle diagram for scrapers

The activity cycle diagram for pushers can be drawn as shown in Figure 8.13.

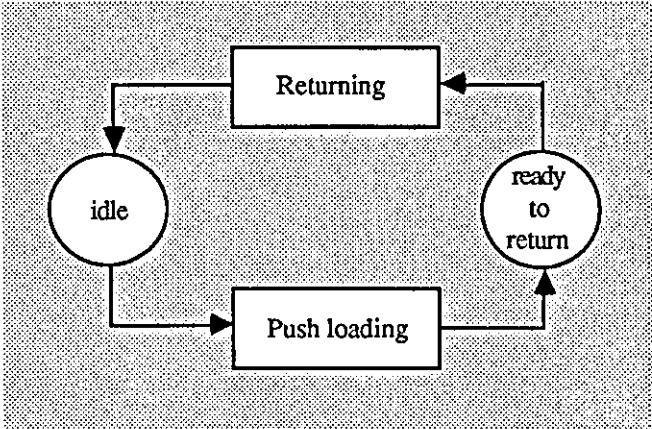


Figure 8.13 - Activity cycle diagram for pushers

Once again the pusher loading activity involves co-operation of scrapers. After loading, it may instantly pass the dead state *ready to return* and starts the next active state *returning*. Subsequently, pusher may restart loading another scraper by either instantly passing the dead state *idle* or after idling until another scraper is available.

The combined activity cycle diagram representing entity interactions can now be drawn as shown in Figure 8.14.

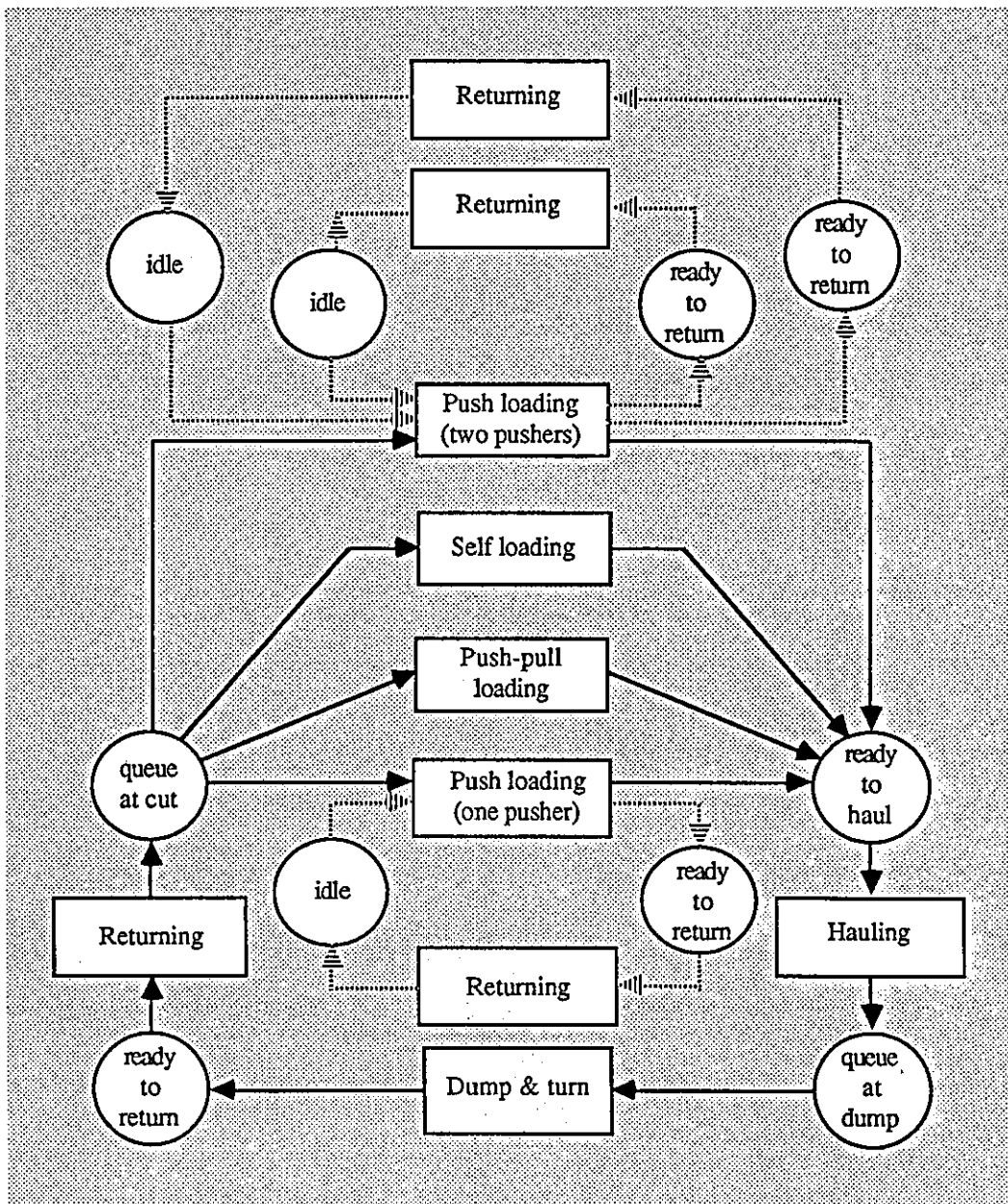


Figure 8.14 - Combined activity cycle diagram for scraper-pusher operations

8.3.2.3 Identification of important events and categorising them to 'B' and 'C' activities

Identification of important events

Similar to loader-truck operations, the important events of scraper-pusher operations can be identified as:

- (i) scraper - end loading and start hauling;
- (ii) scraper - end hauling and begin dump & turn;
- (iii) scraper - end dump & turn and start returning;
- (iv) scraper - end of return (& start loading only for self loading scrapers);
- (v) pusher - end loading and start returning;
- (vi) pusher - end of returning;
- (vii) scraper and pusher - push loading begins with one pusher;
- (viii) scraper - push-pull loading begins; and
- (ix) scraper and pusher - push loading begins with two pushers.

Clearly, *end of return* and *start loading* of both scrapers and pushers must be considered as separate events since they may not occur at the same time depending on the prevailing conditions and so as the case in push-pull loading scrapers. Also, *begin loading* for scrapers and that of pushers were taken as two different events for two reasons. Firstly, they involve two different classes of entity thus making it logical to consider them separately, secondly, they may not be the same if different loading methods are adopted for different scrapers.

Categorising into 'B' and 'C' activities

Similar to loader-truck operations the above identified events can be categorised into 'B' and 'C' activities as follows.

- (i) *Scraper - end loading and start hauling*
Similar to truck end loading and start hauling this activity is a 'B' activity.
- (ii) *Scraper - end hauling and begin dump & turn*
Similar to truck end hauling and begin dump & turn this again is a 'B' activity.
- (iii) *Scraper - end dump & turn and start returning*
With similar arguments this again is a 'B' activity.

(iv) *Scraper - end of return (& start loading only for self loading scrapers)*

Once a scraper ends dump & turn and start returning is commenced, its returning time to the loading phase can be scheduled and bound to occur at that time. However, for push loading or push-pull loading scrapers loading cannot start until certain conditions are satisfied, but self loading scrapers can immediately commence loading without satisfying any other condition at loading phase. Thus, end return is a 'B' activity for push loading (both with one pusher and two pushers) and push-pull loading scrapers but end returning and start loading together is a 'B' activity for self loading scrapers.

(v) *Pusher - end loading and start returning*

Once pushing is commenced its end pushing and start returning to push another scraper is bound to occur after elapsing the pushing time generated by an appropriate probability distribution. Hence this is a 'B' activity.

(vi) *Pusher - pusher end of returning*

With similar arguments this is a 'B' activity.

(vii) *Scraper and pusher - push loading begins with one pusher*

Clearly, at least two conditions must be satisfied before executing this activity. Firstly, there should be a push loading scraper waiting to be loaded and secondly, a free pusher should be available for assistance. This activity is therefore conditional and co-operative thus it is a 'C' activity.

(viii) *Scraper - push-pull loading begins*

Here again there should be at least two push-pull scrapers available to start push-pull loading. Hence this again is a 'C' activity.

(ix) *Scraper and pusher - push loading begins with two pushers*

This is similar to push loading begins with one pusher except in this case two free pushers are required for loading. This in effect requires co-operation of three entities. Hence this is a 'C' activity.

Thus, for scraper operations the above activities can be designated as:

B1 = Scraper - end loading and start hauling;

B2 = Scraper - end hauling and begin dump & turn;

B3 = Scraper - end dump & turn and start returning;

- B4 = Scraper - end of return (& start loading only for self loading scrapers);
- B5 = Pusher - end loading and start returning;
- B6 = Pusher - end of return;

- C1 = Scraper and pusher - push loading begins with one pusher;
- C2 = Scraper - push-pull loading begins; and
- C3 = Scraper and pusher - push loading begins with two pushers.

As in loader-truck operations one additional 'B' activity *statistics collection* (B7) should be included to complete the activity identification. Here again, all the activities can be programmed as separate segments and the flow diagrams for each of these activity routines are similar to those of loader-truck operations.

Functions of the three phase scraper-pusher executive too is almost identical to that described for loader-truck operations.

8.3.3 A description of the simulation model

Figure 8.15 shows a conceptualised representation of the processes embodied in the simulation model. On entry to the model, the module *system_initialisation* is called to obtain necessary project input. During this process, for each and every section of roadway, information on: whether the section is a cut or fill; material type; quantities involved; swell/shrinkage factors; possible number of haulage operations; average haul and return distances for each such haul, is obtained and saved in two files designated as 2 and 3 in Figure 8.15. Official break times are also obtained at this stage and saved in file 1 for later retrieval. At the end of this module the user is provided with a feed back as shown in Figure 8.16 for his approval.

After *system_initialisation*, the next module *individual_simulation* is called to individually simulate each possible haulage operation using a given plant team. The first task of individual simulation routine is to retrieve the official break times together with other information on the next haulage operation to be simulated, by making contacts with files 1, 2, and 3 in Figure 8.15. For example, according to Figure 8.16, material movement from section one to fill section two is taken as the first haulage operation. Subsequently, the user is requested to input number of plant teams to be tested on this haulage operation which possibly be 1, 2 or more depending on his requirement.

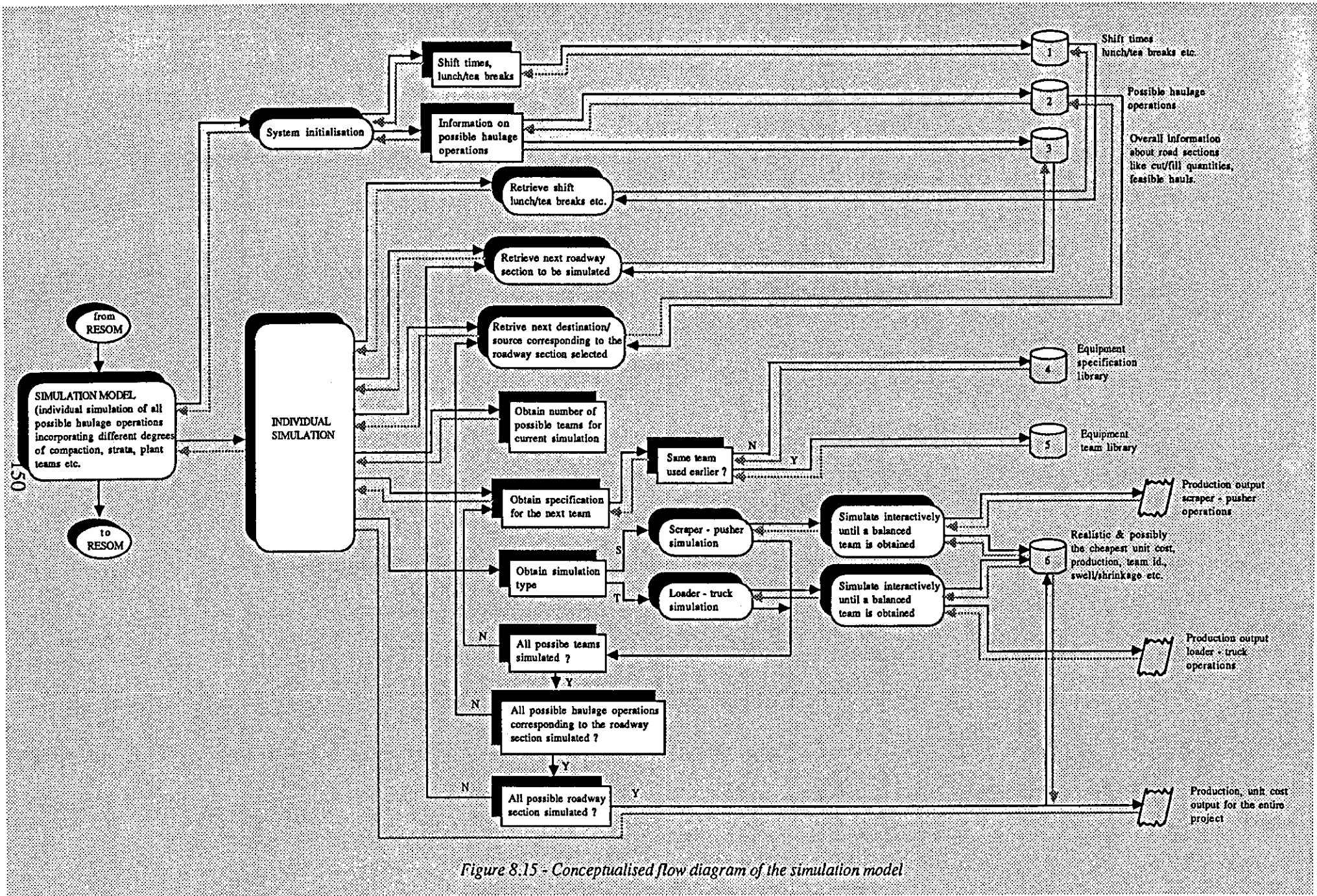


Figure 8.15 - Conceptualised flow diagram of the simulation model

These are the possible haulage operations with other relevant information.

<u>section</u>	<u>cut/fill</u>	<u>mat.tpye</u>	<u>qty (m3)</u>	<u>possible hauls</u>
1	cut	c.earth	5000	fill 2, fill 4, disposal 1
2	fill	c.earth	7468	borrow 1, borrow 2
3	cut	w.rock	2100	fill 2, fill 4, disposal 1
4	fill	c.earth	4000	borrow 1, borrow 2
_____	_____	_____	_____	_____

** Press C to continue **

Figure 8.16 - Project cut/fill information

Details of only one such team are obtained at a time and fully simulated before the next. At first, the plant team identification number and team hire charge are requested and if that team has already been used for a previous haulage operation, overall information on that team is directly obtained from file 5 (see Figure 8.15), otherwise the model of each plant item is requested in which case other specifications are obtained from equipment specification library. If specifications on a particular plant item is not in the library they have to be user fed. Here again, once the plant team is input, it is saved in file 5 for later use at any time during simulation and the selected team is displayed for user approval as shown in Figure 8.17.

Once the plant team has been approved, the selected haulage operation for current simulation is also displayed as shown in Figure 8.18 for user approval.

The suggested team consists of following equipment items
The team identification number = 1

<u>Title</u>	<u>Make</u>	<u>Model</u>	<u>Type</u>	<u>Struck cap(m3)</u>	<u>Heaped cap(m3)</u>	<u>no.engines</u>
scraper1	cat	631E	pushed	16.1	23.7	1
scraper2	cat	631E	pushed	16.1	23.7	1
scraper3	cat	631E	pushed	16.1	23.7	1
scraper4	cat	631E	pushed	16.1	23.7	1
pusher1	cat	D8				

** Press C to continue **

Figure 8.17 - An example of a selected team for current simulation

These are the information corresponding to the haulage
operation to be carried out

Cutting section or source	1
Filling section or destination	fill 1
Material type	common earth
Swell factor in haul	1.1
Shrikage factor in compaction	0.9
Haul distance	1000 m
Return distance	1000 m
Operational factor	1
Site condition	2

** Press C to continue **

Figure 8.18 - An example of selected haulage operation for current simulation

Keeping the information retrieved in memory, control is passed to a decision box where the user has to decide whether to go for scraper-pusher simulation, loader-truck

simulation or exit altogether. If the user does not want to exit from simulation, either scraper-pusher or loader-truck simulation module is called. Before actual simulation begins the appropriate three phase executive needs further information on simulation conditions. It requests the number of replications required for the haulage operation under consideration. A replication is one complete simulation run and in this case it was taken as to be one full working day. Clearly, the greater the number of replications the more reliable the answer would be. At this stage the user is also requested the required frequency of printed output which provides a hard copy of collected statistics and finally a value to be used to control the simulation speed for increased visual examination. Now, all the required features have been input and this is where the actual individual simulation is commenced. How the screen displays an intermediate stage during simulation of a scraper-pusher run is shown in Figure 8.19.

Simulation is driven by the appropriate three phase executive as explained earlier and at appropriate locations statistics such as total number of loads done, total quantity moved, productive time, idle time, external delay times, queuing time histograms, queue length histograms, idle time histograms are recorded. In addition individual statistics corresponding to each plant item are also recorded.

SIMULATION TABLE							
Clock10:38:51							
Name	event-time	next-acty	pre-acty	loads	idle-time	delay	prod-time
pusher1	38312	-1	6	97	723	2107	5782
scraper1	38352	3	2	24	1311	1306	6035
scraper2	38440	2	1	24	1314	1129	6297
scraper3	38331	3	2	26	1414	1701	5516
scraper4	38391	2	1	23	1759	1152	5780
Press any key for interaction							
1-End load & start haul (scraper)				5-End load & start return (pusher)			
2-End haul & start unload (scraper)				6-End return (pusher)			
3-End unload & st. return (scraper)				-1-Start push loading			
4-End return (& st. load (scraper))				-2-Start push-pull loading			

Figure 8.19 - The screen display of an intermediate stage during simulation of a scraper-pusher run

The official break times are appropriately embodied into simulation statistics. For example, if a hauling unit is arrived to the loading area within an official break, it is allowed to rest until the scheduled official break time is elapsed from the time of arrival and not until the end of scheduled official break. This was found to be what happens in real life. If the start of an official break occurs when a hauling unit is in a loading queue, it is removed from the queue and is allowed to rest. The program makes sure that every equipment item enjoys appropriate official break times.

If the process is not interrupted, simulation continues dynamically by changing all simulated figures on the computer display (Figure 8.19). The user can visually see for each entity, what is going to happen next, how each entity is behaving, what is the simulation clock etc. If the user observes that the current team is unbalanced or some equipment items are idling or simulation conditions need changing he can easily interact the process. If interacted, a decision box as shown in Figure 8.20 appears on the screen.

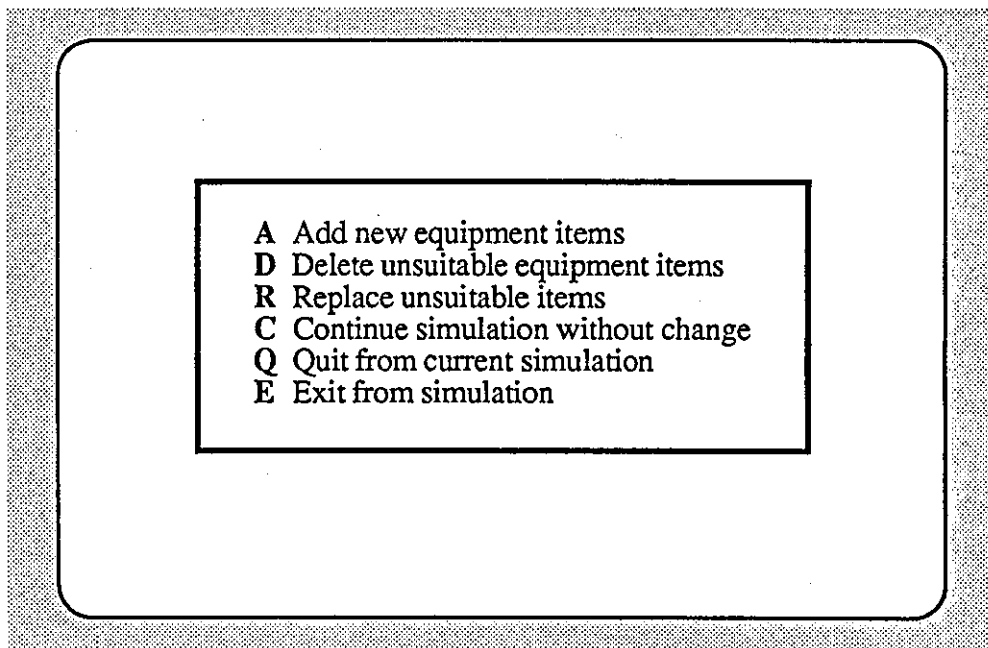


Figure 8.20 - Interactive options available in the simulation model

As can be clearly seen, any equipment item can be added, deleted or replaced at this stage. At the end of this, the user is posed another question by asking whether to continue simulation or restart the process for the particular haulage operation being simulated. This way, simulation continues providing outputs at a given interval until

the set simulation duration is over and then restarting until the required number of replications are carried out. A typical intermediate output is shown in Figure 8.21 and a kind of output obtained at the end a replication is shown in Figure 8.22.

<u>OVERALL SIMULATION STATISTICS AT 13:0 hrs.</u>				
Total earth quantity moved = 3274.91 m3(bank)				
Overall percentage of productive time of scrapers = 68.84 %				
Overall percentage of idle time of scrapers = 18.89 %				
Overall percentage of external delay of scrapers = 12.66 %				
Total number of scraper loads = 152				
Overall percentage of productive time of pushers = 67.22 %				
Overall percentage of idle time of pushers = 7.33 %				
Overall percentage of external delay of pushers = 25.45 %				
<u>INDIVIDUAL STATISTICS AT 13:0 hrs.</u>				
Entity name -----	Total loads -----	productive time (%) -----	idle time (%) -----	external delay (%) -----
pusher1	152	67.22	7.33	25.45
scraper1	36	70.76	15.22	14.01
scraper2	39	67.94	17.80	14.26
scraper3	39	68.43	19.90	11.67
scraper4	38	68.22	21.13	10.65

Figure 8.21 - A typical intermediate simulation output

<u>SUMMARY RESULTS AT THE END OF CURRENT REPLICATION</u>	
The plant team used for the haulage operation is	
<u>Name</u>	<u>Model</u>
pusher1	D8
scraper1	631E
scraper2	631E
scraper3	631E
scraper4	631E
Total number of loads	= 295
Total earth quantity moved	= 6355.91 m3 (bank)
Simulation duration	= 9.00 hours
Team hire charge	= 2500.00 £/day
Material source	= road section 1
Material type	= common earth
Destination	= Fill 2
Swell factor in haul	= 1.10

Figure 8.22 - A typical simulation output at the end of a replication (Cont..next page)

Shrinkage factor in compaction = 0.90
Haul distance = 1000.00 m
Team identification number = 1
Team production rate = 6355.91 m³(bank)/day
Team unit earthmoving cost = 0.39 £/m³(bank)

Queuing time histogram of push loading scrapers

midpoint(sec.) frequency

5	72
15	16
25	14
35	12
45	15
55	22
65	15
75	18
85	17
95	96

Idle time histogram of pusher at cutting phase

midpoint(sec.) frequency

5	245
15	10
25	10
35	8
45	5
55	4
65	5
75	4
85	1
95	5

Queue length histogram of push loading scrapers

midpoint(sec.) frequency

0	189
1	88
2	17
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0

SIMULATION RESULTS AFTER 2 REPLICATIONS

Average team production rate = 6280.50 m³(bank)/day
Average unit cost = 0.40 £/m³(bank)

*Figure 8.22 - A typical simulation output at the end of a replication
(cont..from previous page)*

Once all the replications have been carried out for a particular haulage operation the major findings include the realistic minimum unit earthmoving cost and the corresponding production obtained under given simulating conditions. These information together with other relevant facts are saved in the file 6 shown in Figure 8.15. In this way, the simulation process is repeated for all plant teams to be tested on that particular haulage operation. At the end of this phase, the minimum realistic earthmoving costs and the corresponding production rates for different plant teams tested with different speeds of operation corresponding to the haulage operation just simulated have been saved in file 6 in Figure 8.15. As explained earlier, different plant teams with various speeds of operation are required to obtain an optimum solution at LP/IP stage for timely project completion.

The next step is to obtain information on the next haulage operation to be carried out corresponding to the particular roadway section under consideration, by contacting file 2 in Figure 8.15 and then simulate for all plant teams to be tested. For example, the next operation according to Figure 8.16 is material movement from section 1 to fill 4. The same procedure described above is repeated until all the haulage operations are simulated for a particular roadway section.

Subsequently, information on the next roadway section to be simulated is retrieved by contacting file 3 in Figure 8.15 and the process is repeated until all haulage operations corresponding to that section are simulated. For example, according to Figure 8.16 the next road section is 2 and the haulage operations are borrow pit 1 to section 2 and borrow pit 2 to section 2. Like this, the entire project is simulated and the results are saved in file 6 in Figure 8.15. A typical output obtained at the end of a project simulation is shown in Figure 8.23.

Further information on the potential of the simulation model is explained in Chapter 10 under application and experimentation with RESOM.

Road section	cut/fill	soil type	source/ destina.	shrin. factor	team id.	unit cost (£/m3)	production (m3/day)
1	cut	c.earth	fill2	0.9	1	0.43	2560.0
1	cut	c.earth	fill2	0.9	2	0.65	3510.0
1	cut	c.earth	fill4	0.9	3	0.75	2100.0
1	cut	c.earth	fill4	0.9	4	0.90	3110.0
1	cut	c.earth	dispos.1	1.0	1	0.35	2750.0
1	cut	c.earth	dispos.1	1.0	2	0.46	3210.0
2	fill	c.earth	borrow1	0.9	1	0.35	2750.0
2	fill	c.earth	borrow1	0.9	2	0.56	3925.0
2	fill	c.earth	borrow2	0.9	5	0.58	2220.0
2	fill	c.earth	borrow2	0.9	6	0.72	2956.0
3	cut	w.rock	fill2	1.0	7	0.35	2850.0
3	cut	w.rock	fill2	1.0	8	0.46	3260.0
3	cut	w.rock	fill4	1.0	7	0.38	2642.0
3	cut	w.rock	fill4	1.0	8	0.50	2968.0
3	cut	w.rock	dispos.1	1.2	7	0.20	3670.0
3	cut	w.rock	dispos.1	1.2	8	0.32	4568.0
4	fill	c.earth	borrow1	0.9	1	0.38	2550.0
4	fill	c.earth	borrow1	0.9	2	0.56	3965.0
4	fill	c.earth	borrow2	0.9	5	0.60	2000.0
4	fill	c.earth	borrow2	0.9	6	0.75	2845.0

Figure 8.23 - A typical output at the end of a project simulation

8.4 Linear/Integer Programming Model

The difficult and skillful part of the LP/IP model is the correct and efficient formulation of the model. After reviewing the past LP/IP models developed on earthwork applications and other literature, new ideas evolved and a complete and comprehensive LP/IP formulations were developed in Chapter 4.

As mentioned in Chapter 1, the main objectives of the LP/IP programming model were to obtain the following subject to various constraints.

- (i) **Minimum overall earthmoving cost** and the corresponding, project duration, material distribution, borrow/disposal sites used, and plant utilisation from available teams.
- (ii) **Minimum project duration** and the corresponding, minimum overall earthmoving cost, material distribution, borrow/disposal sites used, and plant utilisation from available teams.
- (iii) **Minimum overall earthmoving cost to complete the project within the given project duration** and the corresponding, material distribution, borrow/disposal sites used, and plant utilisation from available teams.

The situations covered in Chapter 4 included:

- (i) same type of soil throughout the site and existing borrow/disposal sites;
- (ii) establishing new borrow/disposal sites;
- (iii) different degrees of compaction at various layers of the same fill and variation of soil strata at cut sections and borrow pits;
- (iv) equipment sharing among different teams; and
- (v) obstructions to material movement due to construction of structures along the roadway.

Clearly, the input to LP/IP stage is from the output of the simulation model together with other information obtained from project drawings and specifications. They include:

- (i) realistic minimum earthmoving cost corresponding to each plant team tested on each and every haulage operation (from simulation);
- (ii) cut quantities corresponding to different types of soil and fill quantities corresponding to different layers or degrees of compaction;
- (iii) capacity limitations of borrow pits and disposal sites;
- (iv) setting-up costs of new borrow/disposal sites;
- (v) project duration; and
- (vi) other constructional constraints.

Since the detailed formulations were developed in Chapter 4, it is not intended to reproduce them here and this section mainly explains the solution process of the LP/IP model and the software used.

8.4.1 Software used for LP/IP model solution

After successful formulation of LP/IP models, the next stage is to find an efficient solution method. The solution process of LP/IP models, however, is mechanical and is therefore best relegated to the computer. There are large number of linear, integer and quadratic programming packages available in the market thus there is no point in writing such a computer program from the scratch as in the simulation stage. For this research, a linear, integer and quadratic programming package called Hyper LINDO - (Linear INteractive Discrete Optimiser), was used and was selected for the following reasons.

- (i) Available for IBM personal computers and close compatibles so that the overall model can be developed and run on the same computer.
- (ii) Capability of solving problems with 2000 constraints and 4000 variables, 1000 of which can be integer variables enabling to handle large earthmoving projects.
- (iii) An interactive solution package so that the problem constraints, objectives and other conditions can be changed interactively during solution process.
- (iv) Has a command level structure rather than menu driven package so that it is comparatively easy to use and solve typical problems.
- (v) Has facilities for Fortran user interface and provides two styles for linking: user's code is the base and call LINDO as a subroutine and vice versa. This facility will be useful for future amalgamation of different stages.
- (vi) Comparatively cheap, good software support and recommended suitable by experts.

In addition, other useful features of LINDO are explained below under general description of LINDO.

8.4.2 General description of LINDO

LINDO is an interactive, linear, integer and quadratic programming package developed in standard Fortran and is designed to be useful to a wide range of applications. The guiding design philosophy is such that for simple problems there should not be a large set up cost to learn necessary features of LINDO. For example, if the user wishes to:

```

Maximise  $2x + 3y$ 
s.t
 $4x + 3y \leq 10$ 
 $3x + 5y \leq 12$ 

```

then this is exactly what the user has to type into LINDO. At the other extreme, LINDO has been used to solve real industrial linear, integer and quadratic problems of respectable size. There are different versions of LINDO developed for various Mainframe systems and large number of other personal computers. The version selected by the author is Hyper LINDO, the most capable version developed for IBM PS/2 computers. LINDO also has features for the mathematician interested in displays of the tableau and steps of Simplex method. It has been mainly developed for interactive computing but can also be run in batch mode. One other important feature of

LINDO is its modular design so that most LINDO features can be accessed via subroutine calls from non-LINDO software.

One of the most important features of any software is its ability to use inputs developed from other software or from other computers. For this LINDO is capable of handling problems formulated in standard MPS format. The MPS format is a widely accepted text file format commonly used in the industry and complete details are given in IBM manuals. LINDO also has features to interact with data management systems.

Needless to say, the sensitivity analysis, which tests the effects of various parameters on the optimal solution, is a very important feature in any of the LP/IP software package. LINDO has facilities to specify the allowable changes for objective function and right hand side coefficients in constraints without causing any changes to the basic solution.

Clearly as seen, typical earthwork optimisation formulations involve several integer variables. Two kinds of integer variables are recognised by LINDO: 0/1 (go/no-go) variables and general integer variables. The branch-and-bound solution method is used to arrive at solutions for integer programming problems. More details of LINDO can be obtained from the LINDO user manual (Schrage 1987). The application of LINDO for a typical earthwork optimisation problem is fully illustrated in Chapter 10.

8.5 Network Model

The final and the simplest stage of the RESOM model is to develop a method to represent the optimum solution obtained from the simulation and LP/IP stages as a construction schedule, so that the constructor can use it to monitor the progress of the project. In effect the output is a conventional network and a barchart representing the sequence of activities arranged to meet all the constraints observed in obtaining a solution to a particular earthwork problem. This process can be done either manually or using a network scheduling software package like Pertmaster (Pertmaster 1987). The choice is user subjective. It would be quite convenient to use a software package if the project is large and a detailed network analysis is required.

8.6 Summary

The development of RESOM (Roadwork Earthmoving System Optimisation Model) was fully explained in three major stages: simulation model building; LP/IP model; and network model. The first step of the development was to select an appropriate hardware and an IBM PS/2 with 1024kb RAM and 30Mb hard disk storage together with a colour monitor was adopted.

Simulation model building was systematically carried out separately for loader-truck operations and scraper-pusher operations providing important assumptions made, developing activity cycle diagrams, identifying important events and categorising them into 'B' and 'C' activities and describing appropriate three phase executives. The driving mechanism of the simulation was explained with a simple example. A brief description of the simulation model was provided with a conceptualised representation of the program structure and the simulation process was explained with various computer screen displays and model outputs.

Development of LP/IP model was not carried out in this chapter as it was fully developed in Chapter 4. Instead the software package used (LINDO) to solve the LP/IP formulation was described. Finally, the network model stage was briefly described providing the main objectives and available solution methods.

CHAPTER NINE

VERIFICATION AND VALIDATION OF 'RESOM'

9.1 Introduction

9.2 Verification of RESOM

9.3 Model Validation

9.3.1 Case Study 1 - Anamaduwa Gam Udawa site (second visit)

9.3.1.1 Description of the project

9.3.1.2 Validation of input distributions

9.3.1.3 Validation of simulated production

9.3.2 Case Study 2 - A42 Measham and Ashby By-pass

9.3.2.1 Description of the project

9.3.2.2 Validation of simulated production with a realistic estimation method

9.3.2.3 Comparison of simulated results with traditional estimates

9.3.3 Evaluation of RESOM by model examination

9.3.3.1 Examination of simulation model

9.3.3.2 Examination of LP/IP model

9.4 Summary

9.1 Introduction

Clearly, a model must be tested and evaluated to ensure that it is reliable, error free, and has credibility with those who are to use it. Model evaluation thus aims to develop an acceptable level of confidence, that inferences drawn from the performances of the model are correct and applicable to the real world system being studied. According to Fishman and Kiviat (1967) this evaluation process can be carried out in three basic stages : *verification*, to ensure that the model behaves as the experimenter intends; *validation*, to test the agreement between the behaviours of the model and that of the real system; and *problem analysis* which deals with analysis and interpretation of the data generated by the experiments.

This chapter systematically evaluates the RESOM developed in the previous chapter, firstly, by describing the verification process, and secondly, by validating the model using two actual case studies, expert examination, relevant theory and past research.

9.2 Verification of RESOM

Verification is the task associated with checking the model and the associated computer programs to ascertain that they perform as intended. Essentially, this process should be done from the beginning of the model development right upto the final product.

The most difficult part of verification occurred during the simulation modelling stage which involved development of activity cycle diagrams, corresponding event routines, random variate generation, debugging, input output checking and considerable amount of programming.

From the beginning of the simulation model development, all possible steps were taken to ascertain that each of the model routines performed as expected. This was achieved by adopting the top down model building approach in which the programmer provides the overall structure and then fills in the details (Helman 1986, Davies 1989). The steps adopted by the author during the simulation model development were as follows.

- (i) Produced activity cycle diagrams separately for scraper-pusher and loader-truck operations, after carefully identifying various entities, attributes, interactions etc.
- (ii) Drew flow diagrams for each of the activity routines and compared them for correct interactions.

- (iii) Coded the activity routines, the executive, and the initialisation routines as simple as possible, using constants rather than variables and using simple distributions such as normal where necessary. More complex matching and scheduling were not considered at this stage and the emphasis was to develop a working program.
- (iv) Tested the running model with different sets of input values and made sure that the output was sensible.
- (v) Modified the programs so that the decision variables can be read in from the keyboard and checked that it produced the same results as earlier.
- (vi) Changed the simulation to sample from appropriate distributions developed in Chapter 7 and repeated steps (iv) and (v).
- (vii) Introduced more complicated logical processes and entity characteristics one at a time and tested at each stage. These were coded as separate procedures so that, they could be tested and verified separately. For example, different loading methods, types of scrapers, loaders, trucks, site conditions etc. were introduced at this stage.
- (viii) Created equipment specification libraries, improved file handling facilities and tested at each stage for correctness.
- (ix) Incorporated other management aspects like variable shift times, official breaks and the model was subsequently tested.
- (x) Incorporated user options like printed output intervals, simulation speed etc. and tested for correctness.
- (xi) Incorporated facilities for increased visual impact.
- (xii) Included interaction facilities to change simulating conditions, plant teams etc.
- (xiii) After developing the full simulation model ran it using a wide range of different data in order to detect more elusive errors.

As expected, a large number of logical errors were detected this way, and each time an error was rectified the model was rerun for all the possible input values to make sure that the change did not cause any bugs in other parts of the program. Furthermore, error checking statements were included into the program to print in detail how the model was running thereby enabling to check manually whether the program behaved as expected.

Clearly, random variates generated by random variate generators were also verified. In this case, since the appropriate algorithms were obtained from relevant theory (Hastings 1975) the verification was only necessary to make sure that the generated values were from a population with given probability distribution having given input parameters. To this end, a stream of random variates was generated for each different type of

distributions, and the generated values were subsequently used to re-evaluate input parameters using a statistical package called Statgraphics run on IBM PS/2 (Statgraphics 1986). These parameters were then compared with those originally used and made sure that they are almost the same.

The above described are the basic steps adopted for model verification but the actual verification process was quite lengthy and verbose if explained in full. However, from the commencement of the model development to the final product the author made sure that the model behaved as intended.

9.3 Model Validation

Validation is the process of assessing the model results rather than the program logic to check whether the model behaves, in important respects, like the real system. If it does not, even after the model is properly verified, the modeller is faced with a problem. He has to go back to:

- (i) the logic of the model structure and review assumptions; and
- (ii) the data collection and analysis to ensure that there are no errors or hidden assumptions.

This process is cyclic and must be carried out until the model has been properly validated. The problem now is to develop method of systematically validating the model.

There are several methods available to validate a model. Two important methods as described by Hillier (1974) are:

- (i) have a knowledgeable person or persons carefully check the credibility of the output data for a variety of real life situations; and
- (ii) conduct a field test to collect some real data to compare with the output of the simulation.

In addition to demonstrations to experts, data collected from two construction sites (one in Sri Lanka and the other in the UK) which were not used during the model development were utilised for model validation and the detail process is described in the following sections.

9.3.1 Case Study 1 - Anamaduwa Gam Udawa site (second visit)

9.3.1.1 Description of the project

The project involved the construction of a road network of about 20 km in length at Anamaduwa, a town in the North Western Province of Sri Lanka. The contract value was approximately Rs. 30 million (£0.5 million). The construction was carried out by the Road Construction and Development Company, the largest road contractor in Sri Lanka. The project basically consisted of about 1.2 million cubic metres of embankment filling by borrowing suitable material from nearby borrow pits specially constructed for this project. At the time of data collection gravelly common earth was being borrowed from 'Naikkulama gravel pit' to three different destinations located approximately about 8 km from the borrow pit. Payments for hauling units were based on the quantity of material moved and due to the urgency of the job the work was carried out both during day and night. The data collected consisted of cycle element times of earthmoving equipment, total equipment utilisation, production achieved, delays caused, causes of delays and were collected by six observers for a period of seven days as described earlier in Chapter 6. The equipment used varied slightly from day to day and those used during the study period are shown in Table 9.1.

Table 9.1 - Equipment used during the study : case study 1 - Anamaduwa Gam Udawa site

Day (1)	Equipment used * (2)
1	Int.wl (1.7m ³)+10@Nissan DT (5@10T,3@12T,2@17T)
2	Int.wl (3.1m ³)+8@Nissan DT (5@10T,12T,17T,30T)
3	Int.wl (3.1m ³)+12@Nissan DT (5@10T,3@12T,2@17T,2@30T)
4	Int.wl (3.1m ³)+9@Nissan DT (4@10T,3@12T,2@17T)
5	Int.wl (3.1m ³)+11@Nissan DT (6@10T,4@12T,17T)
6	Int.wl (3.1m ³)+10@Nissan DT (5@10T,3@12T,2@17T)
7	Int.wl (3.1m ³)+10@NissanDT (4@10T,2@12T,2@12T,2@30T)

* Provide the type and the capacity of the loader and the total number of dump trucks. The break down of trucks with their tonnages are given within brackets. Int.wl represents International wheel loader.

9.3.1.2 Validation of input distributions

In Chapter 7, various probability distributions were developed after identifying the most important factors affecting different cycle element times of earthmoving equipment and categorising them into various treatment levels. Later, these distributions were used as input to simulation model. As seen, these distributions were developed from field data based on several construction projects. However, it is necessary to identify that these distributions are representative to any other construction site having comparable operating conditions. The following section attempts to achieve this by using data collected at Anamaduwa Gam Udawa site.

Procedure adopted for input distribution validation

Clearly, the basic principle in validating input distributions is the comparison of the model generated cycle element times with those actually observed. If it can be proved statistically that these two samples are from a single population then it can be said that the developed probability distributions are closely representative to any other projects with similar operating conditions.

The MINITAB statistical package (Ryan 1985) used for the data analysis was again the ideal choice for the purpose. The techniques adopted were:

- (i) dotplots;
- (ii) histograms;
- (iii) other plots;
- (iv) Mann-Whitney test; and
- (v) Confidence interval and paired-t test.

Since the fitted distributions except those for hauling and returning times were non normal, the standard procedures used to compare two samples such as *two sample-t* test (which is based on the normality assumption) are not properly applicable. The *Mann-Whitney* test is a nonparametric procedure (which does not require normality) for comparing two populations. The test examines the null hypothesis that the medians of the two populations are equal with the alternative hypothesis that one population is shifted from the other. The *paired-t* test is a parametric test used to compare matched samples from normal populations and in this case it is applied to hauling and returning times.

As in the data analysis the first step was to calculate the appropriate cycle element times and to transfer them to a MINITAB worksheet. Subsequently, cycle element times

generated from developed distributions were also transferred to the same worksheet for further analysis using the above techniques.

Validation of positioning delay time, hauling delay, returning delay and dump and turn time generators

Due to the similarity of statistical analysis validation of the above four elements is collectively explained. Out of the four elements only *positioning delay* had two operating levels applicable to Anamaduwa Gam Udawa site: no queue at cut with average operational factor; and queue exists at cut with average operational factor (see Table 7.9). Therefore, they were separately tested. Although the dump and turn times can take four operating levels (Table 7.9) the observed data fell into only one category with good site condition with truck size 1 and 2. After various plots drawn for visual examination the *Mann-Whitney* test was applied to each pair of the above four elements and found that there is sufficient evidence to infer statistically that the generated cycle element times and those observed are from a single population. In effect, this means that the developed distributions can be successfully used in generating cycle element times during simulation. The test results are summarised in Table 9.2.

Table 9.2 - Validation results of non normal element time generators applied to case study 1 : Anamaduwa Gam Udawa site

Cycle element (1)	Generator (2)	Plot results (3)	Mann-Whitney test at 95% CI (4)
1. Positioning delay with no queue	10+W(0.4,7.0,S)	satisfactory	satisfactory
2. Positioning delay when queue exists	20+W(0.5,14.3,S)	satisfactory	satisfactory
3. Dump & turn	8+W(1.9,28.5,S)	satisfactory	satisfactory
4. Hauling delay	0+W(0.4,9.2,S)	satisfactory	nearly failed
5. Returning delay	0+W(0.6,63.0,S)	satisfactory	nearly failed

Validation of hauling and returning time generators

The approach adopted in this case is different to the above for two major reasons. Firstly, hauling and returning time distributions can be taken as normally distributed.

Secondly, there is a close relationship between each pair of generated and observed times since they correspond to a particular truck and a haul distance. Therefore, by considering these sets as paired data, *tinterval* and *paired-t* tests were carried out in addition to examination of various plots. The *tinterval* test provides a 95% confidence interval for the difference between two sample medians whilst the *paired-t* test examines the null hypothesis that the average difference between the generated and observed data in the population is zero. Although these two tests nearly failed for the hauling and returning times, the plots provided sufficient evidence to consider that the appropriate samples come from similar populations.

Furthermore, the 95% prediction intervals of appropriate predictors were plotted superimposed with observed data in order to test the closeness of the two samples. These graphs clearly showed that most observed data fall within the 95% prediction band derived according to the following equation.

$$44.8 + 0.139 \times \text{haul distance} \pm 1.96(137.8) \quad [\text{Neter 1988}]$$

where $44.8 + 0.139 \times \text{haul distance}$ = mean of the fitted hauling time generator (sec.);
 137.8 = standard deviation about the fitted regression line (sec.); and
 1.96 = value of standard normal statistic corresponding to 95%.

Clearly, the above validation incorporated only some cycle element time generators corresponding to operating levels encountered at Anamaduwa Gam Udawa site. However, the author believes that the other generators, although not validated by actual data can be successfully used as input to simulation model for most projects. Situations where extreme project conditions exist more accurate distributions under those circumstances are recommended.

9.3.1.3 Validation of simulated production

Essentially, the validation carried out in the previous section was only sufficient to conclude that the input distributions or cycle element time generators used in the simulation model are valid for simulation input. But, it does not provide sufficient evidence to infer that the simulated output obtained for a particular haulage operation is comparable to what actually achieved. This is essential if the simulation model is to be used in planning and estimating real jobs. This section attempts to achieve this using the production data collected from the Anamaduwa Gam Udawa site.

Procedure adopted for simulation production validation

As in the previous case, the basic requirement is to statistically compare the simulated results with those actually observed. There are seven actual production values observed during seven days of data collection together with the teams used, operating conditions and other special occurrences. To compare with simulated results each of these operating days should be simulated using the same teams under same operating conditions. Clearly, several replications are required for each day to obtain a reliable mean simulated production. Planning of the required sample size is always preferable if the user would like to have an estimate with a certain precision at a certain confidence level. The number of replications required can be calculated in advance using the following formula (Neter 1988) if the required accuracy is known.

$$n = \frac{z^2 \sigma^2}{h^2}$$

where n = required sample size;

h = desired half width;

z = $z(1 - \alpha/2)$ - standard normal statistic with confidence coefficient of $1 - \alpha$;

σ = planning value of the population standard deviation.

Suppose that it is desired to have an interval estimate of the mean simulated production for one day operation within $\pm 20\text{m}^3$ with a confidence level of 95%. The 20m^3 accuracy was thought to be sufficient for one day production. The planning value of the population standard deviation (σ) is unknown but can be obtained from a pilot study (Neter 1988). A sample of 20 simulation replications for a particular haulage operation revealed that an estimate for σ is 47m^3 .

Therefore, for the problem at hand;

$$h = 20$$

$$z = z(1 - 0.05/2) = 1.96 \text{ (from tables of standard Normal distribution)}$$

$$\sigma = 47$$

Substituting these values to the above equation it was found that 22 replications are required to achieve the desired accuracy.

Consequently, 22 replications were performed for each observed day to obtain a sample of seven mean simulated productions and both samples (observed and simulated) were then converted to production achieved during an eight hour working day for comparison purposes. However, the two samples cannot be considered independent

since the plant teams used on different days are not identical. Hence the comparison was done using the confidence interval and the *paired-t* test applicable to matched samples (Neter 1988). The testing process and the results obtained are described below.

Comparison of actual and the simulated production

The average simulated production obtained from 22 replications and the 95% confidence interval for the simulated mean are shown in columns 2 and 3 of Table 9.3. The variation of these confidence intervals from the planned value (± 20) is due to different standard deviations observed on different days and conversion of production to eight hour basic unit. The observed production is shown in column 4 and the production differences are provided in column 5.

The first step of any sample comparison is usually the visual examination of their closeness. To this end, the actual and simulated production rates were plotted on the same graph and is shown in Figure 9.1. The graph shows a reasonably good fit but indicates the requirement of further analysis. Since the sample size in this case is comparatively small, the necessary statistical tests can be done manually as shown below and was preferred to explain the underlying principle.

Table 9.3 - Observed and simulated production : case study 1 - Anamaduwa Gam Udawa site

Observation (1)	Average sim. production $m^3/8hr$ (X_i) (2)	95% CI for simulated production $m^3/8hr$ (3)	Observed production $m^3/8hr$ (Y_i) (4)	Production differ. $m^3/8hr$ ($D_i = X_i - Y_i$) (5)
1	719	705 -- 734	702	17
2	666	652 -- 679	675	-9
3	1077	1050 -- 1103	1190	-113
4	732	729 -- 734	814	-82
5	543	489 -- 596	600	-57
6	696	663 -- 729	745	-49
7	994	977 -- 1012	922	72

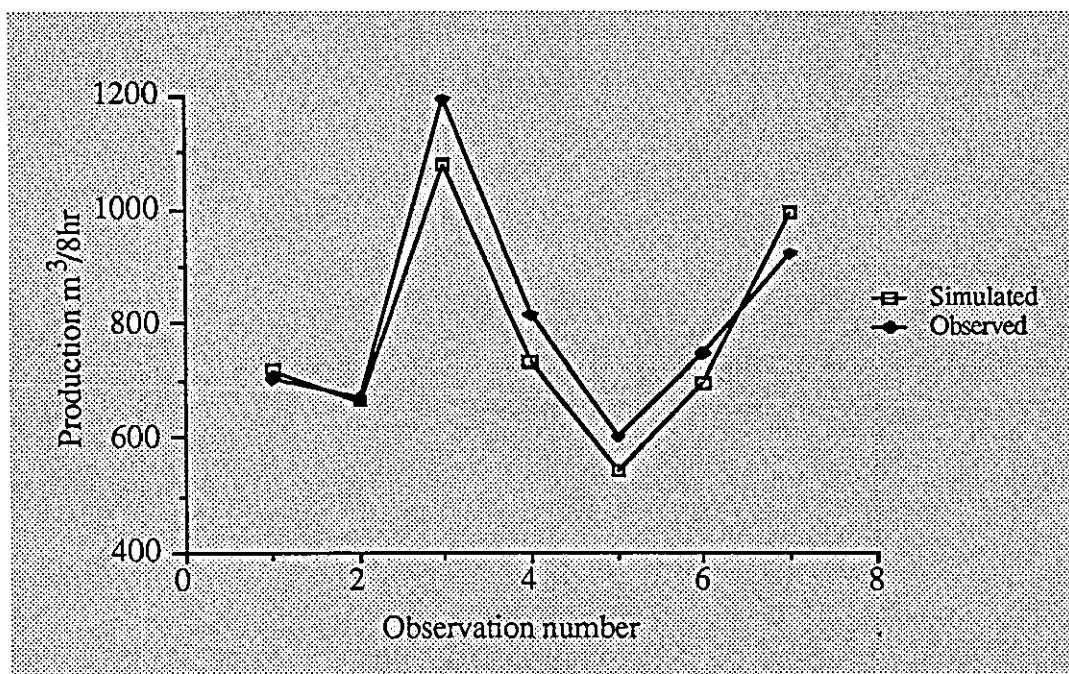


Figure 9.1- Graphs of simulated and observed production : case study 1 - Anamaduwa Gam Udawa site

(a) Confidence interval for the mean production difference

The confidence limits for the difference in means with a confidence coefficient of $1-\alpha$ can be expressed as;

$$\bar{D} \pm t S\{\bar{D}\} \quad [\text{Neter 1988}]$$

where \bar{D} = the mean of sample differences;

$t = t(1-\alpha/2; n-1)$, t statistic from standard t distribution with $n-1$ degrees of freedom; n = sample size; and

$S\{\bar{D}\}$ = standard deviation of \bar{D} .

$$\begin{aligned} \text{From Table 9.3 } \bar{D} &= -31.57 \text{ m}^3/8\text{hr} \\ S\{\bar{D}\} &= 23.76 \text{ m}^3/8\text{hr} \end{aligned}$$

t statistic for 95% confidence interval $t = t(0.975; 6) = 2.447$ (from standard t distribution tables)

Therefore, the confidence interval for the mean production difference

$$\begin{aligned} &= -31.72 \pm 2.447(23.76) \\ &= -90.33 \text{ -- } +26.65 \text{ m}^3/8\text{hr}. \end{aligned}$$

From the above analysis, one may suspect that the simulation production is slightly less than the actual production. The reason probably is the higher cycle element times and

delay times generated from theoretical distributions outside the range of values actually observed. However, the mean difference -31.6 m³ per eight hours is comparatively very small. Furthermore, the zero mean production difference is well within the 95% confidence interval. This evidence is sufficient for a statistician to infer that there is no difference between the sample means. However, to ascertain the fact a further statistical test is desirable.

(b) Paired-t test for two sample means

The comparison of two sample means can be achieved by the following hypothesis test.

$$\text{Null hypothesis} \quad H_0 : \bar{X} - \bar{Y} = 0$$

$$\text{Alternative hypothesis} \quad H_1 : \bar{X} - \bar{Y} \neq 0$$

where \bar{X} = mean simulated production; and
 \bar{Y} = mean observed production.

Assuming the production differences are normally distributed or not significantly deviated from normality, the test concerning the mean difference when the two samples are small and are matched is based on the following standardized test statistic:

$$t^* = \frac{\bar{D} - 0}{S\{\bar{D}\}} \quad [\text{Neter 1988}]$$

where \bar{D} and $S\{\bar{D}\}$ are as defined earlier;
 α risk is controlled at $\bar{X} - \bar{Y} = 0$; and
 when $\bar{X} - \bar{Y} = 0$, t^* follows the t distribution with n-1 degrees of freedom.

The appropriate decision value is based on the t distribution. Assuming the α risk is to be controlled at 0.05 (95% confidence) when mean difference is zero, the decision value corresponding to two-sided hypothesis test is $t(0.975; 6) = 2.447$.

$$\text{The test statistic } t^* = \frac{31.57}{23.76} = 1.33$$

Since $t^* < 2.447$, the null hypothesis is satisfactory.

Therefore, with 95% confidence it can be concluded that there is no difference between the means of simulated and actual production.

9.3.2 Case Study 2 - A42 Measham and Ashby By-pass

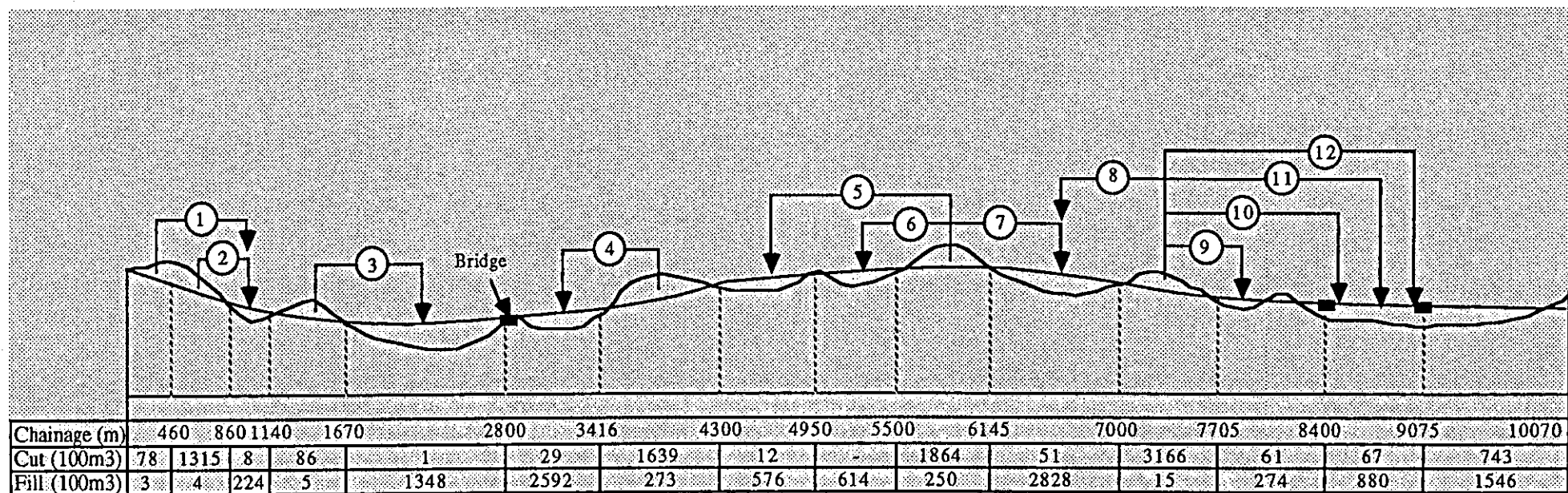
9.3.2.1 Description of the project

The project consisted the construction of approximately 10 km long, three lane concrete highway connecting the M1 and M42 Motorways in the Midlands region of the UK. The grade along the haul road was approximately within $\pm 15\%$ and the earthwork involved almost 5 million cubic metres of common earth and rock with major movements between cut and fill sections.

The road profile, cut/fill quantities together with the major haulage operations are shown in Figure 9.2. Table 9.4 shows the details of those major haulage operations including the plant teams used by the contractor, to be used in validating the simulation model.

Table 9.4 - Details of major haulage operations : case study 2 - A42 Measham and Ashby By-pass

Haulage operation (1)	Haul distance (m) (2)	Quantity involved (m ³) (3)	Plant team used (4)
1	905	7565	Cat 235+4@Moxys
2	475	14001	D8N+4@Cat 631 Scrapers
3	695	8111	D8N+4@Cat 631 Scrapers
4	750	136552	D8N+4@Cat 631 Scrapers
5	1197	51422	Cat 245+3@Cat 769 Trucks
6	597	56421	D8N+4@Cat 631 Scrapers
7	750	5592	Cat 245+3@Cat 769 Trucks
8	780	237242	D8N+5@Cat 631 Scrapers
9	700	15661	D8N+5@Cat 631 Scrapers
10	1048	21901	Cat 245+3@Cat 769 Trucks
11	1385	15661	Cat 245+4@Cat 769 Trucks
12	1723	24638	Cat 245+4@Cat 769 Trucks



Note - Tag attached to each arrow indicates the haulage operation number

Figure 9.2 - Road profile, cut/fill quantities and major haulage operations : case study 2 - A42 Measham and Ashby By-pass

9.3.2.2 Validation of simulated production with a realistic estimating method

The previous case study proved that the model predicted results are quite similar to those observed on site. As seen, it involved observation of one haulage operation (can be considered as one) with approximately the same plant team. But how about the situations where large number of hauling operations having different haul distances and equipment configurations are involved? Can the simulated model still provide realistic production? This section attempts to answer these questions by comparing simulated results with those obtained from a realistic estimating method applied to A42 Measham and Ashby By-pass.

Realistic estimating method

The method adopted was that used by Alkass (1988) in his expert system ESEMPS developed for earthmoving operations and equipment selection. It follows the traditional deterministic method but with modified cycle element times to incorporate real life problems. Fixed times (cycle elements except travel time) are taken from manufacturers' performance books (Caterpillar 1987) with an added allowance of one minute to avoid any unexpected delays. Travel times are obtained from graphs developed using observed data from A42 highway and also from previous workstudy undertaken at Loughborough University (Harris 1985). In developing these graphs Alkass has limited travelling speeds to 19 km/hr when the travel distance is less than 3.2 km and 24 km/hr otherwise.

Comparison of estimated (realistic) and simulated production

The above described estimating procedure was first applied for each haulage operations given in Table 9.4 and the production rates obtained are presented in column 2 of Table 9.5. A specimen calculation and the associated travel time charts used are provided in the Appendix F. Similar to the previous case study, each haulage operation was then simulated 22 times and the resulted mean production rates and the 95% confidence intervals are shown in columns 3 and 4 of Table 9.5. The graph shown in Figure 9.3 depicts the similarity of simulated and estimated production.

Confidence interval and paired-t test for two sample means

By adopting the same procedure as in the previous case a confidence interval for the mean production difference was calculated. It was found that with 95% confidence the mean difference between the estimated(realistic) and the simulated production should be within $-28.9 \text{ -- } +3.3 \text{ m}^3/\text{hr}$.

The *paired-t* test also showed that the null hypothesis that there is no difference between two means cannot be rejected with 95% confidence limit. Therefore, it can be further concluded that the simulation model can be used to obtain realistic estimates for most practical applications.

Table 9.5 - Simulated and estimated (realistic) production : case study 2 - A42 Measham and Ashby By-pass

Haulage operation (1)	Estimated (realistic) production m ³ /hr (X _i) (2)	Average sim. production m ³ /hr (Y _i) (3)	95% CI for simulated average production m ³ /hr (4)
1	213	230	222 -- 239
2	715	716	706 -- 726
3	645	685	672 -- 697
4	667	685	676 -- 694
5	199	217	212 -- 223
6	645	702	692 -- 712
7	269	269	259 -- 278
8	734	725	715 -- 735
9	780	825	820 -- 829
10	269	236	229 -- 243
11	269	274	267 -- 281
12	257	252	245 -- 260

9.3.2.3 Comparison of simulated results with traditional estimates

Production corresponding to each of the above haulage operations was again estimated using the traditional deterministic methods explained in Caterpillar Performance Handbook (Caterpillar 1987) and the results obtained are shown in column 2 of Table 9.6. Column 3 lists the mean simulated results developed earlier whereas column 4 represents the type of plant team used (T indicates a loader-truck team and S indicates a scraper-pusher team).

Confidence interval and the paired-t test for two sample means

The same procedure was adopted as earlier and found that with 95% confidence, the mean difference between the estimated and simulated production should be within $+18.28$ -- $+75.1$ m³/hr. Since this interval does not include zero it can be said that the production rates obtained by traditional deterministic methods are greater than that of simulated production. This fact was further confirmed by a *paired-t* test indicating that the alternative hypothesis that there is a difference between two means cannot be rejected with 95% confidence limit. This is clearly seen in the graph shown in Figure 9.3.

Table 9.6 - Estimated (caterpillar performance book) and simulated production: case study 2 - A42 Measham and Ashby By-pass

Haulage operation	Estimated (CPB) production m ³ /hr (X _i)	Average sim. production m ³ /hr (Y _i)	Team type
(1)	(2)	(3)	(4)
1	240	230	T
2	837	716	S
3	728	685	S
4	721	685	S
5	269	217	T
6	742	702	S
7	269	269	T
8	862	725	S
9	901	825	S
10	269	236	T
11	269	274	T
12	269	252	T

Having validated the simulated results with actual production, in effect, it can be confirmed that the traditional deterministic production always overestimates reality. However, there are some important aspects to be noted in Table 9.6. It is clearly seen that the deterministic production rates for scraper-pusher operations are well above the simulated production rates but the differences are comparatively small for loader-truck operations. The main reason for the reduced production for loader-truck operations

was the limitation of the team production by the loader output. The truck production in all the above cases was considerably higher than the rated loader production. This leads to conclude that for loader-truck operations the production obtained by traditional deterministic methods considerably closely represents reality if the production is governed by the loading unit.

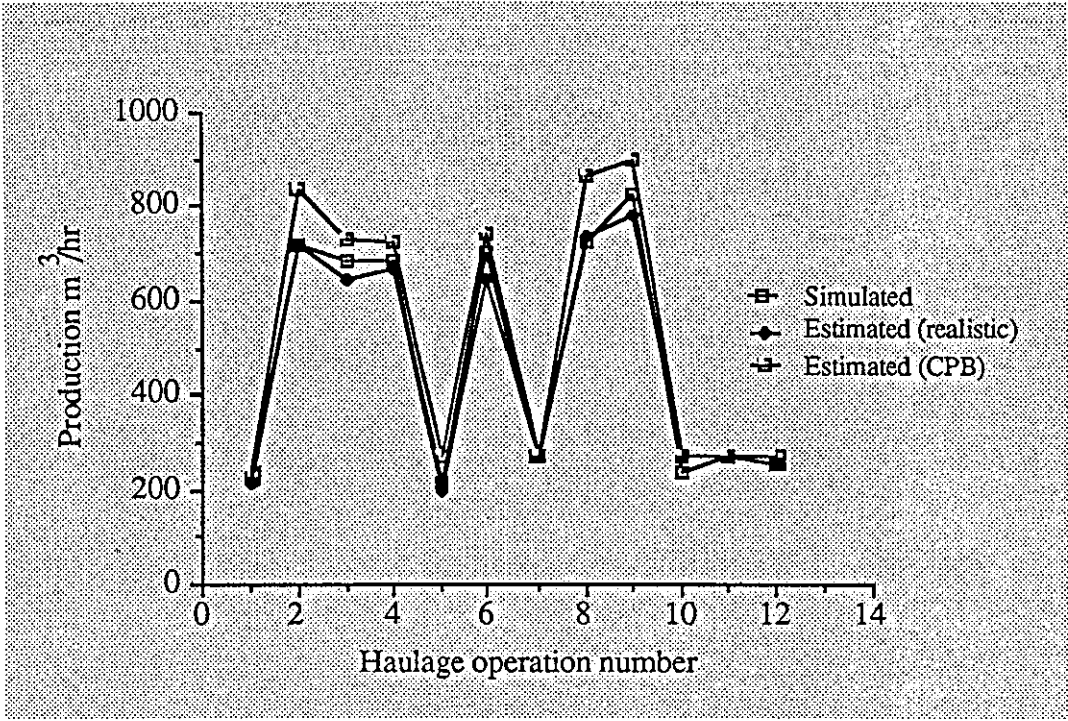


Figure 9.3 - Graphs of estimated(realistic), simulated and estimated (CPB) production : case study 2 - A42 Measham and Ashby By-pass

9.3.3 Evaluation of RESOM by model examination

Although the simulation part of the RESOM was validated by applying to actual projects, the critical examination of model outputs, how the model is run and also the LP/IP formulations cannot be underestimated as an alternative way of validation. The following sections explain how this was achieved both for simulation and LP/IP models.

9.3.3.1 Examination of simulation model

The simulation model was demonstrated to number of novices and experts including post-graduate students, fellow researchers and experienced earthmoving engineers. According to experts' comments the following conclusions can be made on the performance of the simulation model.

- (i) Simulated production times, idle times and delay times corresponding to both the entire team and individual equipment items seem to represent the actual behaviour according to input provided.
- (ii) Simulated output queue time histograms, queue length histograms and idle time histograms also seem to provide a sensible picture of reality and are helpful in identifying the behaviour of the team.
- (iii) Careful examination of the dynamic simulation display shows the entity status of each piece of equipment and how they are changed with time. The changing behaviour also seems realistic.
- (iv) The interaction facility is quite helpful in obtaining a balanced plant team by adding, deleting or replacing various equipment items.
- (v) An improved user interface and inclusion of graphical displays would be an added advantage in using the model by other users.

9.3.3.2 Examination of LP/IP model

The LP/IP formulations developed in Chapter 4 were critically examined by two operational research experts at Loughborough University and confirmed that they represent interesting and correct formulations. Similar comments were made by two other experts in the United States in reviewing one of the author's papers (Jayawardane 1990). The validity of the results obtained by applying this LP/IP model to a typical earthmoving problem is illustrated elsewhere (Jayawardane 1990). Further validation of LP/IP model and associated results is carried out in the next chapter during experimentation, application and further validation of RESOM by applying the entire model to another actual project and comparing the model predicted results with those of the contractors.

9.4 Summary

Model verification process was carried out throughout the model development and the steps adopted by the author were briefly explained. Model validation, was performed in detail using two actual case studies, expert examination, relevant theory and past research. Data collected from Anamaduwa Gam Udawa site (Sri Lanka) were used to validate the various cycle element time generators and established their validity as input to simulation model. Comparison of simulated and observed production of the same site showed no significant difference indicating the validity of the simulation model as a predictor. Simulated production was also compared with that obtained by a realistic estimating method using data collected at A42 Measham and Ashby By-pass (UK) and proved that the simulation model is still valid in situations where different haul distances and equipment configurations are involved. Comparison of simulated production with that obtained by traditional deterministic methods explained in Caterpillar Performance Book (Caterpillar 1987) showed that the traditional methods always over-estimate actual production. However, in loader-truck operations the traditional estimates are close to reality if the team production is governed by the loading unit.

Furthermore, demonstrations of the simulation model to various people also confirmed the correctness of the model. The LP/IP formulations were thoroughly examined by two operational researchers in the UK and two more in the USA confirming their soundness. Further validation of LP/IP model, in particular its application and output, is performed in the next chapter during application, experimentation and further validation with RESOM.

CHAPTER TEN

APPLICATION, EXPERIMENTATION AND FURTHER VALIDATION

10.1 Introduction

10.2 Application and Experimentation with RESOM Applied to Case Study 3 - M40 Banbury By-pass

10.2.1 Application and experimentation with the simulation model

10.2.1.1 Application of the simulation model : stage one of RESOM

10.2.1.2 Experimentation with the simulation model

10.2.2 Application of LP/IP model and comparison with contractor's method

10.2.2.1 Application of LP/IP model : stage two of RESOM

10.2.2.2 Comparison of RESOM solution with contractor's estimate

10.3 Advance Use of RESOM

10.3.1 Formulation of case study 4

10.3.2 The cheapest solution with available plant for timely project completion

10.3.3 The cheapest solution with available plant

10.3.4 The shortest completion time with available plant

10.4 Sensitivity Analysis

10.4.1 Effect of variation of road sectional interval

10.4.2 Effect of variation in plant team selection

10.5 Summary

10.1 Introduction

The difficult part of the modelling process is over when the model has been properly developed and successfully validated. Clearly, the two case studies applied in the previous chapter together with expert examination, and the like, proved the validity of RESOM. The remainder of the modelling process is the interesting part and involves application and experimentation. Further validation can also be achieved as a by-product of this process.

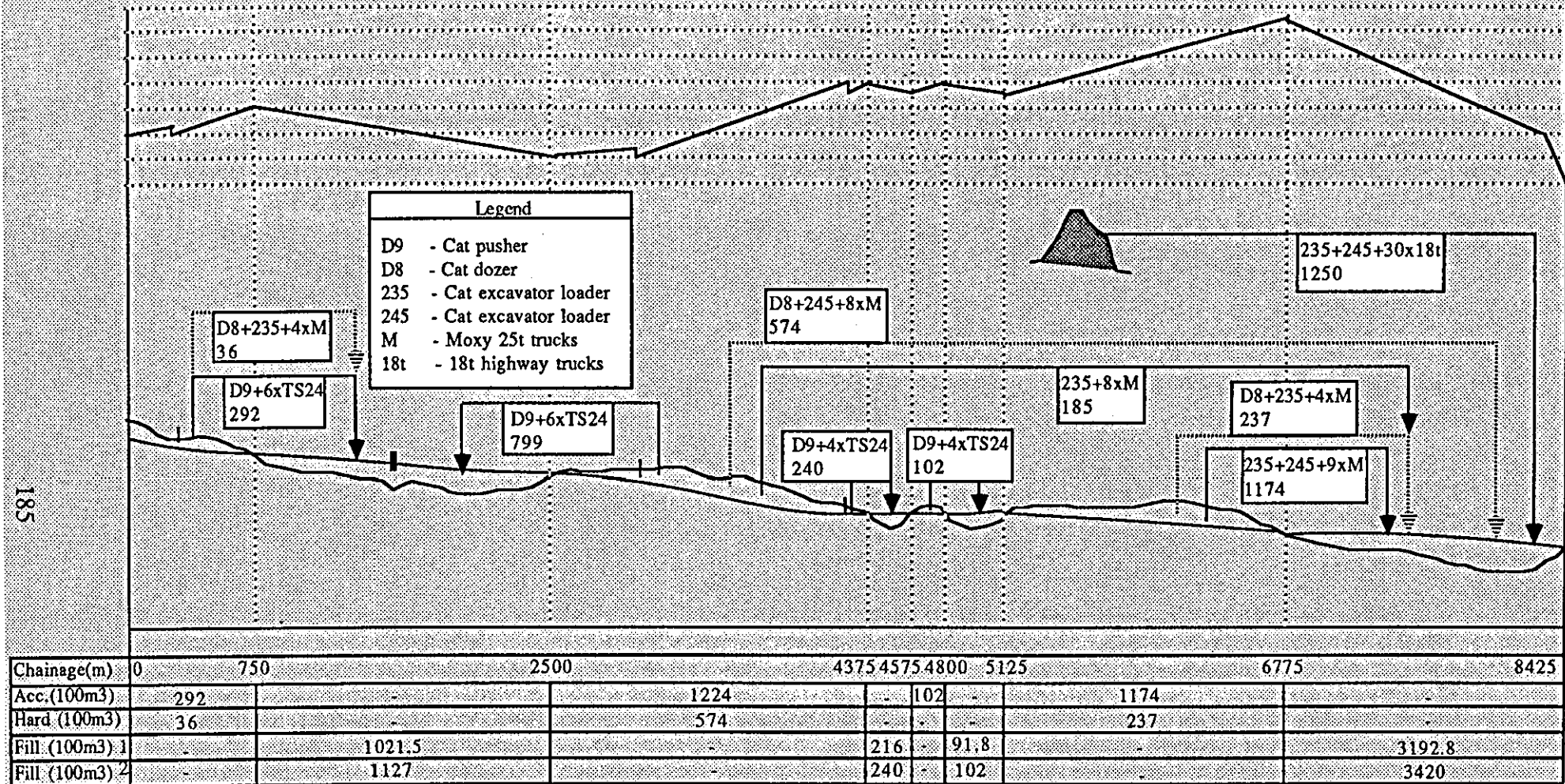
This chapter is intended to systematically apply and experiment with the RESOM model. RESOM is applied step-by-step to an actual case study and tested at each stage. In addition, the advanced features of RESOM are explained by applying the model to a hypothetical case study. Finally, the sensitivity analysis of RESOM is also illustrated.

10.2 Application and Experimentation with RESOM Applied to Case Study 3 - M40 Banbury By-pass

The case study used was the construction of 8.4 km long highway connecting Wendlebury and Ardley, two cities of Oxfordshire in the UK. The project involved about 670000 m³ excavation, 100000 m³ of imported fill and the estimated project cost was about £25 million. It also involved the construction of eight reinforced concrete bridges with side roads to motorways and the estimated total project duration was 104 weeks. The contractor who gave the project data had lost the tender but provided a detailed estimate and a plan for constructing the job. Being a tendering stage estimate and a plan, this project was an ideal choice for application and experimentation with RESOM. A profile view of the road, estimated material distribution together with the associated Mass-haul diagram used by the contractor are shown in Figure 10.1.

10.2.1 Application and experimentation with the simulation model

As seen in Chapter 4, the first stage of RESOM is the application of simulation model which basically involves determination of realistic unit cost and production for each feasible haulage operation. Application of simulation model is not complete without experimenting with the model to find out well balanced plant teams. The following sections describe these two processes using the aforementioned case study.



1 - Actual fill quantity measured from drawings

2 - Adjusted fill after swell/shrinkage (shrinkage for common earth = 0.9, for limestone = 1.1)

Note - Cut quantities have been calculated after any fill in the same section. The label attached to each haulage operation represents the plant team used and the associated quantity. Dotted and solid lines represent operations for rock and common earth respectively.

Figure 10.1 - Road profile, Mass-haul diagram and the contractor's planning schedule : case study 3 - M40 Banbury By-pass (not to scale)

10.2.1.1 Application of the simulation model : stage one of RESOM

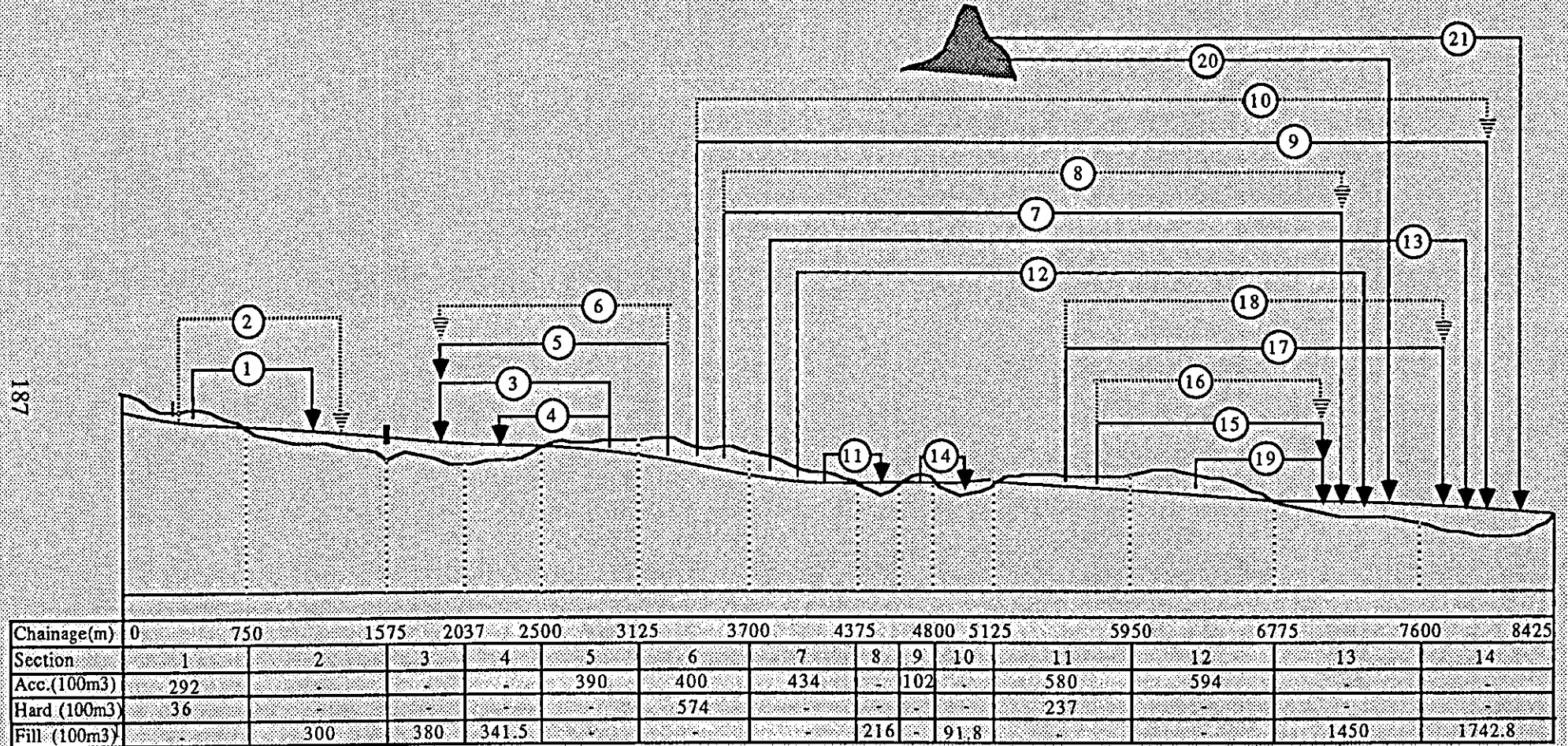
Given the earthmoving problem, the application of simulation model basically comprises the following steps.

Step 1 : Using project drawings, divide the road profile into appropriate intervals to be used as the basis in planning the job. These intervals may or may not be the same but unequal intervals may be preferable so that the division lines can be taken through the changing points from cut to fill or vice versa. Those intervals taken for the case study 3 are shown in Figure 10.2.

Step 2 : Using the cross sectional and longitudinal sectional drawings, calculate the quantities involved in each roadway section treating separately, different strata (material types) in cut sections and different layers (subgrade, subbase, sidefill etc.) in fill sections. Those corresponding to the problem at hand are also shown in Figure 10.2.

Step 3 : Find out the locations of available borrow pits and disposal sites. If new sites are to be established, decide on possible locations and calculate setting up costs. There was only one borrow pit available for this problem and was located about 6 km away from the last embankment. Excess material in this case could be disposed of at road sides.

Step 4 : Decide on all feasible haulage operations (These include all material movements between cut and fill sections, cut sections to disposal sites and borrow pits to fill sections, which would probably be in the optimum solution) together with appropriate plant team or teams to be tested on each such haulage (optimum operations will be decided by LP/IP model and the plant teams can be balanced by simulation model). The feasible haulage operations decided on this case study are also shown in Figure 10.2 and the details of each such haulage operation are given in Table 10.1. The plant teams shown in Table 10.1 are balanced teams for each operation (The model user may not start with balanced teams but can be balanced using the simulation model as explained in the next section). Any number of plant teams can be tested on each haulage operation but as for demonstration purposes this was limited to one in the case study. The plant items used were almost similar to those used by the contractor and was so decided for comparison purposes.



1 - Actual fill quantity measured from drawings

Note - Tag attached to each arrow indicates the haulage operation number

Figure 10.2 - Possible haulage operations to be tested by RESOM : case study 3 - M40 Banbury By-pass (not to scale)

*Table 10.1 - Details of possible haulage operations and balanced plant teams :
case study 3 - M40 Banbury By-pass*

Haulage No. (1)	Source-Des. ¹ (2)	Mat. type ² (3)	Haul distance (m) (4)	Plant team ³ (5)	Team id ⁴ No. (6)
1	1 - 2	CE	788	D9+3@TS24	S3
2	1 - 2	R	1000	D8+245+4@M	T4d
3	5 - 3	CE	1100	D9+4@TS24	S4
4	5 - 4	CE	644	D9+3@TS24	S3
5	6 - 3	CE	2620	245+10@M	T10
6	6 - 3	R	2620	D8+245+5@M	T5d
7	6 - 13	CE	3880	245+12@M	T12
8	6 - 13	R	3880	D8+245+7@M	T7d
9	6 - 14	CE	4575	245+13@M	T13
10	6 - 14	R	4575	D8+245+8@M	T8d
11	7 - 8	CE	412	D9+2@TS24	S2
12	7 - 13	CE	3230	245+12@M	T12
13	7 - 14	CE	4050	245+12@M	T12
14	9 - 10	CE	275	D9+2@TS24	S2
15	11 - 13	CE	1640	D9+5@TS24	S5
16	11 - 13	R	1640	D8+245+5@M	T5d
17	11 - 14	CE	2335	245+9@M	T9
18	11 - 14	R	2335	D8+245+5@M	T5d
19	12 - 13	CE	1090	D9+4@TS24	S4
20	B - 13	CE	5000	235+245+30@18t	HT1
21	B - 14	CE	6000	235+245+30@18t	HT1

1 - Source and destination have been named according to the section numbering in Figure 10.2

2 - CE - common earth, R - Limestone

3 - Symbols are as given in Figure 10.1

4 - The first letter S=scrapper team (TS24), T=truck team (Moxy), the next integer=no.of hauling units, the last letter (if present)=an additional D8 for rock excavation

Step 5: Simulate each haulage operation using the selected teams treating separately, different types of strata in cut sections and different layers in fill sections. Use the interacting facility of the simulation model to obtain a balanced team or teams. Each haulage operation of the case study was simulated for 15 replications after deciding the

Table 10.2 - Simulated results of case study 3 : M40 Banbury By-pass

Column		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
row	Cut	1		5	6		7	9	11		12	B
	strata fill	CE	R	CE	CE	R	CE	CE	CE	R	CE	CE
(1)	2	28 56.32 X1 .9 S3	92 15.55 X2 1.1 T4d	-	-	-	-	-	-	-	-	-
(2)	3	-	-	31 65.05 X3 .9 S4	74 31.08 X5 .9 T10	25 13.13 X6 1.1 T5d	-	-	-	-	-	-
(3)	4	-	-	27 59.27 X4 .9 S3	-	-	-	-	-	-	-	-
(4)	8	-	-	-	-	-	26 45.84 X11 .9 S2	-	-	-	-	-
(5)	10	-	-	-	-	-	-	25 47.22 X14 .9 S2	-	-	-	-
(6)	13	-	-	-	88 31.05 X7 .9 T12	151 13.44 X8 1.1 T7d	80 34.39 X12 .9 T12	-	34 69.48 X15 .9 S5	105 15.41 X16 1.1 T5d	30 66.88 X19 .9 S4	243 44.23 B1 .9 HT1
(7)	14	-	-	-	97 30.36 X9 .9 T13	152 14.61 X10 1.1 T8d	89 30.90 X13 .9 T2	-	70 30.14 X17 .9 T2	116 14.00 X18 1.1 T5d	-	267 38.61 B2 .9 HT1
(8)	Road side disposal	7 58.38 D1 1.2 D	10 40.00 D2 1.3 D	7 58.38 D3 1.2 D	7 58.38 D4 1.2 D	10 40.00 D5 1.3 D	7 58.38 D6 1.2 D	7 58.38 D7 1.2 D	7 58.38 D8 1.2 D	10 40.00 D9 1.3 D	7 58.38 D10 1.2 D	-

Note - Top left, top right, bottom left, bottom right and centre of each appropriate box indicates unit cost (£/100m³), production (100m³/day), swell (shrinkage) factor in compaction, plant team id, number and the associated variable name respectively.

well balanced team by experimentation (explained in the next section) and the results obtained are shown in Table 10.2 where top left, top right, bottom left, bottom right corners and centre of appropriate boxes indicate unit cost, production, swell (shrinkage) factor, team identification number and associated quantity variable name respectively. Plant team costs used in simulation model were calculated using current market plant hire rates shown in Table 10.3.

Table 10.3 - Plant hire rates

Plant description (1)	Hire rates per 60hr. week (all inclusive) (£) (2)
Moxy (25t)	1151
Highway trucks (18t)	1335
TS24 scrapers	2378
Cat. 245 loader	2600
Cat. 235 loader	1898
Cat. D9 pusher	2399
Cat. D8 dozer	1462

10.2.1.2 Experimentation with the simulation model

Clearly, an optimum solution to an earthmoving problem requires the plant teams to be well balanced. As briefly mentioned earlier in step 4, a balanced plant team can always be obtained by interacting the simulation model and adding, deleting or replacing equipment items in an unbalanced team. This facility is particularly important for a novice who is unable to decide the exact number of loading and hauling units corresponding to a particular haul distance, material type and other operating conditions. By examining the simulation table, which indicates the behaviour of each plant item, printed statistics, histograms etc., the user can easily find a well balanced team. To illustrate the effect of different plant configurations, the unit costs obtained for the first haulage operation in Table 10.1 for various plant configurations were plotted and is shown in Figure 10.3. The larger variation of unit costs clearly indicates the importance of a balanced team for an optimum solution.

An alternative and a quick way to decide a balanced team for a particular haulage operation under given operating conditions is to use pre-simulated unit cost tables. Table 10.4 shows such a table developed for teams containing a Cat. 245 loader and 25t

Moxy trucks and was developed averaging 15 replications for each haulage operation. If such tables are developed for commonly used plant configurations and operating conditions the model user can straight away use a balanced team in the simulation model.

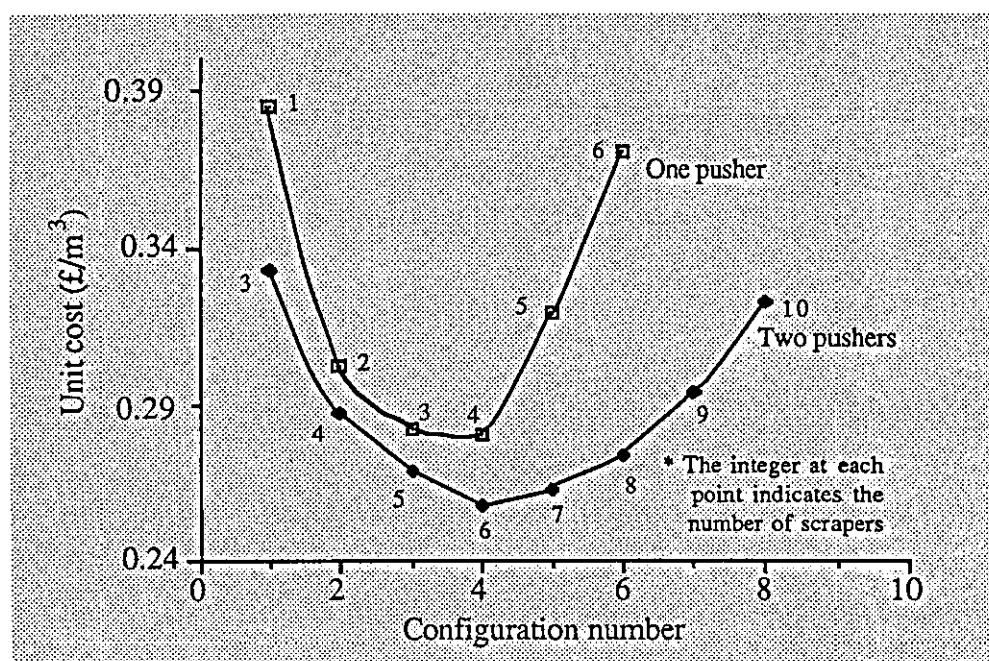


Figure 10.3 - Variation of unit cost for different plant configurations : haulage operation 1 of the case study 3 - M40 Banbury By-pass

10.2.2 Application of LP/IP model and comparison with contractor's method

LP/IP model is the second stage of RESOM and involves determination of an optimum earthmoving plan using realistic costs and production rates obtained from the simulation stage. The potential of the LP/IP formulation developed in Chapter 4 is quite considerable but due to the nature of the case study only certain features are applicable to the problem at hand.

10.2.2.1 Application of LP/IP model : stage two of RESOM

By substituting the simulated results (Table 10.2) and other necessary data to the appropriate LP/IP equations developed in Chapter 4 the following formulation can be obtained.

Table 10.4 - Simulated unit costs (£/100 m³) for various plant configurations and haul distances under poor operating conditions (loading unit is a Cat. 245)

Haul distance (m) (1)	Number of Moxy trucks (2)													
	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1000	60	53	51	49	49	53								
1100		56	52	49	50	53	57							
1200		57	53	53	52	53	57							
1400			59	56	55	55	59	61						
1600			61	60	58	58	58	63						
1800				64	61	61	62	63	67					
2000				67	63	64	64	65	67					
2400					72	72	70	69	71	72				
2800					80	76	75	74	73	74	77			
3200						83	82	81	79	79	80	83		
3600						89	88	87	85	84	83	87		
4000							94	93	92	91	90	89	91	
4500										98	96	96	97	
5000										108	105	104	103	105

Objective function

Substituting the values to the equation (4.26) the objective function is;

$$\begin{aligned} \text{Min} = & 28X_1 + 92X_2 + 31X_3 + 27X_4 + 74X_5 + 125X_6 + 88X_7 + 151X_8 + 97X_9 + \\ & 152X_{10} + 26X_{11} + 80X_{12} + 89X_{13} + 25X_{14} + 34X_{15} + 105X_{16} + 70X_{17} \\ & + 116X_{18} + 30X_{19} + 7D_1 + 10D_2 + 7D_3 + 7D_4 + 10D_5 + 7D_6 + 7D_7 + 7D_8 \\ & + 10D_9 + 7D_{10} + 243B_1 + 267B_2 \dots\dots\dots(10.1) \end{aligned}$$

Constraints

Substituting values to equation (4.27) the constraints corresponding to each strata in each cut section are;

$$X_1 + D_1 = 292.0 \dots\dots\dots (10.2) \quad [\text{section 1, CE}]$$

$$X_2 + D_2 = 36.0 \dots\dots\dots (10.3) \quad [\text{section 1, R}]$$

$$X_3 + X_4 + D_3 = 390.0 \dots\dots\dots (10.4) \quad [\text{section 5, CE}]$$

$$X_5 + X_7 + X_9 + D_4 = 400.0 \dots\dots\dots (10.5) \quad [\text{section 6, CE}]$$

$$X_6 + X_8 + X_{10} + D_5 = 574.0 \dots\dots\dots (10.6) \quad [\text{section 6, R}]$$

$$\begin{aligned}
X_{11} + X_{12} + X_{13} + D_6 &= 434.0 & (10.7) & \text{[section 7, CE]} \\
X_{14} + D_7 &= 102.0 & (10.8) & \text{[section 9, CE]} \\
X_{15} + X_{17} + D_8 &= 580.0 & (10.9) & \text{[section 11, CE]} \\
X_{16} + X_{18} + D_9 &= 237.0 & (10.10) & \text{[section 11, R]} \\
X_{19} + D_{10} &= 594.0 & (10.11) & \text{[section 12, CE]}
\end{aligned}$$

Substituting values to equation (4.28) the constraints corresponding to each fill section are;

$$\begin{aligned}
0.9X_1 + 1.1X_2 &= 300.0 & (10.12) & \text{[section 2]} \\
0.9(X_3 + X_5) + 1.1X_6 &= 380.0 & (10.13) & \text{[section 3]} \\
0.9X_4 &= 341.5 & (10.14) & \text{[section 4]} \\
0.9X_{11} &= 216.0 & (10.15) & \text{[section 8]} \\
0.9X_{14} &= 91.8 & (10.16) & \text{[section 10]} \\
0.9(X_7 + X_{12} + X_{15} + X_{19} + B_1) + 1.1(X_8 + X_{16}) &= 1450.0 & (10.17) & \text{[section 13]} \\
0.9(X_9 + X_{13} + X_{17} + B_2) + 1.1(X_{10} + X_{18}) &= 1742.8 & (10.18) & \text{[section 14]}
\end{aligned}$$

No plant team utilisation constraints (equation 4.33) are required for this problem since there is no limitation of equipment resources. However, other constraints (equations 4.41, 4.42 and 4.42) applicable to cut and fill sections should be applied to sequence of operations required and to avoid traffic congestions. In doing so, it was assumed that road side disposal and material movements in opposite directions can be carried out concurrently with any other haulage operation in a particular roadway section. Furthermore, the project duration used in these constraints is 102 days which is the contractor estimated value for completion of earthmoving operations.

Substituting values to equation (4.41 or 4.42) the constraint equations for cut sections are;

$$\begin{aligned}
X_1/56.32 + X_2/15.55 &\leq 102.0 & (10.19) & \text{[section 1]} \\
X_3/65.05 + X_4/59.27 &\leq 102.0 & (10.20) & \text{[section 5]} \\
X_5/31.08 + X_6/13.33 &\leq 102.0 & (10.21) & \text{[section 6, lhs]} \\
X_7/31.05 + X_8/13.44 + X_9/30.36 + X_{10}/41.61 &\leq 102.0 & (10.22) & \text{[section 6, rhs]} \\
X_{11}/45.84 + X_{12}/34.39 + X_{13}/30.90 &\leq 102.0 & (10.23) & \text{[section 7]} \\
X_{14}/47.22 &\leq 102.0 & (10.24) & \text{[section 9]} \\
X_{15}/69.48 + X_{16}/15.41 + X_{17}/30.14 + X_{18}/14.00 &\leq 102.0 & (10.25) & \text{[section 11]} \\
X_{19}/66.88 &\leq 102.0 & (10.26) & \text{[section 12]}
\end{aligned}$$

Substituting values to equation (4.43) the constraints for fill sections are;

$$X3/65.05 + X5/31.08 + X6/13.33 \leq 102.0 \dots\dots\dots (10.27) \text{ [section 3]}$$

$$X7/31.05 + X8/13.44 + X12/34.39 + X15/69.48 + X16/15.41 \\ + X19/66.88 + B1/44.23 \leq 102.0 \dots\dots\dots (10.28) \text{ [section 13]}$$

$$X9/30.36 + X10/14.61 + X13/30.90 + X17/30.14 + X18/14.00 \\ + B2/38.61 \leq 102.0 \dots\dots\dots (10.29) \text{ [section 14]}$$

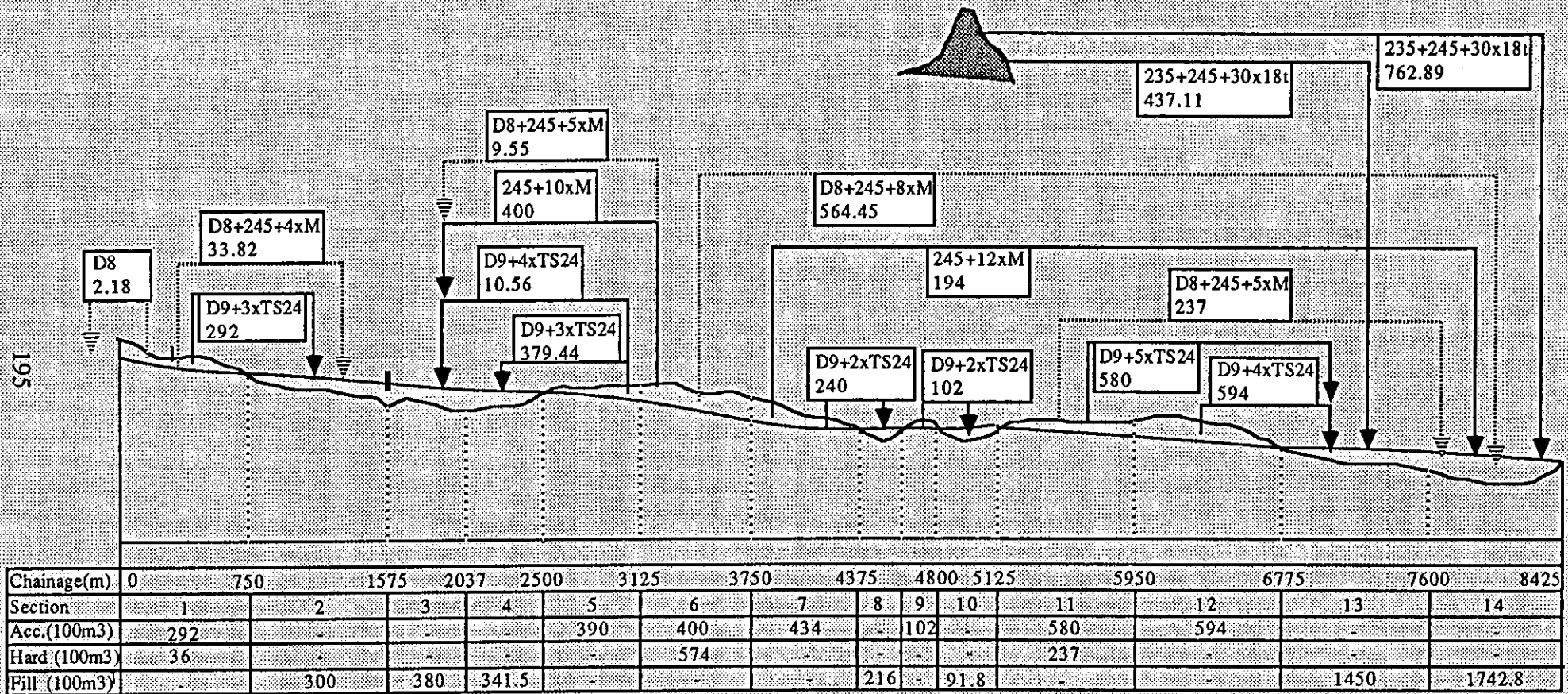
In applying the equation (4.43) clear redundant constraints were disregarded. For example, filling operation constraint at section 2 has already been incorporated in cutting constraint (10.19) in section 1 and hence not considered.

The only remaining set of constraints applicable to the problem at hand are the non negativity condition for all the X, B and D variables.

The above formulation now is a simple linear programming problem and was solved using the LINDO LP/IP package. The value of the objective function was £539469 and the corresponding material distribution is shown in Figure 10.4.

10.2.2.2 Comparison of RESOM solution with contractor's estimate

The material distribution and the corresponding cost components resulted by LP/IP solution can now be compared with that obtained by the contractor based on the Mass-haul diagram. The comparison can be carried out using an arrow diagram for both solutions as shown in Figure 10.5. The 20% cost saving achieved (Figure 10.5) by LP/IP solution is very encouraging and further cost savings are possible if better operating conditions can be maintained. The main reason for this cost difference, as explained in Chapter 1, is due to the limitations of the potential use of the Mass-haul diagram for typical practical applications.



1 - Actual fill quantity measured from drawings
 Note - Notations are as given in Figure 10.1

Figure 10.4 - Optimum haulage operations obtained form RESOM : case study 3 - M40 Banbury By-pass (not to scale)

Contractors' Method				LP/IP Solution			
Chainage (m)	Cut (m3)	Fill (m3)	Cost (£)	Chainage (m)	Cut (m3)	Fill (m3)	Cost (£)
0	29200	16667		0	29200	8176	
	3600	7964			3600	3382	3111
750				750	218	30000	22
		112700			Waste		
1575				1575			
2037				2037		38000	
2500				2500		34150	327
	79900	58334			1056		10245
	122400	24000	16667	3125	39000	37944	29600
	18500	22212			40000		1194
	57400	62288		3750	57400	955	85796
		24000			56445		17266
4375				4375	43400	19400	6240
4575				4575	24000	21600	
4800	10200	8333		4800	10200	2550	
		10200				9180	
5125				5125			
	117400	89142			58000		19720
	23700	31856			23700		27492
				5950			
					59400		17820
6775				6775			
					Borrow	145000	
					43711		106218
				7600			
	Borrow	342000			Borrow	174280	
	125000	361038			76289		203692
8425				8425			
	Total		674502		Total		539469

Cost saving = 20 %

10.3 Advanced Use of RESOM

Clearly, the previous case study used only a fraction of the facilities available in RESOM. For example, it did not test different plant configurations having various speeds of production for each haulage operation, nor did it consider setting up of new borrow/disposal sites or constraints on project completion time. This section illustrates these facilities by applying the LP/IP model and network model to a hypothetical case study.

10.3.1 Formulation of case study 4

This case study was formulated with a view to achieving the following objectives.

- (i) To test different plant teams for individual haulage operations.
- (ii) To incorporate project completion time constraints.
- (iii) To investigate the possibility of establishing new borrow/disposal sites.
- (iv) To incorporate capacity limitations of borrow/disposal sites.
- (v) To determine the cheapest solution with available plant for timely project completion.
- (vi) To determine the cheapest solution with available plant.
- (vii) To determine the shortest project completion time with available plant.

Consider the earthwork problem shown in Figure 10.6 for which earthwork optimisation is required. The problem has six roadway sections, each 500 m long, an existing borrow pit and existing disposal site near section 6 and 1 respectively. The possibility of setting up another borrow pit is to be investigated and the contractor has found one site near station 3 for which the set up costs were estimated to be £5000. Suppose that the cut quantities of various strata in cut sections and the fill quantities required for various fill sections together with capacity limitations of borrow/disposal sites have been calculated from drawings and bore hole data and are shown in Table 10.5. Varying degree of compaction can be achieved for different sections (subgrade, subbase, sidefill etc.) but for simplicity the degree of compaction for all roadway fill sections was assumed to be the same.

Furthermore, assume that the construction is to be carried out in Sri Lanka where contractors prefer to use their own fleet due to limitation of plant hire companies. Consequently, the contractor awarded the job decided to use his own fleet given in Table 10.6 in various team combinations shown in Table 10.7, selecting appropriate

plant teams for different haul distances to complete the earthmoving phase of the job within 18 days. Notice in Table 10.7 that teams 1 to 5 and 6 to 10 share equipment items among teams.

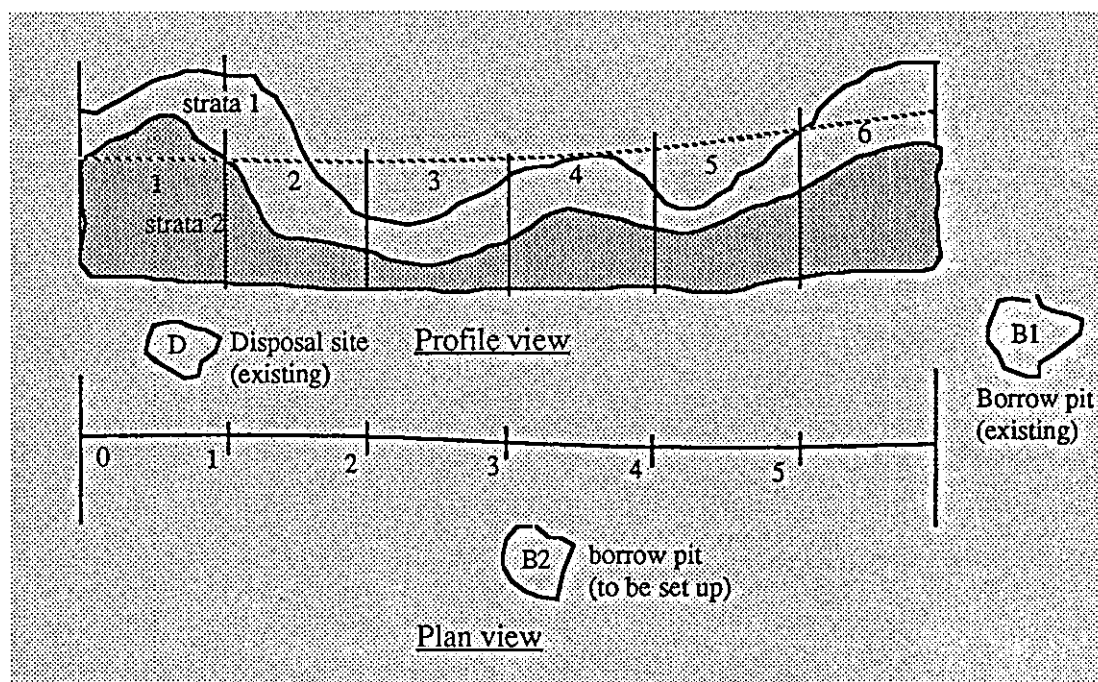


Figure 10.6 - Plan and profile views of the proposed highway : case study 4

Table 10.5 - Cut/fill quantities and capacity limitations of borrow/disposal sites : case study 4

Cut/fill quantities and capacity limitations of borrow/disposal sites (100m³)										
Section/location (1)		1 (2)	2 (3)	3 (4)	4 (5)	5 (6)	6 (7)	B1 (8)	B2 (9)	D (10)
cut	Strata 1	748	395	-	-	-	650	2500	1500	
	Strata 2	340	-	-	-	-	-	-	-	-
fill	Subgrade	-	195	600	100	850	-	-	-	7500

Finally, assume that the simulation stage of RESOM has already been applied to the problem and the unit cost, production, swell (shrinkage) factor and the team identification number for each possible haulage operation are shown in Table 10.8.

Table 10.6- Contractor's equipment fleet with specifications : case study 4

Model (1)	Description (2)	Number (3)	Identification (4)
Cat 769C	Off highway trucks with 17.3 m ³ struck capacity	8	T1 - T8
Cat 773B	Off highway trucks with 26.0 m ³ struck capacity	8	T9 - T16
Cat D4H LGP	Bulldozer with straight blade with 2.17 m ³ capacity	1	B1
Cat D6H	Bulldozer with straight blade with 3.35 m ³ capacity	1	B2
Cat 980C	Wheel loader with 4.7 m ³ bucket capacity	1	L1
Cat 988B	Wheel loader with 6.3 m ³ bucket capacity	1	L2
Cat D3B LGP	Bulldozer equipped with push plate	1	B3
Cat 651E	Standard scraper with 24.5 m ³ struck capacity	4	S1 - S4
Cat 825C	Compactors	3	C1 - C3
Cat 14G	Motor graders	2	G1 - G2
Cat D4H	Dozer equipped with power angle and tilt blade	2	B4 - B5

10.3.2 The cheapest solution with available plant for timely project completion

In addition to the constraints applied in the previous case study, the team utilisation constraints and equipment sharing constraints developed in Chapter 4 are also applicable to the problem at hand. In this way, the entire formulation applicable to this problem are;

- (i) Objective function (Equation 4.26)
- (ii) Quantity constraints at cut sections (Equation 4.27)
- (iii) Quantity constraints at fill sections (Equation 4.28)
- (iv) Capacity constraints of borrow pits (Equation 4.29)
- (v) Capacity constraints of disposal sites (Equation 4.30)
- (vi) Capacity constraints of borrow pits (to be set up) (Equation 4.31)

- (vii) Plant team utilisation constraints (Equation 4.40)
- (viii) Plant team congestion and sequence of operation constraints (Equations 4.41 - 4.46)

Table 10.7 - Proposed equipment team configurations : case study 4

Equipment combination (1)	Team identification (2)	Suitable haul distance (m) (3)
T1-T4,L1,B1,B4,C1,G1	1	400 - 650
T1-T5,L1,B1,B4,C1,G1	2	500 - 1000
T1-T6,L1,B1,B4,C1,G1	3	900 - 1500
T1-T7,L1,B1,B4,C1,G1	4	1250 - 2000
T1-T8,L1,B1,B4,C1,G1	5	1750 - 2500
T9-T12,L2,B2,B5,C2,G2	6	400 - 700
T9-T13,L2,B2,B5,C2,G2	7	600 - 950
T9-T14,L2,B2,B5,C2,G2	8	750 - 1300
T9-T15,L2,B2,B5,C2,G2	9	1200 - 1800
T9-T16,L2,B2,B5,C2,G2	10	1700 - 2500
S1-S4,B3,C3	11	400 - 600

The entire substituted formulation and the solution report obtained from LINDO LP/IP package are given in Appendix G. The total cost of the project in the optimum solution was found to be £77850. The corresponding optimum material distribution together with the plant teams used in the optimum solution are shown in Figure 10.7 where broken lines and solid lines represent cheaper and more expensive teams respectively.

Table 10.8 - Assumed simulated results of case study 4

Column		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
row	cut strata fill	1				2		6		B1		B2	
		S1		S2		S1		S1		S1		S1	
1	2	28 40 .9 1	32 55 .9 11	30 38 1 1	35 50 1 6	23 53 .9 1	28 71 .9 11	-	-	-	-	-	-
2	3	33 39 .9 3	40 53 .9 8	34 36 1 2	42 45 1 8	28 40 .9 2	32 52 .9 11	38 36 .9 4	46 48 .9 9	45 34 .9 5	53 45 .9 10	27 41 .9 1	31 56 .9 11
3	4	38 36 .9 4	46 48 .9 9	40 33 1 3	48 41 1 9	33 38 .9 3	40 49 .9 8	33 39 .9 3	40 54 .9 8	38 36 .9 4	46 48 .9 9	26 45 .9 1	30 59 .9 11
4	5	44 35 .9 5	52 46 .9 10	46 31 1 4	54 39 1 10	38 36 .9 4	46 46 .9 9	28 40 .9 1	32 55 .9 11	33 39 .9 3	40 53 .9 8	32 38 .9 2	40 52 .9 8
5	D	20 48 1.4 1	26 60 1.4 11	22 44 1.3 1	29 57 1.3 6	22 42 1.4 1	28 55 1.4 11	45 38 1.4 5	55 45 1.3 10	-	-	-	-

Note - Top left, top right, bottom left and bottom right corners of appropriate boxes indicate unit cost (£/100m³), production (100m³/day), swell (shrinkage) factor in compaction and plant team number respectively

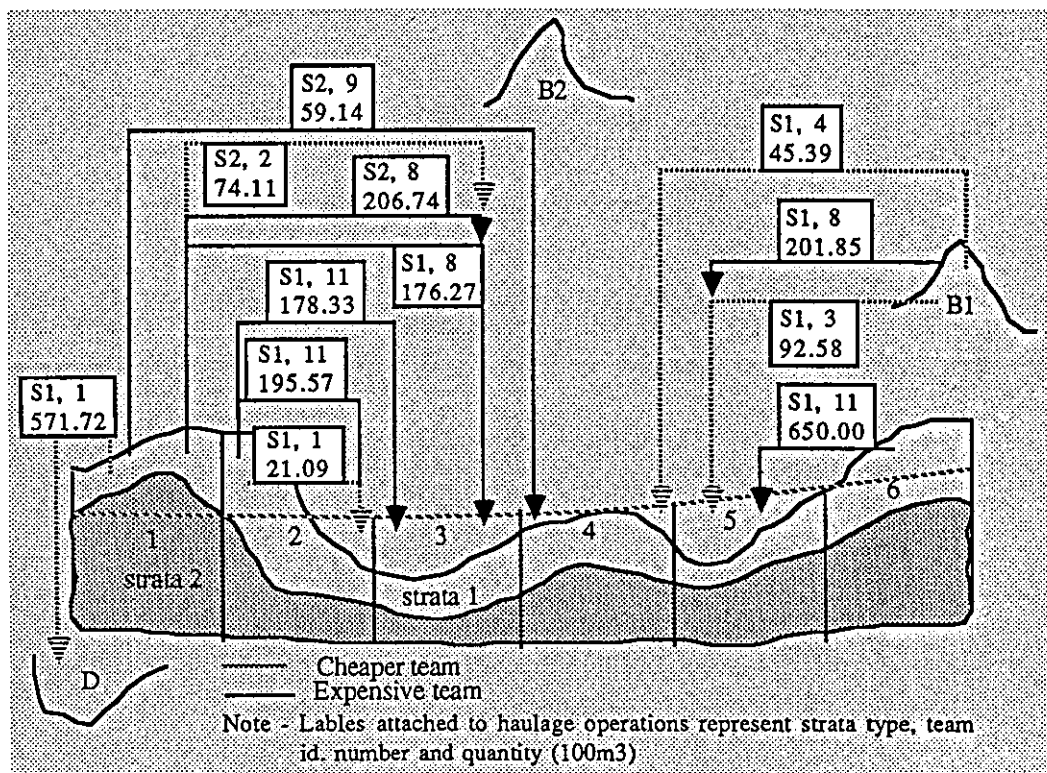
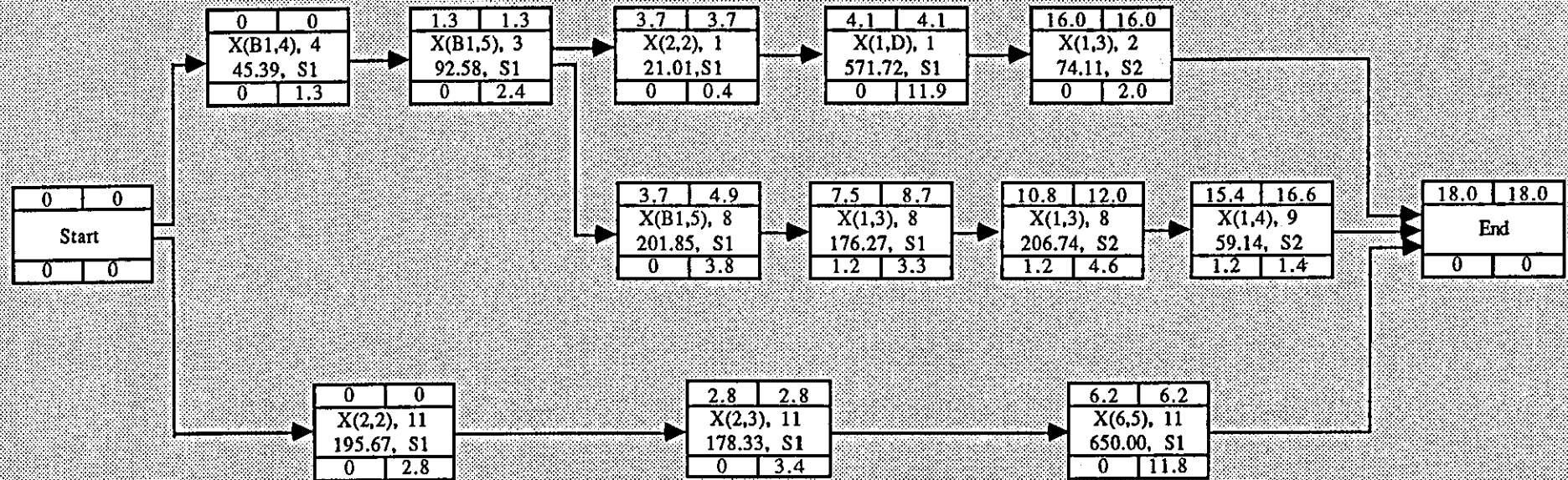


Figure 10.7 - Material distribution obtained from RESOM : case study 4

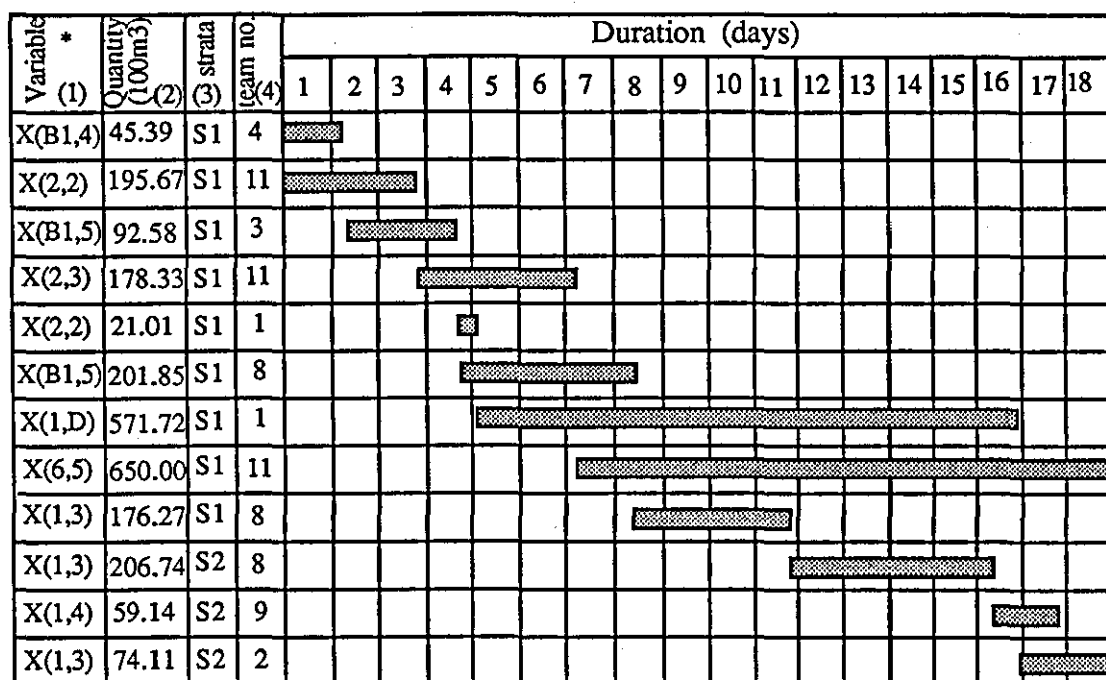
Application of the Network model

The simplest and the final part of RESOM is the application of the network model to obtain a construction schedule. To this end, the duration required for each optimum haulage operation was first calculated using the quantities involved and the production rate of the corresponding plant team. These durations together with appropriate resources were then utilised to develop the network plan and the barchart schedule shown in Figures 10.8 and 10.9 respectively. Essentially, the earthmoving phase of the job must be completed within 18 days according to the set of constraints applied in the LP/IP formulation. This is clearly adhered to in the final plan and it is interesting to note that team 11, and teams 1 to 5 (team group 1) are fully utilised throughout the project duration.



Note - Activity description provides variable name with source and destination, team number, quantity (100m³), and strata type

Figure 10.8 - Network diagram representing sequence of operations : case study 4



* first subscript indicates the source and the second subscript indicates the destination

Figure 10.9 - Barchart schedule representing sequence of operations : case study 4

10.3.3 The cheapest solution with available plant

There are situations, although not very common, where the primary criteria of the job is to construct it with minimum cost irrespective of the completion time. The same formulation used in the previous section can be extended to achieve the cheapest project cost and the corresponding construction plan. The basic principle in this case is to increase the project duration in the team utilisation constraints and, cut/fill section or borrow/disposal congestion and sequence of operation constraints until no further reduction of cost in the optimum solution is obtained. With a view to achieving the cheapest cost the above problem was solved by varying the project duration from 18 days to 60 days. As the duration is increased beyond 18 days, the use of expensive teams capable of higher production rates and the resulting total cost was gradually reduced upto £64906 which corresponds to 54 days of project duration. The relationship between the total cost and the project duration is shown in Figure 10.10. If the tested plant teams are to be used, no further reduction in cost is possible by increasing the project duration. The resulting material distribution and the plant utilisation are shown in Figure 10.11 where it is clearly seen that only the cheaper teams (team group 1) is utilised throughout the project indicating that no concurrent operations are possible.

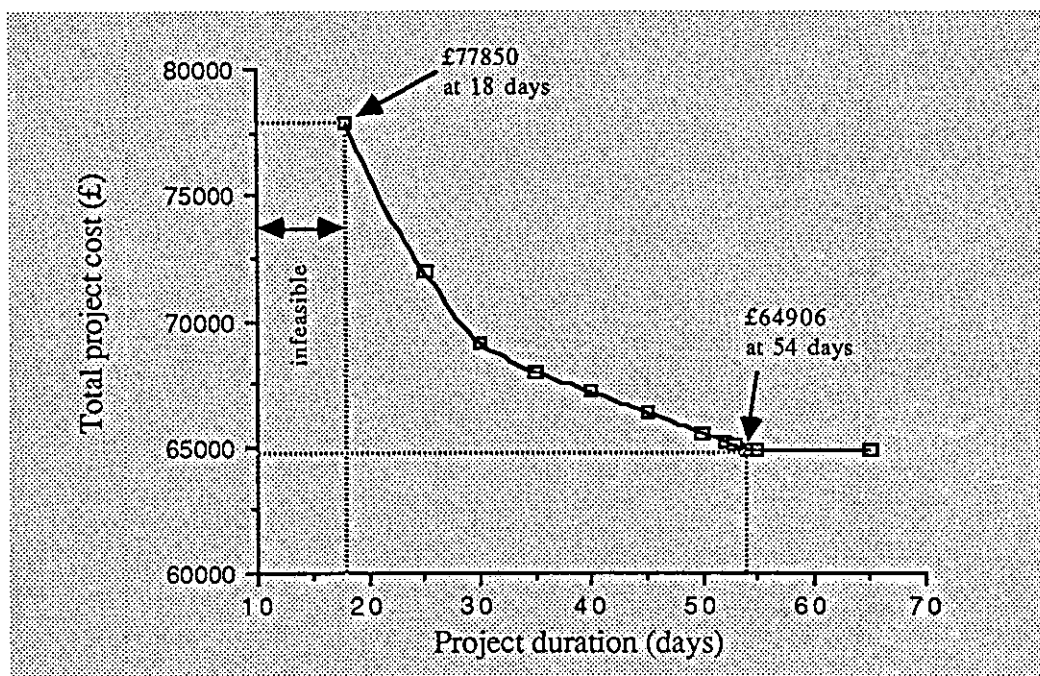


Figure 10.10 - Variation of the total cost with project duration

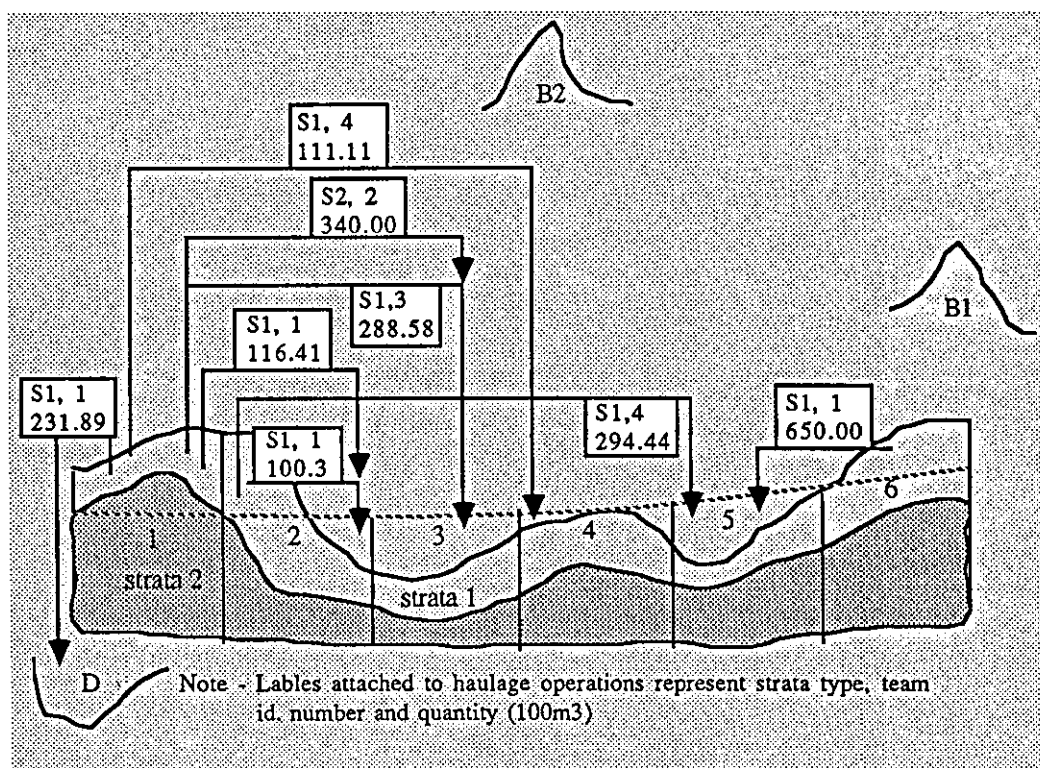


Figure 10.11 - Material distribution obtained from RESOM at the cheapest cost : case study 4

10.3.4 The shortest completion time with available plant

Situations where the project should be completed at its earliest irrespective of the cost are quite common. These situations arise particularly when the construction obstructs other processes such as a closure of another road. Similar to the previous case, the same formulation used in section 10.3.2 can be utilised to obtain the shortest possible project completion time using the given plant. The underlying principle in this case is to reduce the project duration in all appropriate constraints until the solution to the LP/IP formulation becomes infeasible. The minimum duration obtained with a feasible solution is clearly, the shortest project completion time with available plant. To this end, the duration of the above formulation was reduced from 18 days and it was found that beyond 18 days the solution is infeasible indicating that the 18 days is the shortest possible project completion time. This aspect is also shown in Figure 10.10. If the contractor wants to complete the project earlier than 18 days then he must use other plant teams with even higher speeds of operation. Needless to say, all these facts could be of considerable importance to the management in decision making.

10.4 Sensitivity Analysis

Sensitivity analysis is the examination of the sensitivity or the effect of variation of different variables on the objective criteria. This is usually carried out by changing the variable of interest whilst keeping all the other factors constant and examining the objective. The sensitivity analysis is also an essential part in modelling and should be carried out before any decision is taken on the behaviour of the model. For example, in case study 3, it was found that the cost saving achievable by LP/IP solution is 20%. Is this 20% representative? Can the same saving be achieved if different sectional interval was decided by the model user when simulating the project? These questions are answered in this section.

10.4.1 Effect of variation of road sectional interval

To test the effect of changing the average sectional interval on the objective criteria, the RESOM model was repeatedly applied to the case study 3 for four different average sectional intervals. How the road sections were divided, details of each possible haulage operation, simulated results and the optimum material distribution for each such average sectional interval are shown in Appendix G. The summary results are provided in Table 10.9.

Table 10.9 - Effect of the sectional interval variation on the objective function

Study number (1)	Average interval (m) (2)	Contractor's estimate (£) (3)	LP/IP estimate (£) (4)	Cost saving (%) (5)
1	495	674502	550717	18.4
2	602	674502	539833	20.0
3	765	674502	521602	22.7
4	936	674502	513367	23.9

According to Table 10.9 there seems to be an increase in cost saving with the average sectional interval. To further investigate this fact the optimum material distribution obtained for all four cases were separately grouped into major sections and were individually compared. In this way, it was found that the above difference in cost saving is mainly due to approximations used in estimating the haul distances and quantity calculations. Therefore, any suitable average sectional interval can be used for a given problem without seriously affecting the final project cost. However, an average sectional interval between 500 m - 750 m seems to be a convenient value and is recommended for typical projects.

10.4.2 Effect of variation in plant team selection

In case study 4, each haulage operation was tested with two equipment teams having different unit costs and speeds of operation. What happens if one or more of these teams are not tested? Does it significantly affect the total cost? Clearly, if the haulage operation for which these teams are not tested is not in the optimum solution the overall cost remains unchanged. On the other hand, if the cheaper teams are not considered, for haulage operations in the optimum solution, clearly, there is an increase in the cost. But the effect diminishes if the specified project duration is closer to the shortest possible completion time where much of team utilisation are those having higher production rates and cost. On the other hand, the effect on the overall cost increases when the project duration is increased and attain maximum at the cheapest possible cost. The best way to investigate this criteria is to neglect all the cheaper plant teams (or expensive teams with higher production rates) for all haulage operations and examine the behaviour of the objective function at the two extremes (project cost at the shortest completion time and the cheapest project cost).

This process was carried out for the case study 4 by neglecting all the cheaper teams, and expensive teams with higher production rates, corresponding to each haulage operation on separate occasions and examining the shortest project completion time and the corresponding cost together with the cheapest project cost and the corresponding duration. The results are shown in Figure 10.12 and Table 10.10.

From these results the following conclusions can be made.

- (i) The omission of cheaper teams does have a considerable cost increase if the objective criterion is the cheapest cost. If the project is to be completed at its shortest possible time the difference is not significant.
- (ii) If the objective criterion is the shortest completion time, the omission of teams having higher production rates considerably reduces the overall cost and increases the shortest possible completion time. On the other hand, there is no cost difference if the project is to be completed at the cheapest cost.

Therefore, it is evident that the selection of certain kinds of plant teams may or may not significantly affect the objective criteria and the model user is responsible to choose teams according to his requirements.

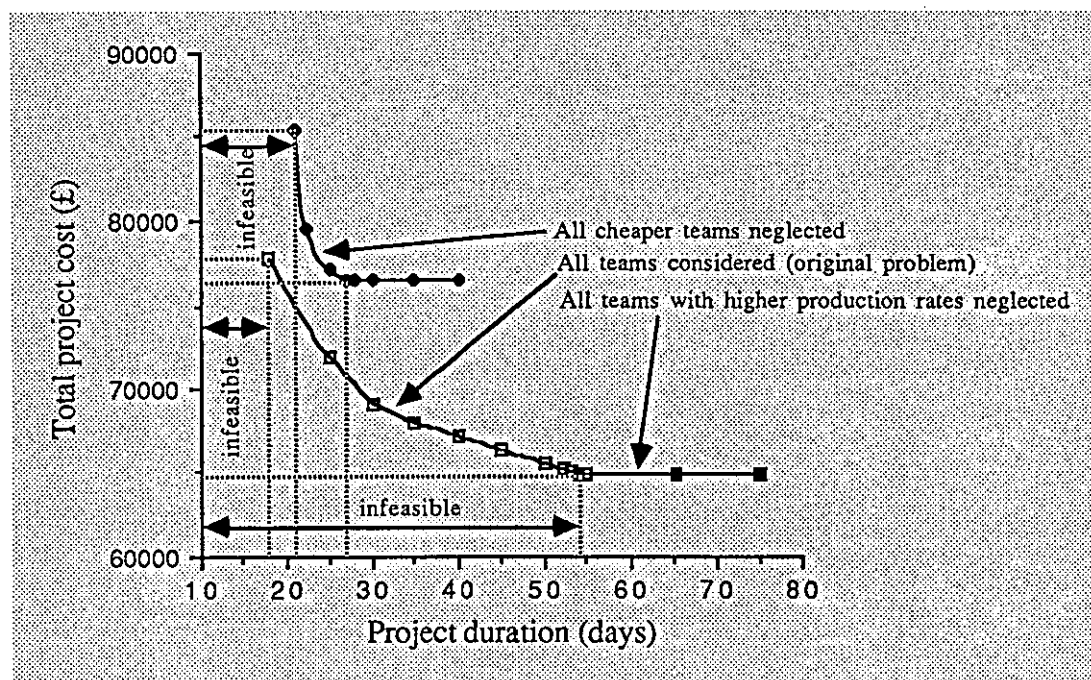


Figure 10.12 - Effect of variation of plant team selection

Table 10.10 - Effect of plant team selection variation on the objective function

Description (1)	Shortest completion time (days) (2)	Cost at shortest time (£) (3)	Cheapest cost (£) (4)	Duration at cheapest cost (days) (5)	Cost differ. at shortest duration (%) (6)	Cost differ. at cheapest cost (%) (7)
Original problem with all teams	18	77850	64906	54	-	-
Cheaper teams with low production	21	85319	76457	28	9.6	17.8
Expensive teams with high production	54	64906	64906	54	16.6	0

10.5 Summary

Application and experimentation with RESOM were systematically explained using two case studies. The simulation model (stage 1 of RESOM) was first applied to an actual case study : M40 - Banbury By-pass, explaining in detail, the application process to obtain realistic unit costs and production rates, and the experimentation to obtain a balanced plant team. The simulated results were then applied to LP/IP model (stage 2 of RESOM) and the optimum solution so obtained was compared with that suggested by the contractor. This revealed that about 20% of cost saving can be achieved by LP/IP model.

The advanced use of RESOM was illustrated by applying it to a hypothetical case study. The situations covered included: testing of different plant teams for individual haulage operations; setting up of new borrow/ disposal sites; incorporation of project duration constraints; determination of optimum project construction plan [material distribution, plant utilisation, overall cost etc.] (a) for a given team and a given duration, (b) corresponding to the cheapest possible cost with a given team and (c) corresponding to the shortest possible completion time with a given fleet. In this way, it was revealed that the use of RESOM can be of considerable help to experiment with typical problems to obtain quite useful results for management in their decision making.

Finally, a sensitivity analysis was carried out to investigate the effect of the average sectional interval and team selection variations on the overall cost. This revealed that there is no significant effect due to variation of average sectional interval, however, the

effect due to plant selection may or may not significantly affect the overall cost depending on the objective criteria.

CHAPTER ELEVEN

CONCLUSIONS, RECOMMENDATIONS AND FURTHER RESEARCH

11.1 Conclusions

11.1.1 Existing earthwork optimisation techniques

11.1.2 Current planning and estimating practices in the industry

11.1.3 Conclusions on RESOM

11.1.3.1 Determination of significant factors affecting
various cycle element times and development of
cycle element time generators

11.1.3.2 Determination of realistic unit costs and
production rates

11.1.3.3 Determination of an optimum earthmoving plan

11.1.3.4 Application, experimentation and further
validation of RESOM

11.2 Recommendations

11.3 Further Research

11.1 Conclusions

The use of an optimum earthmoving plan for any highway construction can not be overlooked for successful tendering and high profit margins. Preparations of construction plans and estimates are mainly based on traditional mass-haul diagrams, skilled engineering judgement and deterministic estimating methods. Information available to assist this process includes work study data, equipment manufacturers' machine performance books and other published and unpublished estimating guidelines. Unfortunately, even the best of these sources generally requires the user to make bold decisions in selecting appropriate equipment, and calculating production rates and associated costs.

As explained in Chapter 1, the potential use of the traditional mass-haul diagram diminishes with increasing complexities in real life situations. Furthermore, the deterministic methods described in most plant manufacturers' handbooks always overestimate the real production due to omission of stochastic variations and interferences inherited in cyclic construction operations. The linear programming formulations and stochastic models developed in the past were aimed at overcoming some of these limitations but those developed hitherto were relatively fundamental and could not be directly applied to a typical earthmoving project to obtain an optimum construction plan. The need for a relatively quick and more accurate planning and estimating procedure emerged, thereby, the estimator or the planning engineer is considerably relieved from guesstimates or trial and error judgements.

The aim of RESOM (Roadwork Earthmoving System Optimisation Model) described in this thesis was to overcome much of these limitations and obtain an optimum earthmoving plan including material distribution, plant selection and utilisation, incorporating real life problems and constraints. RESOM was developed by combining two powerful techniques, computer simulation and linear/integer programming. In this way, the three basic stages of RESOM consisted: simulation model; LP/IP model; and network model, the aim of the last model being the presentation of the LP/IP results.

RESOM was validated using two actual case studies (Anamaduwa Gam Udawa project, Sri Lanka and A42 - Measham and Ashby By-pass, UK). In addition to development and validation, the potential use of RESOM was explained and further validated using two more case studies (M40 - Banbury By-pass, UK and a hypothetical example). The conclusions resulting from reviews of earthwork planning and estimating methods, data collection, analysis, model building, validation, application, experimentation and

sensitivity analysis of RESOM have been discussed throughout the thesis under appropriate headings. They are now collectively summarised in following sections.

11.1.1 Existing earthwork optimisation techniques

A review of the history of earthmoving operations revealed that the over-estimation of production obtained by deterministic methods and the necessity for stochastic approaches for real production were identified as early as in 1958. Since then various stochastic models have been developed in the form of Queuing theory models (Griffis 1968, Cabrera 1973, Maher 1973, Maher 1975, Carmichael 1986(a), Carmichael 1986(b)) and Simulation models (Douglas 1967, Gaarslev 1969, Willenbrock 1975, Clemmens 1978). Queuing models were limited to relatively simple applications due to intractability of associated mathematics whilst simulation models were gradually improved to incorporate complex situations. Despite these improvements, the available simulation models can only be applied between a particular set of source and a destination to obtain realistic production rates and unit costs. Except the scraper simulation model developed by Clemmens (1978), the applicability of other models for typical applications is arguable since they have been developed only for specific situations.

Except in very early attempts by Shaffer (1963), the potential use of linear programming techniques applicable to earthwork optimisation was identified fairly recently in 1972, and since then several models have been proposed with improvements at each stage (Stark 1972, Mayer 1981, Nandgaonkar 1981, Easa 1987, 1988). Although some of these models are attractive, their applicability to real life projects is limited for two main reasons. Firstly, the application of the formulation requires pre-determination of unit earthmoving costs between different sources and destinations. This in effect demands the identification of plant teams and other resources utilised in the job. Secondly, is the lack of facilities available in these models to incorporate real life constraints like, project duration and resource limitations.

Among all the available techniques, the mass-haul diagram is undoubtedly the oldest and the simplest optimisation procedure in determining a suitable material distribution. If properly applied, much needed information can be obtained but, as mentioned earlier, its potential diminishes in complex real life situations. Another technique available to optimise material distribution is the arrow allocation diagram and provides a similar solution as in the mass-haul diagram.

11.1.2 Current planning and estimating practices in the industry

Discussions with experts in the industry, both in Sri Lanka and in the UK, revealed that except the mass-haul and arrow allocation diagrams, none of the other techniques (stochastic models and LP models) are usually adopted for planning and estimating road projects. The main reason for this reluctance is due to aforementioned incompleteness of these optimisation techniques and unavailability of user friendly software packages embodying them.

Detail investigation into earthmoving practices in Sri Lanka resulted in the following conclusions.

- (i) Mass-haul diagrams are usually used to determine the material distribution but they are not properly applied by testing for various haul distances and evaluating appropriate costs to obtain an optimum solution. Situations where even this simple technique is not applied are quite common in particular for small jobs. In such cases, the material distribution is purely selected by experience and any inaccuracies or losses made at this stage are not as serious as in the UK due to flexibility of contracts particularly when much competition among tenderers is not involved.
- (ii) Appropriate equipment teams for different haulage operations are mainly selected using available information and estimators' subjective judgement of operating conditions. Unlike in the UK, Sri Lankan contractors tend to use their own fleet as much as possible without giving much consideration to the suitability and convenience. This is particularly due to unavailability of sufficient plant hire companies to choose from.
- (iii) The production rates and unit costs are calculated either using historical data in the form of trips/day or using cycle element times set out in estimating manuals based on plant manufacturers' handbooks. The methods adopted vary among contractors and when estimates are based on estimating manuals they are modified with different efficiency factors (guessed) to represent reality. Real life problems, weather effects and constraints are incorporated from available information and, by estimators skilled judgement combined with trial and error approaches. However, there are situations (particularly for urgent jobs) where no production rates are calculated or different plant teams are assessed, and the teams are allocated mainly by subjective judgement and resource availability.

Unlike in the UK, a Sri Lankan contractor is unable to obtain accurate weather data and sub-surface information due to the lack of readily available sources. Furthermore, information provided by the client is not adequate or sometimes inaccurate for accurate project costing. In situations where contractors are responsible for obtaining this information, their attempts vary considerably among contractors and projects. Due to these ad hoc practices and absence of proper investigations of site conditions, contractors agreed that the project duration and the corresponding cost usually exceed in the range of 5% to 100% or even more in exceptional situations.

11.1.3 Conclusions on RESOM

As aforementioned, development of RESOM was the result of the author's attempts to overcome the limitations of existing earthmoving optimisation procedures and the conclusions derived at various stages of its development are collectively summarised in the following sections.

11.1.3.1 Determination of significant factors affecting various cycle element times and development of cycle element time generators

Simulation model building required the systematic identification of significant factors affecting various cycle element times and the development of cycle element time generators under different operating levels categorised according to those significant factors. After identifying the possible factors by a questionnaire survey, past research, through discussions and author's experience, their significance was statistically tested using data collected from four large construction sites in Sri Lanka. Subsequently, theoretical distributions were statistically fitted to observed cycle element times after categorising them to different operating levels and their input parameters were evaluated. The significant factors and the fitted distributions together with their parameters for loader-truck and scraper-pusher operations (Clemmens 1978) were shown in Table 7.4, 7.9 and 7.10 respectively. These fitted distributions were subsequently used as input to simulation model.

Specific conclusions drawn during field data collection and analysis were as follows.

- (i) Dozer operations are not significantly affected by other equipment and dozer cycle time varies considerably from cycle to cycle particularly due to frequent variation of haul and return distances. Consequently, the benefit obtained by developing a valid simulation model for dozer hauling operations does not justify

the effort, and a comparable or better production estimates could be obtained by existing methods.

- (ii) Observations on grading and compacting operations proved that there is very little effect of these on hauling operations. The large number of qualitative variables affecting these operations make it very difficult to simulate grading and compacting operations.
- (iii) The cycle time of loader (move forward + load + lift and turn + dump) for both wheel and backhoe loaders can be well represented by Erlang distributions with shape parameters between two and ten depending on the operating condition (Table 7.9).
- (iv) Truck positioning delay, hauling delay, dump and turn time, and returning delay times can be well represented by Weibull distributions (Table 7.9).
- (v) Hauling and returning times of both trucks and scrapers can be represented as a normally distributed regression line with haul or return distance as the independent variable.
- (vi) All cycle element times of scrapers and pushers, except scraper travel time, can also be represented by appropriate Erlang distributions (Clemmens 1978).

11.1.3.2 Determination of realistic unit costs and production rates

The main aim of the simulation model of RESOM was to obtain realistic unit costs and production rates for individual haulage operations in a given project. To this end, a detailed simulation model comprising both loader-truck and scraper-pusher operations was developed in the Pascal language using the fitted distributions as the cycle element time generators. The next event time handling technique and the Three Phase modelling approach were selected as the most suitable for earthmoving simulation. The simulation model can be applied to any earthmoving problem as a whole to sequentially simulate each and every possible haulage operation having varying degree of operating levels and different plant teams. The results from simulation model can then be used as input to LP/IP model to obtain an optimum earthmoving plan.

The main conclusions derived during the simulation model building, verification, validation and experimentation were as follows.

- (i) Feed back from the simulation model demonstrations indicated that the facilities available to: simulate an entire project simultaneously; the visual dynamic display of behaviour of each plant item; interacting facilities available to add, delete or replace unsuitable equipment items; and printed individual and overall statistics together with idle time and queuing time histograms are of considerable use to experiment with simulation model, test various strategies and identify balanced plant teams.
- (ii) A statistical comparison of observed cycle element times from an independent case study (Anamaduwa Gam Udawa, 2nd visit, Sri Lanka) and the generated cycle element times proved the validity of the cycle element time generators as input for typical simulation problems.
- (iii) A statistical comparison of simulated and observed production applied to the above case study proved that there is no significant difference, indicating that the simulation model outputs represent real production.
- (iv) Results obtained by the simulation model applied to another case study (A42 - Measham and Ashby By-pass) showed the similarity of production rates with those obtained by a realistic method described elsewhere (Alkass 1988).
- (v) A statistical comparison of simulated production of A42- By-pass and those obtained by a traditional deterministic method (Caterpillar 1987) confirmed the previous finding that deterministic methods over-estimate real production.

11.1.3.3 Determination of an optimum earthmoving plan

The second stage of RESOM was the LP/IP model and was aimed at determining an optimum earthmoving plan satisfying real life constraints. To this end, a detailed and comprehensive LP/IP formulations were developed and validated by critical expert examination and applying them to two other case studies (M40 - Banbury By-pass and a hypothetical example). The situations incorporated in the formulations included:

- (a) testing of different plant teams for individual haulage operations;
- (b) investigation of possibilities for new borrow/ disposal sites;
- (c) treatment for different soil types (strata) at cut sections and borrow pits;
- (d) treatment for different degrees of compaction for various layers of fill sections (subgrade, subbase, sidefill etc.); and

- (e) incorporation of real life constraints like project duration, plant availability, capacity limitations of borrow/disposal sites, sequence of operations, equipment sharing among teams and obstructions for haulage operations due to construction of other structures along the roadway.

The LINDO software package (Linear, INteger and Discrete Optimiser) available for IBM PS/2 was used to solve the above formulations.

The main conclusions derived during LP/IP model development, validation, application and experimentation can be better explained with the aid of the other two models (simulation model and network model) and hence presented in the next section.

11.1.3.4 Application, experimentation and further validation of RESOM

The use of RESOM to a typical road construction project was explained by a step-by-step application of RESOM to case study 3 (M40 - Banbury By-pass). The results obtained were compared with those proposed by the contractor. The advanced use of RESOM was also explained using a hypothetical example. The results obtained were very encouraging and the main conclusions derived during this process were as follows.

- (i) A comparison of RESOM solution (material distribution, plant utilisation, overall cost etc.) obtained from LP/IP model and that used by the contractor based on the traditional mass-haul diagram, applied to case study 3 (M40 - Banbury By-pass) indicated that about 20% of earthmoving costs (Figure 10.5) can be saved by RESOM still satisfying all the contractor's constraints.
- (ii) The advanced use of RESOM was explained using a hypothetical example (case study 4) and showed that most real life constraints like project duration, resource limitations, sequence of operation, equipment sharing constraints etc. can easily be incorporated in obtaining an optimum earthmoving plan.
- (iii) The results obtained by experimentation with RESOM are of considerable help to management in decision making. For example, the model user can easily obtain an optimum construction plan for the following cases.
 - (a) For a given fleet and a given project duration.

- (b) Corresponding to the cheapest possible project cost with a given fleet irrespective of the duration.
- (c) Corresponding to the shortest possible completion time with a given fleet irrespective of the cost.

If the available fleet cannot be successfully utilised for timely project completion the message is readily conveyed. All these aspects were illustrated using case study 4 and the validity of the results was further confirmed by the network model.

- (iv) The sensitivity analysis of the road sectional interval used during the simulation stage indicated that there is no significant effect of average sectional interval variations on the overall project cost. Hence any suitable average sectional interval can be adopted but a value between 500 m and 750 m is recommended.
- (v) The sensitivity analysis of the plant team selection indicated that the variation of the plant team selection may or may not be significant depending on the objective criteria. The important cases noted were:
 - (a) The omission of cheaper teams does have a considerable cost increase if the objective criterion is the cheapest cost. If the project is to be completed at its shortest possible time the difference is not significant.
 - (b) If the objective criterion is the shortest completion time, the omission of teams having higher production rates considerably reduces the overall cost and increases the shortest possible completion time. On the other hand, there is no cost difference if the project is to be completed at the cheapest cost.
- (vi) Finally, the combination of computer simulation and LP/IP programming is a very powerful technique to be used in earthwork optimisation and if appropriate constraints developed in Chapter 4 are applied with understanding and subjective judgement, realistic optimum construction plans can be obtained under various operating levels satisfying real life constraints.

11.2 Recommendations

As far as the future of the construction industry is concerned, contractors should appreciate that more accurate and realistic construction plans and estimates are required to cope with the increasing competition of the construction industry. Past records show that in most situations the estimated project durations and the costs are exceeded when the project is completed. This aspect is particularly common in Sri Lanka.

Application of more systematic and sophisticated models like RESOM not only provides realistic construction plans but a considerable amount of cost savings can be obtained satisfying contractors' constraints. RESOM applied to one case study in the UK showed that 20% of earthmoving costs could have been saved (Figure 10.5). Compared to the UK, more savings may be obtained if the Sri Lankan industry is considered.

Most earthmoving contractors have a very little idea of existing optimisation techniques like computer simulation and linear programming. Even the full potential of the mass-haul diagram is unknown. To improve the situation the availability of these techniques should be made aware of.

Although the present form of RESOM may not be very attractive to the industry, due to its lack of user friendliness, improving these aspects, in particular, by combining all three stages of RESOM, the author strongly feels that such a model can contribute considerable amount of information much needed to an earthwork estimator and planning engineer. If this can be achieved even an inexperienced estimator is capable of producing much accurate and realistic estimates saving valuable resources.

11.3 Further Research

Throughout this research, the author's main intention was to develop a new concept for earthmoving optimisation and to examine its validity and applicability for real life situations. Consequently, RESOM developed in this thesis lacks facilities to be considered as a comprehensive model.

One of the main areas to be worked on is the development of cycle element time generators in the form of theoretical distributions or frequency histograms for other operating conditions, plant team configurations which are not covered in the thesis. This requires additional field data collection and systematic statistical analysis.

Clearly, the accuracy of RESOM output depends on the correct input of the operating conditions. Hence, the effects of subjective factors: operational factor; fill site condition; cut site condition; and the soil type, on the optimum solution should be further investigated.

As far as the computer programming aspect of the RESOM is concerned, an improved user interface, and a possible assembling of all three stages of RESOM: simulation model, LP/IP model and network model would greatly enhance its applicability as a true optimiser. If these aspects are properly incorporated, practising contractors can easily be convinced the potential of RESOM and its cost savings. This way the model can be improved as a commercial software package.

Although RESOM does not require a usage of balanced plant team to start with, the model user should at least identify the type of plant to be used for a particular operating condition under consideration. For example, a scraper team cannot be used for hard rock excavation. Consequently, a novice may have difficulties with RESOM. To overcome this drawback, the possibility of combining with an expert system like the one developed by Alkass (1988) is worth investigating.

APPENDIX A

SYSTEM VARIABLE DEFINITIONS

$C(i,j,n)$	= unit cost of hauling of 1m^3 of soil (including excavation and compaction) from cut section i to fill section j by team n ;
$C(i,j,s,c,n)$	= unit cost of hauling of 1m^3 of soil type s from cut section i to layer c in fill section j by team n ;
$C_B(p,j,n)$	is defined similar to $C(i,j,n)$ for borrow pit p ;
$C_B(p,j,s,c,n)$	= unit cost of hauling soil type s from borrow pit p to layer c in fill section j by team n ;
$C_c(i,j,n)$	= unit cost of compaction of soil cut from section i and compacted in fill j by team n ;
$C_D(i,k,n)$	= unit cost of disposing soil cut from section i and disposed in disposal site k by team n ;
$C_D(i,k,s,n)$	= unit cost of disposing soil type s from cut section i to disposal site k by team n ;
$C_e(i,n)$	= unit cost of excavation in cut section i by team number n ;
$C_h(i,n)$	= unit cost of hauling from cut section i by team number n ;
$C_{SB}(b,j,s,c,n)$	= unit cost of hauling soil type s from borrow pit b (to be set up) to layer c in fill section j by team n ;
$C_{SD}(i,d,s,n)$	= unit cost of disposing soil type s from cut section i to disposal site d (to be set up) by team n ;
D	= project duration in days;
$d(i,j)$	= distance in kilo metres between centre of masses of cut i and fill j ;
d_s	= construction duration of structure s in days;
ϵ	= a very small positive value;
$K_{SB}(b)$	= set up cost of borrow pit b ;
$K_{SD}(d)$	= set up cost of disposal site d ;
N	= entire set of team identification numbers available to the contract;
n	= any plant team identification number;
$N_{i,d}$	= a set of identification numbers of plant teams which will be used to haul material from cut i to disposal site d (to be set up);
$N_{i,d,s}$	= a set of identification numbers of plant teams which will be used to dispose material from strata type s of cut i to disposal site d (to be set up);
$N_{i,j}$	= a set of identification numbers of plant teams which will be used to haul material from cut i to fill section j ;

- $N_{i,j,s,c}$ = a set of identification numbers of plant teams which will be used to haul material from strata type s in cut i to be compacted in layer c in fill j ;
- $N_{i,k}$ = a set of identification numbers of plant teams which will be used to dispose material from cut i to disposal site k ;
- $N_{i,k,s}$ = a set of identification numbers of plant teams which will be used to dispose material from strata type s of cut i to disposal site k ;
- $N_{p,j}, N_{b,j}$ are defined similar to $N_{i,j}$ for borrow pit p and b (to be set up);
- $N_{p,j,s,c}, N_{b,j,s,c}$ are defined similar to $N_{i,j,s,c}$ for borrow pit p and b (to be set up);
- N_T = a set of equipment teams which share individual equipment items;
- $P(i,j,n)$ = production (m^3/day) when moving soil from cut i to fill j by team n ;
- $P(i,j,s,c,n)$ = production (m^3/day) when moving soil type s from cut i to layer c in fill j by team n ;
- $P_B(p,j,n), P_{SB}(b,j,n)$ are defined similar to $P(i,j,n)$ for borrow pit p and b (to be set up) respectively;
- $P_B(p,j,s,c,n), P_{SB}(b,j,s,c,n)$ are defined similar to $P(i,j,s,c,n)$ for borrow pit p and b (to be set up) respectively;
- $P_D(i,k,n)$ = production (m^3/day) when disposing soil from cut i to disposal site k by team n ;
- $P_D(i,k,s,n)$ = production (m^3/day) when disposing soil type s from cut i to disposal site k by team n ;
- $P_{SD}(i,d,n)$ is defined similar to $P_D(i,k,n)$ for disposal site d (to be set up).
- $P_{SD}(i,d,s,n)$ is defined similar to $P_D(i,k,s,n)$ for disposal site d (to be set up);
- $Q_B(p), Q_D(k)$ = capacity limitations of borrow pit p and disposal site k (m^3) respectively;
- $Q_B(p,s)$ = capacity limitation of soil type s in borrow pit p ;
- $Q_C(i), Q_F(j)$ = cut required in section i and fill required in section j respectively in metre cubes;
- $Q_C(i,s)$ = cut required at section i corresponding to soil type s ;
- $Q_F(j,c)$ = fill required at section j corresponding to layer c ;
- $Q_{SB}(b)$ = capacity limitation of borrow pit b (to be set up);
- $Q_{SB}(b,s)$ = capacity limitation of soil type s in borrow pit b (to be set up);
- $Q_{SD}(d)$ = capacity limitation of disposal site d (to be set up);
- $S_{i,d,n}^f$ = swell (or shrinkage) factor in fill for soil excavated at cut i by team n to be disposed at disposal site d (to be set up);

$S_{i,j}^f$	=	swell (or shrinkage) factor in fill for soil excavated at cut i to be compacted in fill j ;
$S_{i,j,s,c}^f$	=	swell (or shrinkage) factor in fill for soil type s excavated from cut i to be compacted in layer c of fill j ;
$S_{i,k,n}^f$	=	swell (or shrinkage) factor in fill for soil excavated at cut i by team n to be disposed at disposal site k ;
$S_{p,j}^f, S_{b,j}^f$		are defined similar to $S_{i,j}^f$ for borrow pit p and b (to be set up);
$S_{p,j,s,c}^f, S_{b,j,s,c}^f$		are defined similar to $S_{i,j,s,c}^f$ for borrow pit p and b (to be set up) respectively;
$T_D(m)$	=	total time required in days to carry out all material movements corresponding to roadway section m without using any structure such as a culvert or a bridge;
$T_{ND}(m)$	=	total time required in days to carry out all material movements corresponding to roadway section m when using a structure such as a culvert or a bridge;
$X(i,j,n)$	=	quantity of soil moved (m^3) from cut i to fill j by team n ;
$X(i,j,s,c,n)$	=	quantity of soil type s moved from cut i to layer c in fill j by team n ;
$X(m,j,s,c,n)$	=	quantity of soil type s moved from section m to layer c in fill j by team n ;
$X_B(p,j,n), X_{SB}(b,j,n)$		are defined similar to $X(i,j,n)$ for borrow pit p and b (to be set up);
$X_B(p,j,s,c,n), X_{SB}(b,j,s,c,n)$		are defined similar to $X(i,j,s,c,n)$ for borrow pit p and b (to be set up) respectively;
$X_D(i,k,n)$	=	quantity of soil disposed (m^3) from cut i to disposal site k by team n ;
$X_D(i,k,s,n)$	=	quantity of soil type s disposed from cut i to disposal site k by team n ;
$X_D(m,k,s,n)$	=	quantity of soil type s disposed from section m to disposal site k by team n ;
$X_{SD}(i,d,n)$		is defined similar to $X_D(i,k,n)$ for disposal site d (to be set up);
$X_{SD}(i,d,s,n)$		is defined similar to $X_D(i,k,s,n)$ for disposal site d (to be set up);
$X_{SD}(m,d,s,n)$		is defined similar to $X_D(m,k,s,n)$ for disposal site d (to be set up);
$Y_{SB}(b)$	=	binary variable for borrow pit b ;
$Y_{SD}(d)$	=	binary variable for disposal site d ;
Z	=	total earthmoving cost;
$\lambda(m)$	=	binary variable for roadway section m .

APPENDIX B

QUESTIONNAIRE SURVEY FORM (A SPECIMEN)

IDENTIFICATION OF IMPORTANT FACTORS AFFECTING EARTHMOVING CYCLE ELEMENT TIMES : A SURVEY

This survey is carried out to identify the important variables affecting various cycle element times of scraper-pusher and loader-truck operations.

Please write the letter corresponding to appropriate category of importance, against each factor listed. You may also add any other important factors that are not listed.

Categories of importance : A - very important
 B - important
 C - not very important
 D - not important at all

Scraper operations

Cycle element	Factor	Category
Scraper - loading	(a) loading method (single pusher, 2 pushers, push-pull, elevating	.....A.....
	(b) capacity of bowl	.....B.....
	(c) engine horse power (scraper)	.....C.....
	(d) type of soil	.....A.....
	(e) grade (up hill, down hill, flat)	.....B.....
	(f) weather	.....A.....
	(g) operator efficiency	.....B.....
	(h) horse power (pusher)	.....B.....
	(i) size and condition at site	.....B.....
	(others specify) (j)	
Scraper - hauling & returning	(a) number of engines	.....B.....
	(b) horse power	.....C.....
	(c) topography (grade of travel)	.....B.....
	(d) weather	.....B.....
	(e) haul road conditions	.....C.....
	(f) operator efficiency	.....B.....
	(g) interaction with external operations	.....C.....
	(h) haul distance	.....A.....

(others specify) (i)

Scraper - dump & turn	(a) ground conditions	.....B.....
	(b) degree of interaction with external operations	.....C.....
	(c) topography	.....B.....
	(d) weather	.....B.....
	(e) operator efficiency	.....B.....
	(f) horse power	.....C.....
(others specify) (g)		

Pusher operations

Cycle element	Factor	Category
Pusher - loading	(a) pushing method	.....B.....
	(b) pusher horse power	.....B.....
	(c) topography (grade)	.....C.....
	(d) weather	.....B.....
	(e) operator efficiency	.....B.....
	(f) soil type	.....B.....
	(g) scraper bowl capacity	.....C.....
	(h) ground conditions	.....B.....
(others specify) (i)		
Pusher - return (after pushing to another scraper)	(a) pusher horse power	.....C.....
	(b) topography	.....C.....
	(c) weather	.....C.....
	(d) operator efficiency	.....B.....
	(e) interaction with external operations	.....C.....
(others specify)	(f)	

Truck operations

Cycle element	Factor	Category
Truck - loading	(a) truck capacity	.....A.....
	(b) bucket capacity	.....A.....
	(c) type of loader (wheel, backhoe)	.....A.....
	(d) type of soil	.....B.....
	(e) bucket fill factor	.....C.....
	(f) topography	.....C.....
	(g) ground conditions	.....B.....
	(h) weather	.....B.....
	(i) operator efficiency	.....B.....
	(j) interaction with external operations	.....B.....
	(k) distance from pile to truck	.....B.....
	(others specify) (l)	
Truck - hauling & returning	(a) haul/return distance	.....A.....
	(b) haul road condition	.....B.....
	(c) horse power	.....C.....
	(d) topography	.....C.....
	(e) weather	.....B.....
	(f) operator efficiency	.....C.....
	(g) interaction with external operations	.....C.....
	(others specify) (h)	
Truck - dump & turn	(a) type of truck (bottom dump, articulated etc.)	.....B.....
	(b) size of truck (capacity)	.....C.....
	(c) topography	.....C.....
	(d) weather	.....C.....
	(e) operator efficiency	.....B.....
	(f) ground conditions	.....B.....
	(g) interaction with external operations	.....B.....
	(others specify) (h)	

Loader operations

Cycle element	Factor	Category
<hr/>		
Loader cycle	(a) type of loader (wheel, backhoe)	.....A.....
	(b) type of soil	.....B.....
	(c) bucket capacity	.....C.....
	(d) topography	.....C.....
	(e) ground conditions (B-wheel loader, C-backhoe loader)	
	(f) weather (B-wheel loader, C-backhoe)	..... . .....
	(g) operator efficiency	.....B.....
	(h) distance from pile to truck	.....A.....
	(others specify) (i)	

THANK YOU FOR YOUR KIND CO-OPERATION

APPENDIX C

OBSERVATION FORMS USED FOR FIELD DATA COLLECTION

- C.1 Study Description and Equipment Specification Form
- C.2 Time Study Observation Form for Scraper, Truck and Dozer Operations
- C.3 Time Study Observation Form for Grading and Compacting Operations
- C.4 Time Study Observation Form for Loader Operations
- C.5 Daily Hauling Report
- C.6 Instructions Given During Field Data Collection
 - C.6.1 Filling instructions - Study description and equipment specification form
 - C.6.2 Filling instructions - Time study observation form for scraper, truck and dozer operations
 - C.6.3 Filling instructions - Time study observation form for grading and compacting operations
 - C.6.4 Filling instructions - Time study observation form for loader operations

APPENDIX C.1

STUDY DESCRIPTION AND EQUIPMENT SPECIFICATION FORM

Project : Gam Udawa 88 - Anamaduwa
 Date : 02/01/88
 Destination : Piramid road
 Weather : Fine
 Source : Naikkulama Borrow pit
 Soil type : Common earth
 Haul distance (m) : 1100
 Return distance (m) : 1100
 Road condition : Average
 Grade of haul road : Negligible
 Degree of supervision : Average
 Associated loader : International wheel loader

Eqt.name	Model	Make	Type	Qty.(m ³)	Id. number
loader	-	Inter.	wheel	3.10	JH90
truck	RD8	Nissan	r-dump	7.07	41/2340
truck	PE6	Nissan	r-dump	7.07	41/3306
truck	PM	Nissan	r-dump	19.80	41/3201
truck	-	Nissan	r-dump	9.91	27/560
truck	PM	Nissan	r-dump	19.80	41/3204
truck	-	Nissan	r-dump	9.91	41/7027
truck	PE6	Nissan	r-dump	7.07	41/3314
truck	-	Nissan	r-dump	9.91	41/5403
truck	-	Nissan	r-dump	9.91	41/5405
truck	RD8	Nissan	r-dump	7.07	41/2325
<div style="border: 1px solid black; padding: 5px; text-align: center;"> Specimen Note: Filling instructions are given in section C.6.1 </div>					

APPENDIX C.2

TIME STUDY OBSERVATION FORM FOR SCRAPER, TRUCK AND DOZER OPERATIONS

Project : Gam Udawa 88 Anamaduwa		Sheet number : 3	
Source : Naikkulama		Date : 02/01/88	
Destination : Piramid road			

Equipment id number	Associated loader	CLOCK TIME								Quantity (m3)	Comments
		End returning	Start loading	End loading	Start hauling	End hauling	Start unloading	End unloading	Start returning		
41/2340	JH90	10/31/35	10/31/35	10/33/05	10/33/05	10/50/06	10/50/06	10/50/35	10/50/35	7.07	* Signing running chart * inspecting the vehicle
41/3201		10/35/03	10/35/35	10/41/21	10/41/21	11/02/45	11/02/45	11/03/20	11/03/25	19.8	
41/3201		10/35/28	10/42/21	10/43/24	10/43/24	11/02/45	11/02/50	11/03/25	11/03/25	7.07	
27/560		10/47/50	10/47/50	10/48/32	10/48/54	11/14/41	11/14/47	11/15/07	11/15/17	9.91	
41/3204		10/48/10	10/49/12	10/53/21	10/53/21	11/18/53	11/18/53	11/19/06	11/19/06	19.8	
41/7027		10/56/21	10/56/21	10/57/24	10/57/24	11/20/38	11/20/38	11/21/05	11/21/05	9.91	
41/2340		11/09/15	11/09/15	11/10/40	11/10/44	11/26/35	11/26/35	11/27/00	11/27/00	7.07	
41/3314		11/13/02	11/13/02	11/14/00	11/14/00	11/29/57	11/29/57	11/30/25	11/40/01	7.07	
41/3306		11/23/31	11/23/31	11/25/10	11/25/10	11/38/10	11/38/30	11/38/51	11/38/51	7.07	
41/2325		11/33/15	11/33/15	11/35/16	11/35/16	11/53/16	11/53/46	11/54/07	11/54/07	7.07	
27/560		11/36/10	11/36/10	11/37/13	11/37/13	11/56/21	11/56/21	11/56/47	11/56/47	9.91	
41/3201		11/39/17	11/39/17	11/42/50	11/42/50	12/03/06	12/03/06	12/04/08	12/04/08	19.8	
41/3204		11/43/37	11/43/37	11/48/31	11/48/31	12/08/31	12/08/31	12/09/58	12/09/58	19.8	
41/2340		-	-	-	-	12/09/06	12/09/06	12/09/31	12/09/31	7.07	

Specimen
Note : Filling instructions are given in section C.6.2

Total

Observer

Checker

APPENDIX C.3

TIME STUDY OBSERVATION FORM FOR GRADING AND COMPACTING OPERATIONS

Project : Gam Udawa 88 Anamaduwa

Date : 26/12/87

Sheet no : 1

Eqt. name	Model	Type	Id. number	Road : Main road	Thickness of layer : 15 cm.	Bulk density (kg/m ³) : 1700
Compactor	Bomag	Vibratory	BW212D	Time start : 10:16 am	Chainage of strip : +780 to +875 m	Field density (kg/m ³) : 2080
				Time finished : 02:47 pm	Width of strip : 23 m	Compaction attained (%) : 102
				Weather : fine	CBR value : 28	Compaction expected (%) : 100
				Soil type : wet gravel	M/C : 8.7	

Eqt. id number	Clock time (compaction / grading)												Total time (min)	Total no. of passes	Comments
	1			2			3			4					
	Start	End	No. of passes	Start	End	No. of passes	Start	End	No. of passes	Start	End	No. of passes			
BW212D	10/16	10/56 ¹	12	11/03	12/00 ²	26	01/03	02/46 ³	60				200	98	1 - stop for refuelling 2 - lunch break 3 - end of compacting that layer

Specimen
Note : Filling instructions are given in section C.6.3

Observer

Checker

APPENDIX C.4

TIME STUDY OBSERVATION FORM FOR LOADER OPERATIONS

Project	: Wallatota (Nilwala Ganga)	Sheet no	: 1	Soil type	: Common earth
Equipment id	: Poclain 170 B	Time started	: 07:21 am	Time finished	: 07:50 am
Location	: Wallatota	Weather	: Cloudy		
Loader type	: Backhoe				
Site condition	: Average				

Truck load no.	Start cycle	End cycle	Start idle	End idle	Comments
1	07/21/38	07/21/59			
	07/21/59	07/22/23			
	07/22/23	07/22/39	07/22/39	07/22/48	
2	07/22/48	07/26/24	07/22/59 *	07/26/10	* dropped the soil bucket and cleaned the truck
	07/26/24	07/27/03			
	07/27/03	07/27/23			
	07/27/23	07/27/44			
	-	-			
3	07/28/20	07/31/14	07/28/28 *	07/31/10	* waiting for the next truck
	07/31/14	07/31/41			
	07/31/41	07/32/03			
	07/32/03	07/32/25			
	07/32/25	07/32/48			
4	07/32/48	07/34/11	07/32/55 *	07/33/55	* waiting for the next truck
	07/34/11	07/34/33			
	07/34/33	07/35/01			
	07/35/01	07/35/25			
	07/35/25	07/36/01	07/35/35 *	07/35/50	* same reason as above
<div style="border: 1px solid black; padding: 5px; margin: 10px auto; width: fit-content;"> Specimen Note : Filling instructions are given in section C.6.4 </div>					

Observer _____

Checker _____

APPENDIX C.5

DAILY HAULING REPORT

Project: Nilwala ganga (Wallatota)

Source : Wallatota borrow pit 201

Distance (one way) : 1.5 km (average)

Number	Description of equipment	Time (started)	Time (end)	No.of loads	Remarks
1	Poclain backhoe loader 170 CKB	07:08 am	05:51 pm	-	4217 - engaged in external work from 9 am to 10:31 am
2	Renault dump truck 4217	07:00 am	05:45 pm	40	
3	Renault dump truck 4216	07:00 am	05:55 pm	44	
4	Renault dump truck 4212	07:00 am	05:52 pm	43	
5	Renault dump truck 4211	08:20 am	05:52 pm	33	
<div style="border: 1px solid black; padding: 5px; text-align: center;">Specimen</div>					

C.6 Instructions Given During Field Data Collection

C.6.1 Filling Instructions - Study description and equipment specification form

<i>Destination</i>	: Filling section or the disposal site;
<i>Source</i>	: The name of the cut section or the borrow pit currently being used;
<i>Soil type</i>	: Whether the type of soil is common earth, weathered rock or hard rock;
<i>Road condition</i>	: Whether the haul road is good, average or poor;
<i>Grade of haul road</i>	: Whether the haul road is steep uphill (on hauling), medium uphill, negligible, medium downhill, or steep downhill;
<i>Degree of supervision</i>	: Whether good, average or poor;
<i>Equipment name</i>	: Whether the equipment item is a dump truck, scraper, loader, dozer etc;
<i>Model</i>	: The model of the equipment item (eg. Cat 631E);
<i>Make</i>	: Equipment make (eg. Caterpillar, Komatsu etc.);
<i>Type</i>	: Scraper - push loading with single pusher, push loading with 2 pushers, push-pull loading or elevating; Truck - side dump, bottom dump, rear dump, articulated etc; Loader - wheel loader or backhoe loader;
<i>Capacity</i>	: Scraper and truck - practical capacity (m^3); Loader - practical bucket capacity (m^3); Dozer - Practical blade capacity (m^3);
<i>Id. number</i>	: Identification number of the equipment item.

C.6.2 Filling instructions - Time study observation form for scraper, truck and dozer operations

<i>Equipment id number</i>	: Registration or the identification number of equipment item;
<i>Associated loader</i>	: Scraper - pusher or any other scraper used to assist the loading during the loading phase; Truck - the wheel loader or the backhoe used to load the truck;
<i>End returning</i>	: Arrival time to the loading queue at cutting section (not including the queuing time);
<i>Start loading</i>	: Scraper - when the blade is lowered and start cutting; Truck - end of positioning the truck or start moving the loader to take the first soil bucket, whichever happens last;
<i>End loading</i>	: Scraper - when the scraper and the associated pusher disengaged; for self loading scrapers - when the blade is lifted and cutting stops; Truck - after the last bucket has been put and ready to move off;
<i>Start hauling</i>	: Truck or scraper actually start leaving for the fill section;
<i>End hauling</i>	: Just off the haul road at the fill section or the disposal site;
<i>Start unloading</i>	: Start unloading after waiting in the queue (if any) at the filling area;
<i>End unloading</i>	: Just after unloading and ready to move from the filling section or the disposal site;
<i>Start returning</i>	: Actually moving off the filling area;
<i>Quantity</i>	: Quantity of soil actually moved by the scraper, truck or dozer corresponding to that trip (m ³);
<i>Comments</i>	: Any unusual happenings like external delays, delays along the haul road, breakdowns (quantify), operator missing, efficiency and any suggestions for improving the situation etc.

C.6.3 Filling instructions - Time study observation form for grading and compacting operations

<i>Eqt. name</i>	: Write whether the equipment piece is a compactor or a grader;
<i>Type</i>	: Compactor - whether it is a road roller, vibratory, sheepsfoot, pneumatic tyred etc.;
<i>Time start</i>	: The first event time recorded in a particular observation sheet;
<i>Time finished</i>	: The last event time recorded in a particular observation sheet;
<i>Soil type</i>	: As instructed in the previous sheet;
<i>Thickness of layer</i>	: Thickness of the soil layer to be compacted;
<i>Chainage of strip</i>	: Chainage of the strip being compacted;
<i>Width of the strip</i>	: Width of the strip being compacted;
<i>CBR value</i>	: California Bearing Ratio value of the soil used;
<i>M/C</i>	: Moisture content of the soil being used;
<i>Bulk density</i>	: Loose density of soil used;
<i>Field density</i>	: Compacted density;
<i>Compaction attained and compaction expected</i>	: Write as a percentage of the maximum dry density;
<i>Eqt. id number</i>	: registration or the id. number of the equipment item;
<i>Start</i>	: Starting time of grading or compacting operations initially or after a break, (next start time [if after a break] should be put under the next column);
<i>End</i>	: End time of grading or compacting operations after completing the job or intermediate endings for other requirements;
<i>No. of passes</i>	: Total number of passes between start and end in the case of compacting equipment only;
<i>Total time</i>	: Total net time spent corresponding to the particular entry row under consideration ;
<i>Total no. of passes</i>	: Total number of passes achieved during the total time above;
<i>Comments</i>	: Any unusual happenings like breakdowns, delays etc. and any suggestions to improve the situation.

C.6.4 Filling Instructions - Time study observation form for loader operations

<i>Equipment id.</i>	: Identification number of the loader;
<i>Loader type</i>	: Whether it is a wheel loader or a backhoe loader;
<i>Site condition</i>	: Whether the condition of the loading site is good, average or poor;
<i>Time started</i>	: The first event time recorded in a particular observation sheet;
<i>Time finished</i>	: The last event time recorded in a particular observation sheet;
<i>Truck load no.</i>	: A sequential figure to represent the start loading to a new truck;
<i>Start cycle</i>	: Start time of a loader cycle and can be any event time convenient to the observer;
<i>End cycle</i>	: End time of a loader cycle taken at the same event considered during the start cycle;
<i>Start idle</i>	: Start time of idling the loader either between two consecutive cycles or within the same cycle without a truck to be loaded or when the truck is not properly positioned;
<i>End idle</i>	: End idling of the loader either between two consecutive cycles or within a cycle and start loading the next truck;
<i>Comments</i>	: Any unusual happenings like external delays, breakdowns etc. and suggestions to improve the situation.

APPENDIX D

SAMPLE COMPUTER OUTPUTS OF DATA ANALYSIS AND PRESENTATION OF OBSERVED AND FITTED HISTOGRAMS

- D.1 Introduction
- D.2 Sample Output of Factor Analysis : Hauling Time
- D.3 Distribution Fitting
 - D.3.1 Distribution fitting : Loader cycle time (wheel loader, common earth with poor operational factor)
 - D.3.1.1 Plotting of various histograms using MINTAB
 - D.3.1.2 Distribution fitting using ECSL
 - D.3.2 Pictorial representation of observed and fitted histograms
 - D.3.2.1 Histograms of loader cycle times
 - D.3.2.2 Histograms of dump and turn times
 - D.3.2.3 Histograms of positioning delay times
 - D.3.2.4 Histogram of return delay time
 - D.3.2.5 Histogram of hauling delay time

D.1 Introduction

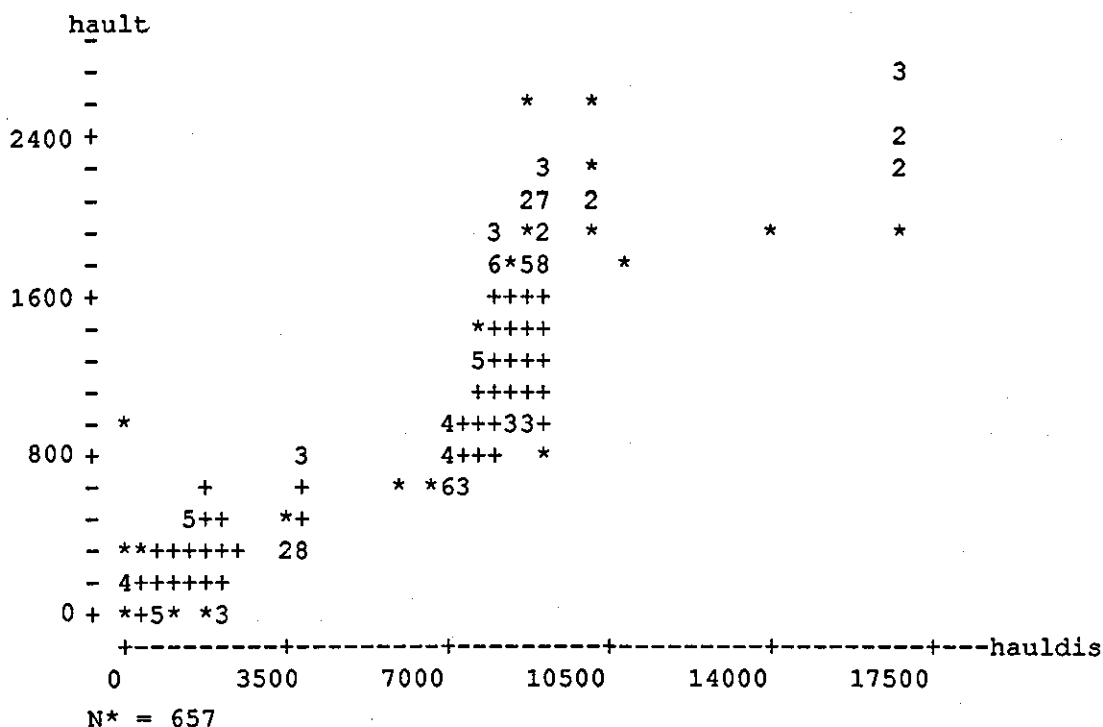
As explained in Chapter 7, a detailed statistical analysis was performed using a statistical package called MINITAB to identify significant factors affecting various earthmoving cycle element times. Subsequently, the simulation package called ECSL in combination with MINITAB was used to fit theoretical distributions to those cycle elements.

The first part of this appendix provides a portion of MINITAB outputs obtained during the identification of significant factors affecting truck hauling time. The second part presents a fraction of both MINITAB and ECSL outputs obtained during distribution fitting for loader cycle time. The final part summarises the distributions by plotting observed and fitted histograms corresponding to different cycle elements and operating levels.

D.2 Sample Output of Factor Analysis : Hauling Time

```
MTB > retrieve 'mhauldat'
MTB > # Analysis of hauling time
MTB > correlation hault hauldis

correlation of hault and hauldis = 0.959
MTB > # Combined analysis without factors
MTB > # C5 - haul time (seconds)
MTB > # C14 - haul distance (metres)
MTB > # C20 - size of truck
MTB > # C21 - grade of haul road
MTB > # C22 - haul road condition
MTB > # C23 - site numbers
MTB > # C25 - operational factor
MTB > plot C5 C14
```



```
MTB > # create indicator variables for regression analysis
MTB > indicator C20 put into C30 C31 C32 C33
MTB > indicator C21 put into C33 C34
MTB > indicator C22 put into C34 C35 C36
MTB > indicator C23 put into C36 C37 C38 C39
MTB > indicator C25 put into C39 C40
MTB > correlation C5 C14 C30-C39
```

	hault	C30	C31	C32	C33	C34	C35
hauldis	0.959						
C30	0.146	0.092					
C31	-0.540	-0.386	-0.372				
C32	0.219	0.171	-0.021	-0.473			
C33	-0.748	-0.647	-0.139	-0.372	-0.176		
C34	0.541	0.552	0.096	-0.257	0.122	-0.392	
C35	-0.529	-0.542	-0.093	0.250	-0.118	0.398	-0.971
C36	0.932	0.821	0.167	-0.448	0.212	-0.832	0.575 -0.558
C37	-0.231	-0.260	-0.040	0.106	-0.050	-0.341	-0.289 0.249
C38	-0.374	-0.373	-0.064	0.173	-0.082	0.464	-0.672 0.692
C39	0.231	0.259	0.040	-0.107	0.050	0.341	0.289 -0.249
	C36	C37	C38				
C37	-0.238						
C38	-0.386	-0.158					
C39	0.238	-1.000	0.158				

```
MTB > regress C5 on 11 predictors C14 C30-C39
```

```
* C37 is highly correlated with other X variables
* C37 has been removed from the equation
```

```
* C39 is highly correlated with other X variables
* C39 has been removed from the equation
```

The regression equation is

hault = 360 + 0.161 hauldis - 199 C30 - 287 C31 - 158 C32 - 68.2 C33
 - 44.3 C34 + 37.0 C35 -226 C36 + 7.98 C38

4072 cases used 657 cases contain missing values

Continue ?

predictor	Coef	Stdev	t-ratio
constant	359.76	18.22	19.74
hauldis	0.160644	0.002693	59.65
C30	-199.26	19.13	-10.41
C31	-287.282	8.385	-34.26
C32	-157.68	14.65	-10.77
C33	-68.159	7.959	-8.56
C34	-44.28	16.42	-2.70
C35	37.05	16.44	2.25
C36	-226.36	21.47	-10.54
C38	7.978	7.034	1.13

s = 116.9 R-sq = 94.2% R-sq(adj) = 94.2%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	9	905510912	100612320
Error	4062	55499728	13663
Total	4071	961010560	

Continue ?

SOURCE	DF	ESQ SS
hauldis	1	883746816
C30	1	25056
C31	1	14868128
C32	1	1515118
C33	1	747105
C34	1	3042800
C35	1	7645
C36	1	1540637
C38	1	17574

MTB > stepwise C5 C14 C30-C39

STEPWISE REGRESSION OF hault ON 11 PREDICTORS, WITH N=4072

N(CASES WITH MISSING OBS.)=657 N(ALL CASES) = 4729

Continue ?

STEP	1	2	3	4	5	6	7
CONSTANT	44.80	280.60	299.58	327.97	358.10	346.99	334.35
hauldis	0.13886	0.13005	0.13713	0.13717	0.13718	0.13801	0.15947
T-RATIO	215.76	199.12	175.41	176.97	179.22	179.40	60.04
C31		-226.3	-222.2	-250.6	-280.7	-279.5	-287.2
T-RATIO		-29.90	-30.18	-31.19	-33.17	-33.22	-34.23
C34			-77.1	-77.2	-77.2	-72.9	-84.6
T-RATIO			-15.52	-15.68	-15.88	-14.97	-16.84
C32				-125	-155	-155	-158
T-RATIO				-8.46	-10.42	-10.49	-10.75
C30					-199	-199	-199
T-RATIO					-10.23	-10.30	-10.41
C37						48.5	60.6
T-RATIO						7.22	8.89

C36							-151
T-RATIO							-8.44
Continue ?							
S	138	125	121	120	119	118	117
R-SQ	91.96	93.41	93.78	93.88	94.04	94.11	94.21

MORE ? (YES, NO, SUBCOMMAND, OR HELP)
SUBC> Y

STEP 8
CONSTANT 294.5

hauldis 0.1603
T-RATIO 59.92

C31 -287.3
T-RATIO -34.26

C34 -46
T-RATIO -2.84

C32 -158
T-RATIO -10.76

C30 -199
T-RATIO -10.41

C37 63.7
T-RATIO 9.20

C36 -156
T-RATIO -8.67

Continue ?

C35 40
T-RATIO 2.46

S 117
R-SQ 94.22

MORE ? (YES, NO, SUBCOMMAND, OR HELP)
SUBC> Y

NO VARIABLES ENTERED OR REMOVED
MORE ? (YES, NO, SUBCOMMAND, OR HELP)
SUBC> n

MTB > regress C5 on 1 predictor C14

The regression equation is
hault = 44.8 + 0.139 hauldis

4072 cases used 657 cases contain missing values

predictor	Coef	Stdev	t-ratio
constant	44.795	3.098	14.46
hauldis	0.138863	0.000644	215.76

s = 137.8 R-sq = 92.0% R-sq(adj) = 92.0%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	1	883746816	883746816
Error	4070	77263792	18984

Total 4071 961010560

MTB > regress C5 on 2 predictors C14 C31

The regression equation is
hault = 281 + 0.130 hauldis - 226 C31

4072 cases used 657 cases contain missing values

predictor	Coef	Stdev	t-ratio
constant	280.600	8.372	33.52
hauldis	0.130051	0.000653	199.12
C31	-226.271	7.569	-29.90

s = 124.8 R-sq = 93.4% R-sq(adj) = 93.4%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	2	897661184	448830592
Error	4069	63349440	15569
Total	4071	961010560	

SOURCE	DF	ESQ SS
hauldis	1	883746816
C31	1	13914350

MTB > # test effects on individual variables

MTB > # effect of size of truck can be tested from Anamaduwa

MTB > unstack (C5 C14 C20 C21 C22 C25) into (C40-C45) (C46-C51) (C52-C57) (C58-C63);

SUBC> subscripts in C23.

MTB > # C40 - haul time (Anamaduwa)

MTB > # C41 - haul distance (Anamaduwa)

MTB > # C42 - size of truck (Anamaduwa)

MTB > # C43 - grade (Anamaduwa)

MTB > # C44 - road condition (Anamaduwa)

MTB > # C45 - operational factor (Anamaduwa)

.
.
.

MTB > # test further the effect of truck size

MTB > unstack (c40,c41) into (C68,c69) (c70,c71) (c72,c73) (c74 c75);

SUBC> subscripts c42.

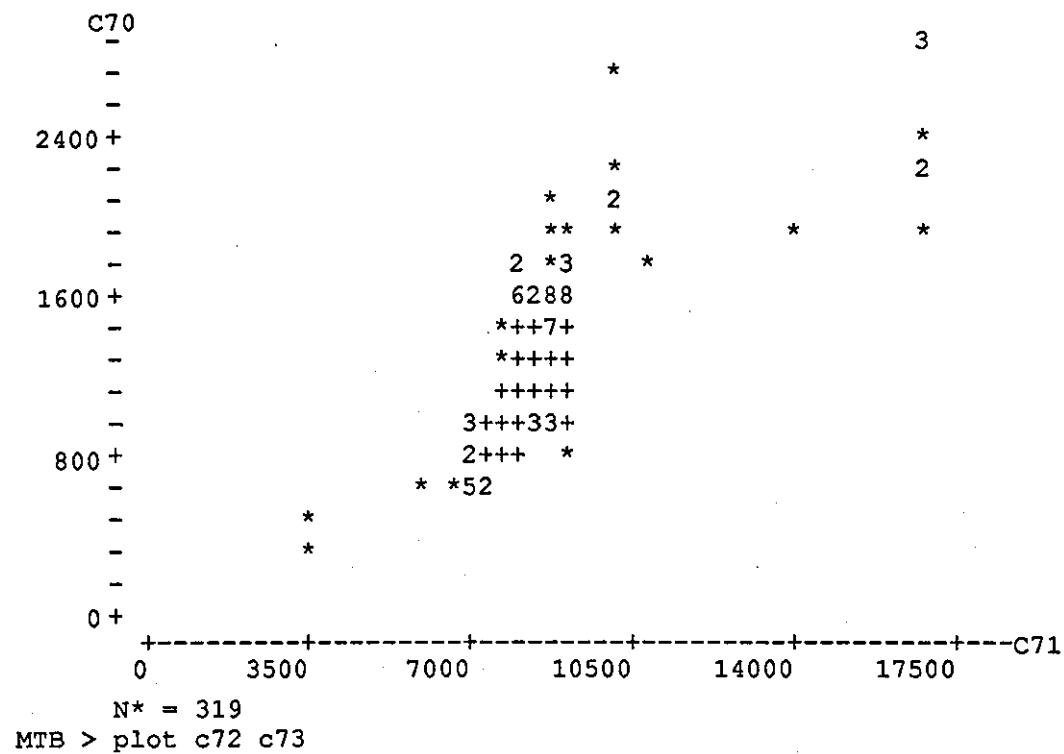
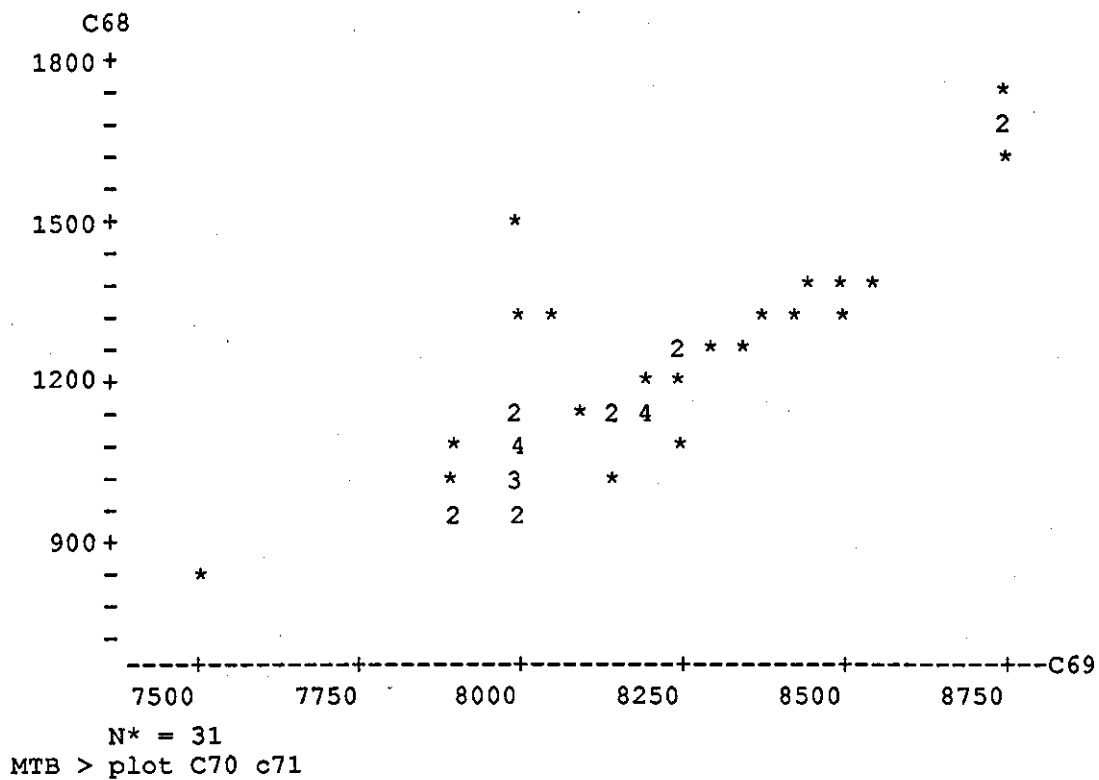
MTB > # C68 and C69 - truck size 1

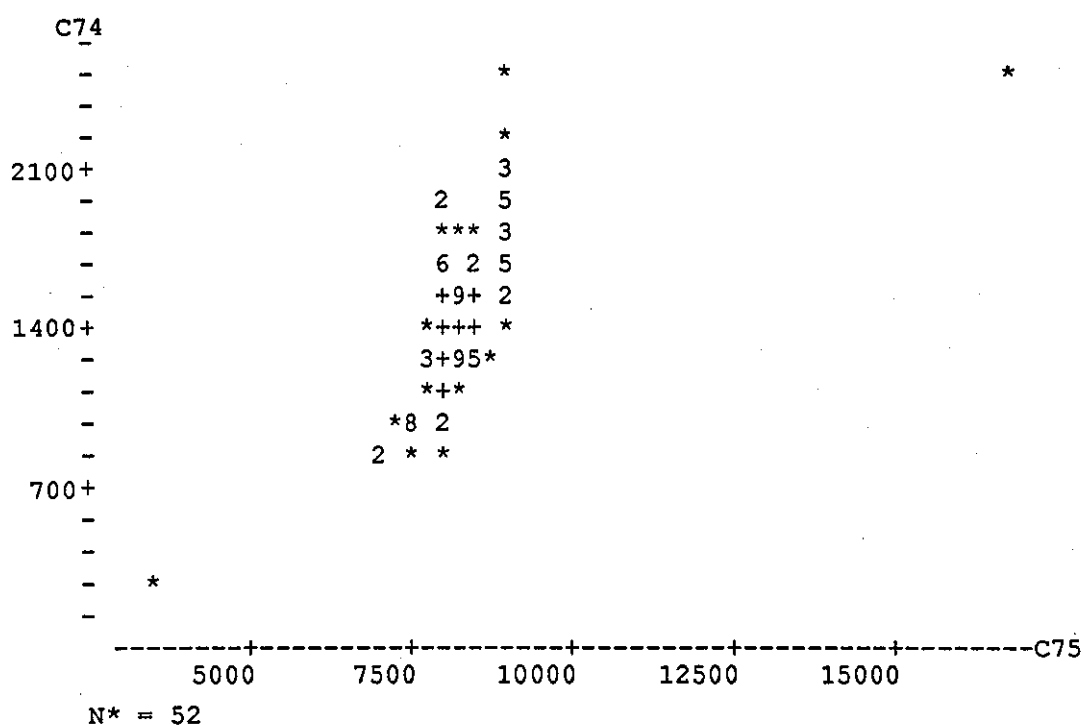
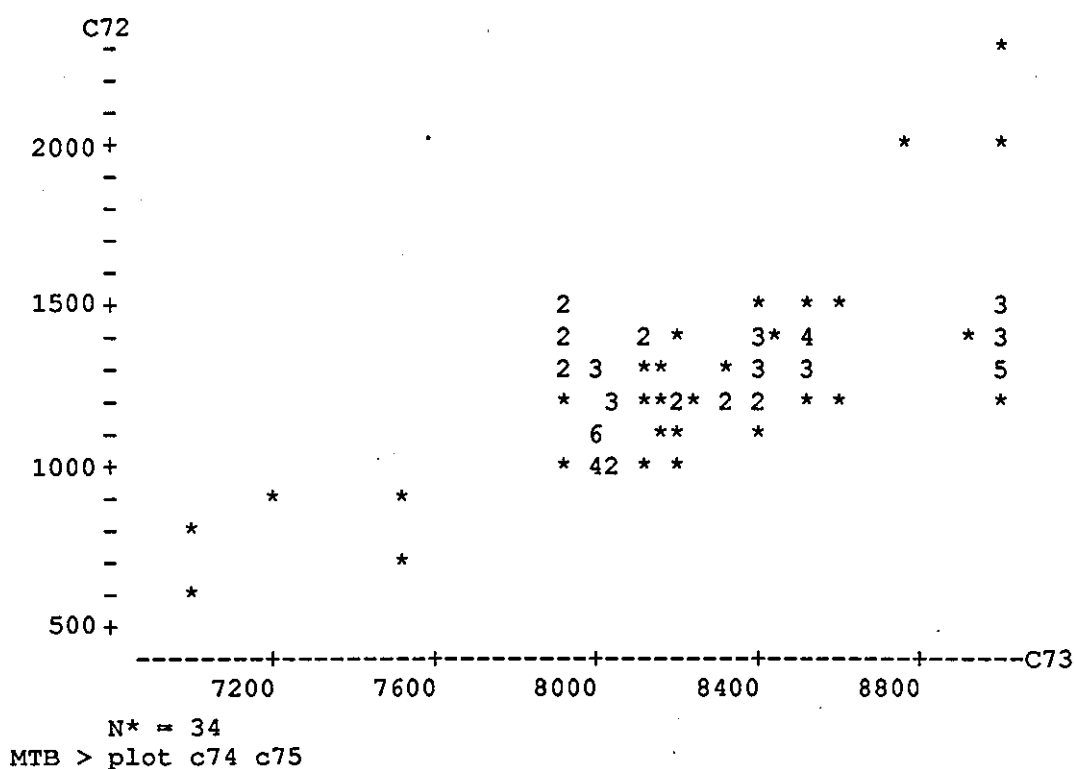
MTB > # C70 and C71 - truck size 2

MTB > # C72 and C73 - truck size 3

MTB > # C74 and C75 - truck size 4

MTB > plot C68 c69





```

MTB > Correlation C68 C69
correlation of C68 and C69 = 0.856
MTB > correlation C70 C71
correlation of C70 and C71 = 0.681
MTB > correlation C72 C73
correlation of C72 and C73 = 0.661
MTB > correlation C74 C75
correlation of C74 and C75 = 0.608
MTB > noconstant
MTB > regress C68 on 1 predictor C69

```

The regression equation is
 $C68 = 0.148 C69$

predictor	Coef	Stdev	t-ratio
Noconstant			
C69	0.147742	0.003176	46.52

S = 172.6

Analysis of Variance

SOURCE	DF	SS	MS
Regression	1	64506720	64506720
Error	43	1281513	29803
Total	44	65788232	

MTB > regress C70 on 1 predictor C71

The regression equation is
 $C70 = 0.137 C71$

926 cases used 319 cases contain missing values

predictor	Coef	Stdev	t-ratio
Noconstant			
C71	0.136924	0.000715	191.50

S = 179.9

Analysis of Variance

SOURCE	DF	SS	MS
Regression	1	1187527936	1187527936
Error	925	29952956	32382
Total	926	1217480704	

MTB > regress C72 on 1 predictor C73

The regression equation is
 $C72 = 0.153 C73$

86 cases used 34 cases contain missing values

predictor	Coef	Stdev	t-ratio
Noconstant			
C73	0.152964	0.002657	57.58

S = 204.4

Analysis of Variance

SOURCE	DF	SS	MS
Regression	1	138534784	138534784
Error	85	3551927	41787
Total	86	142086688	

MTB > regress C74 on 1 predictor C75

The regression equation is
 $C70 = 0.172 C75$

246 cases used 52 cases contain missing values

predictor	Coef	Stdev	t-ratio
Noconstant			

C75 0.171927 0.001644 104.55

S = 211.6

Analysis of Variance

SOURCE	DF	SS	MS
Regression	1	489398208	489398208
Error	245	10969738	44774
Total	246	500367936	

MTB >

D.3 Distribution Fitting

D.3.1 Distribution fitting : Loader cycle time (wheel loader, common earth with poor operational factor)

D.3.1.1 Plotting of various histograms using MINITAB

```

MTB > retrieve 'loadat'
MTB > # separate loading data into significant operating levels for
distribution fitting and parameter evaluation
MTB > # C2 - loader cycle time (seconds)
MTB > # C6 - soil type
MTB > # C8 - loader type (wheel, backhoe)
MTB > # C16 - operational factor
MTB > unstack (C2,C6,C8) into (C20-C22) (C23-C25);
SUBC> subscripts in C16.
MTB > # C20-C22 all Bandattara and Wallatota data
MTB > # C23-C25 all Randenigala data
MTB > # unstack Randenigala data for loader type
MTB > unstack (C23,C24) into (C26,C27) (C28,C29);
SUBC> subscripts in C25.
MTB > # C26,C27 wheel loader
MTB > # C28,C29 backhoe
MTB > # unstack backhoe data
MTB > unstack C28 into C30,C31;
SUBC> subscripts in C29.
MTB > # now find distributions to
MTB > # C20 - Bandattara + Wallatota
MTB > # C26 - wheel loader, common earth with poor o.f.
..
MTB > histogram C26;
SUBC> start=15;
SUBC> increment=3.

```

Histogram of C26 N = 369
Each * represent 2 obs.

Midpoint	Count	
15.00	1	*
18.00	0	
21.00	3	**
24.00	1	*
27.00	1	*
30.00	2	*
33.00	19	*****
36.00	35	*****
39.00	51	*****
42.00	54	*****
45.00	53	*****
48.00	52	*****
51.00	44	*****
54.00	26	*****
57.00	15	*****
60.00	9	*****
63.00	2	*
66.00	0	
69.00	0	
Continue ?		
72.00	1	*

D.3.1.2 Distribution fitting using ECSL

ECSL> * FIT (21,3) 3,1,1,2,19,35,51,54,53,52,44,26,15,9,2,0,0,1
Do you want the output at your terminal ?
Y

After each page, I will pause until you press "RETURN"

The original data has -

Mean	44.7	Standard Deviation	7.48	Skewness	0.02
Median	46.0	Modal interval	42.	Kurtosis	3.32

The following analysis is performed on the basis that it is required to generate integer variates. When a Real valued function is given, it should be truncated to an integer in the usual way

.

ERLANG Distribution

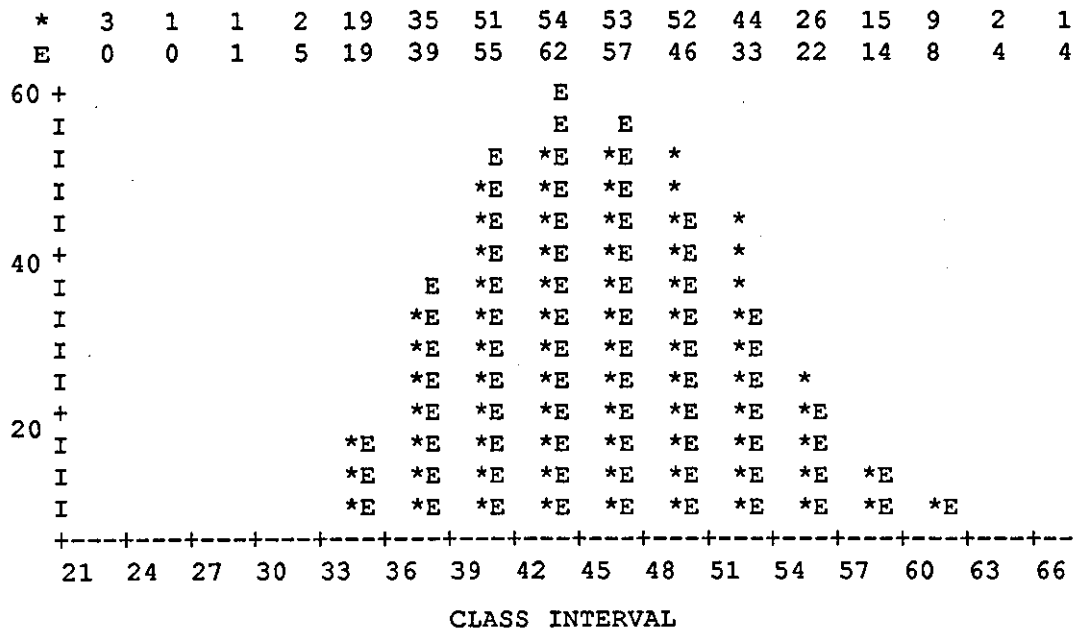
20+ERLANG(10, 2.4,S)

Statistics of Fitted Distribution

Mean	44.7	Standard Deviation	7.49	Skewness	0.63
Median	45.2	Mode	42.3	Kurtosis	3.60

KOLMOGOROV-SMIRNOV TEST value 19. 5 percent level is 26.1
Hypothesis that DISTRIBUTION fits data is not rejected
CHI SQUARED TEST FOR GOODNESS OF FIT - 95PC ONE SIDED Confidence level The observed value is 10.44 on 9 DEGREES OF FREEDOM
In the CHI SQUARED TABLE 16.92 is exceeded with probability 5 PER CENT Hypothesis that DISTRIBUTION fits data is not rejected
The original data has -

Mean	44.7	Standard Deviation	7.48	Skewness	0.02
Median	46.0	Modal interval	42.	Kurtosis	3.32



D.3.2 Pictorial representation of observed and fitted histograms

D.3.2.1 Histograms of loader cycle times

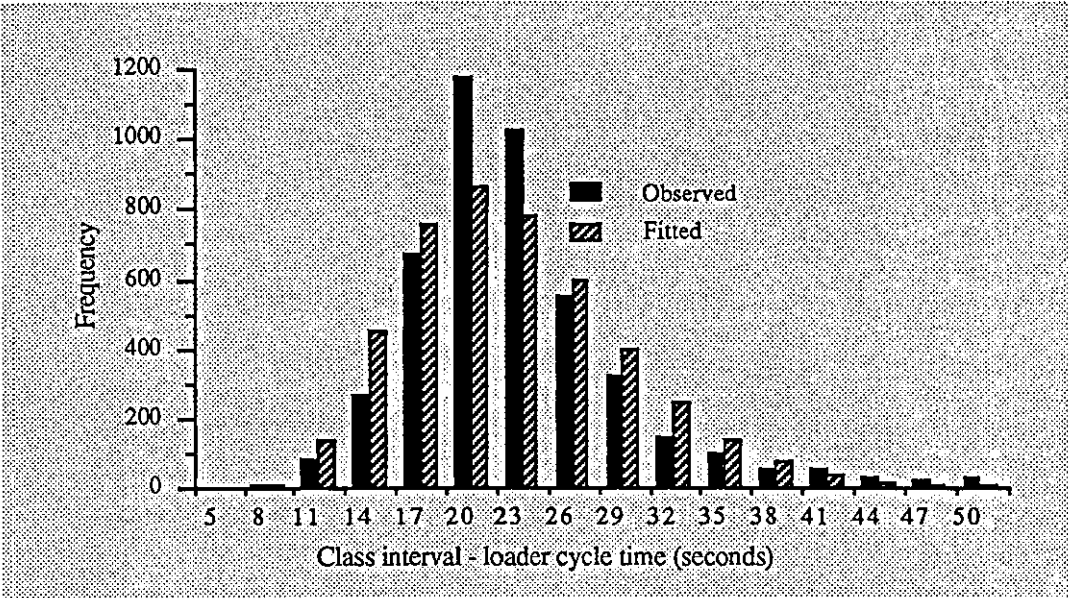


Figure D.1 - Observed and fitted histogram for loader cycle time (backhoe, common earth with average operational factor, 4+Erlang[7,2.5,S])

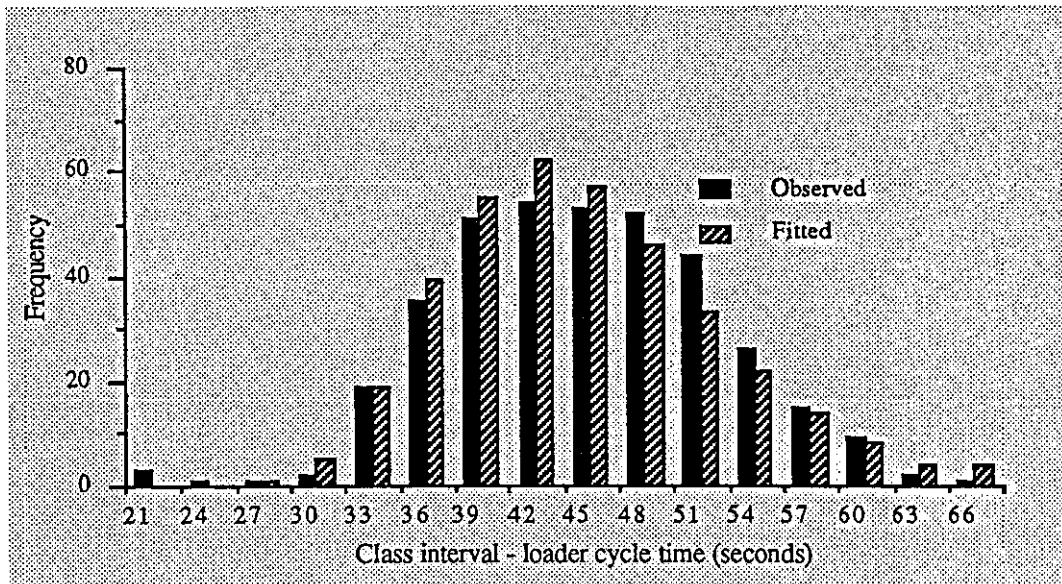


Figure D.2 - Observed and fitted histogram for loader cycle time (wheel loader, common earth with poor operational factor, $20 + \text{Erlang}[10, 2.4, S]$)

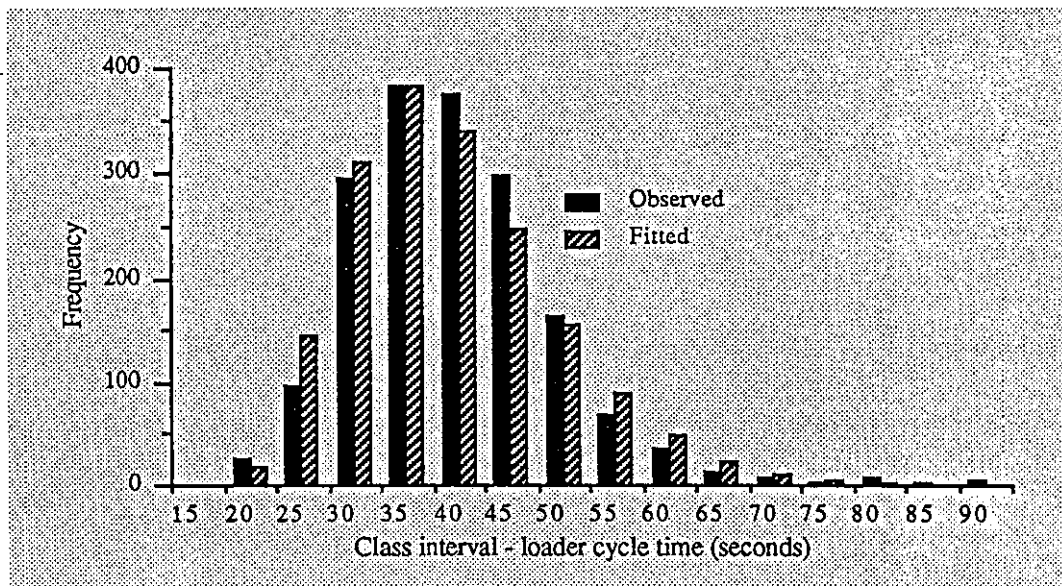


Figure D.3 - Observed and fitted histogram for loader cycle time (backhoe, common earth with poor operational factor, $13 + \text{Erlang}[6, 4.1, S]$)

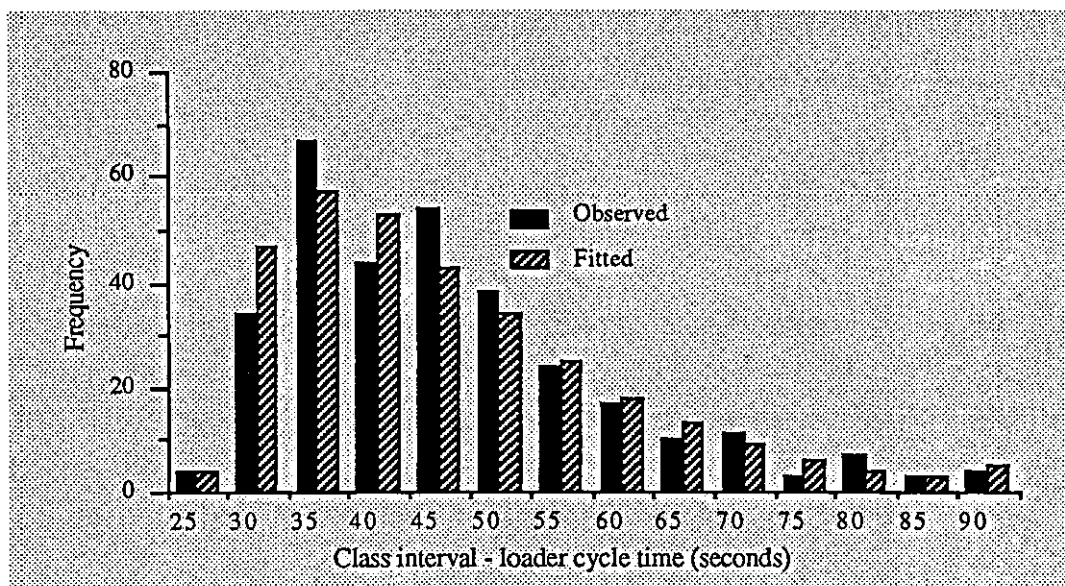


Figure D.4 - Observed and fitted histogram for loader cycle time (backhoe, weathered rock with poor operational factor, $23 + \text{Erlang}[2, 10.5, S]$)

D.3.2.2 Histograms of dump and turn times

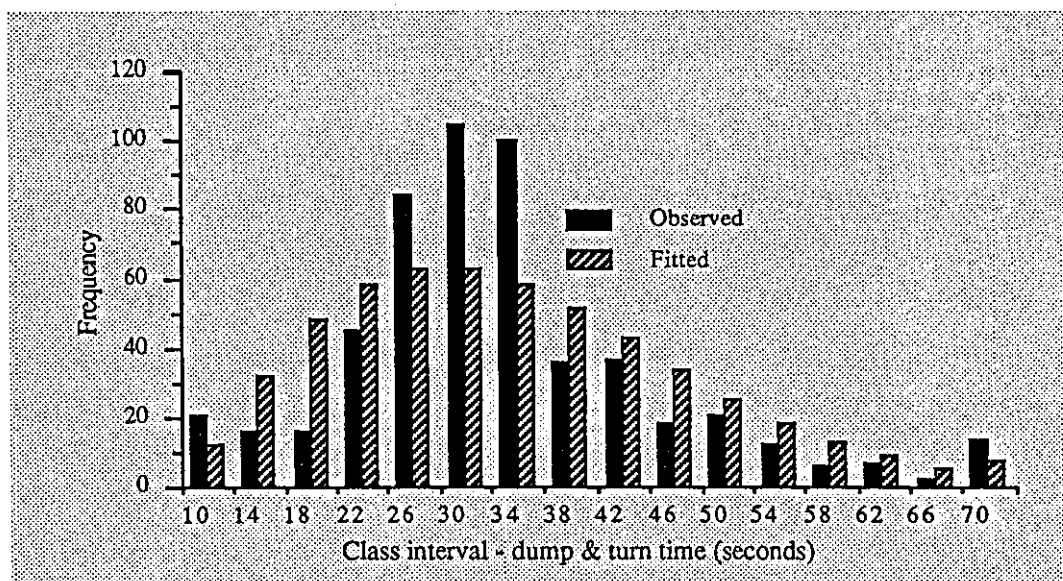


Figure D.5 - Observed and fitted histogram for dump & turn time (good site condition with truck size 1 & 2, $8.0 + \text{Weibull}[1.9, 28.5, S]$)

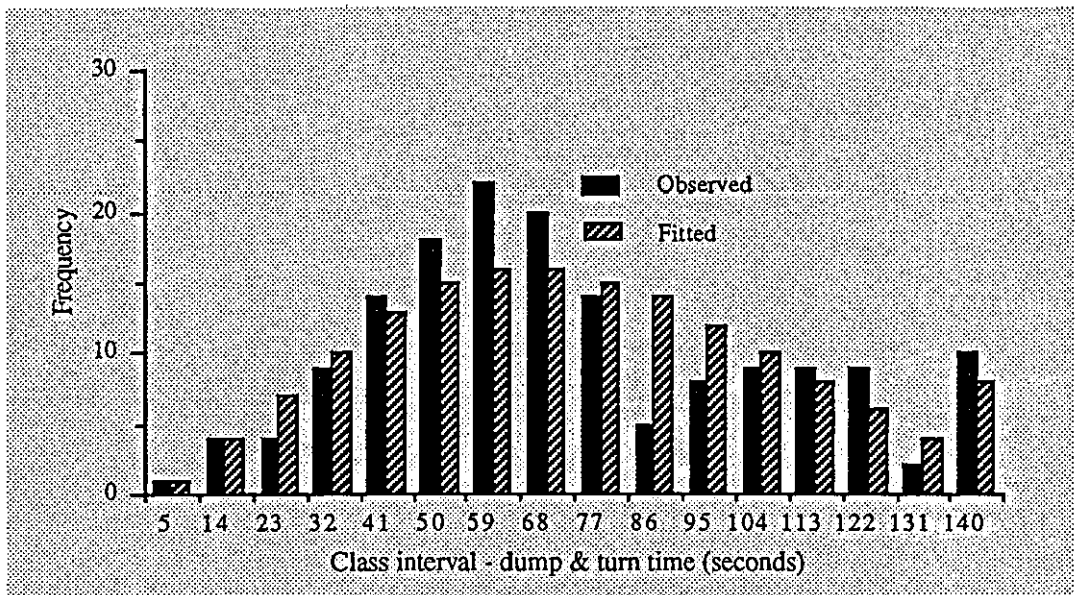


Figure D.6 - Observed and fitted histogram for dump & turn time (poor site condition with truck size 4, $1.0 + \text{Weibull}[2.3, 83.9, S]$)

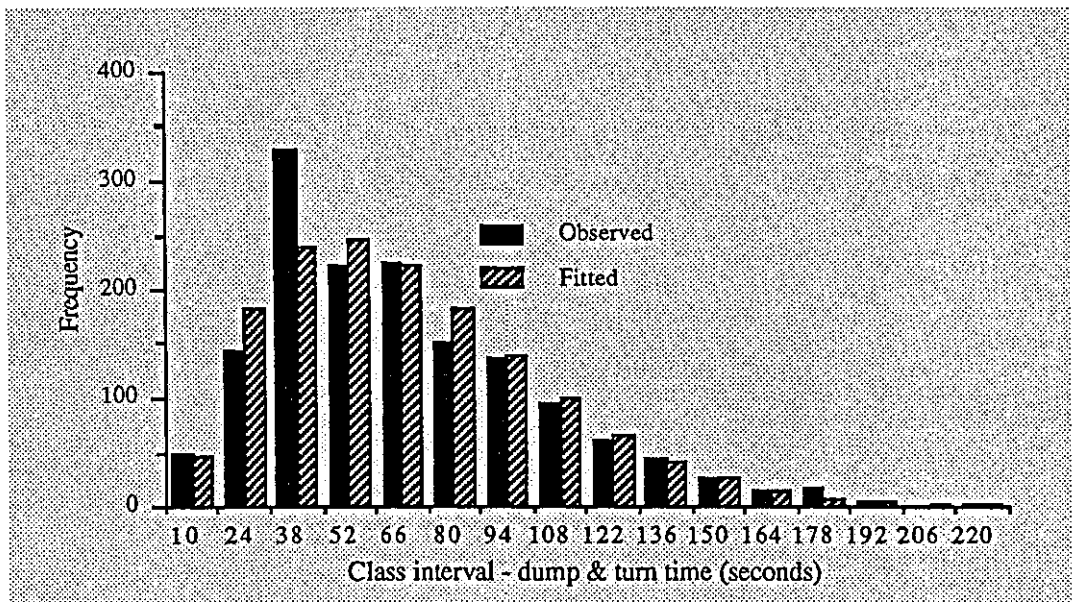


Figure D.7 - Observed and fitted histogram for dump & turn time (poor site condition with truck size 1 & 2, $8.6 + \text{Weibull}[1.7, 66.1, S]$)

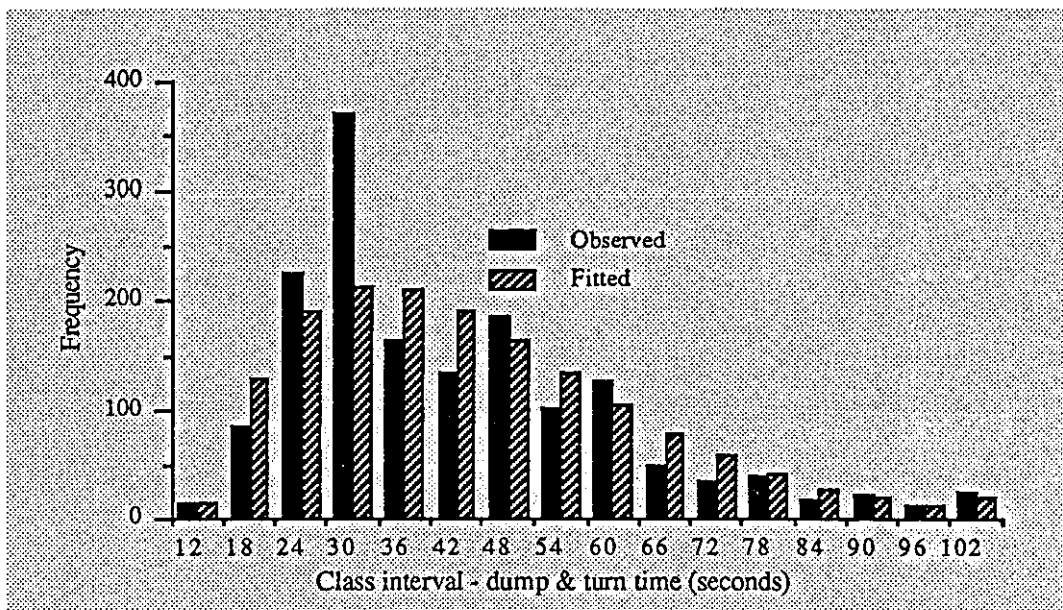


Figure D.8 - Observed and fitted histogram for dump & turn time (average site condition with truck size 1 & 2, $13.2 + \text{Weibull}[1.6, 34.1, S]$)

D.3.2.3 Histograms of positioning delay times

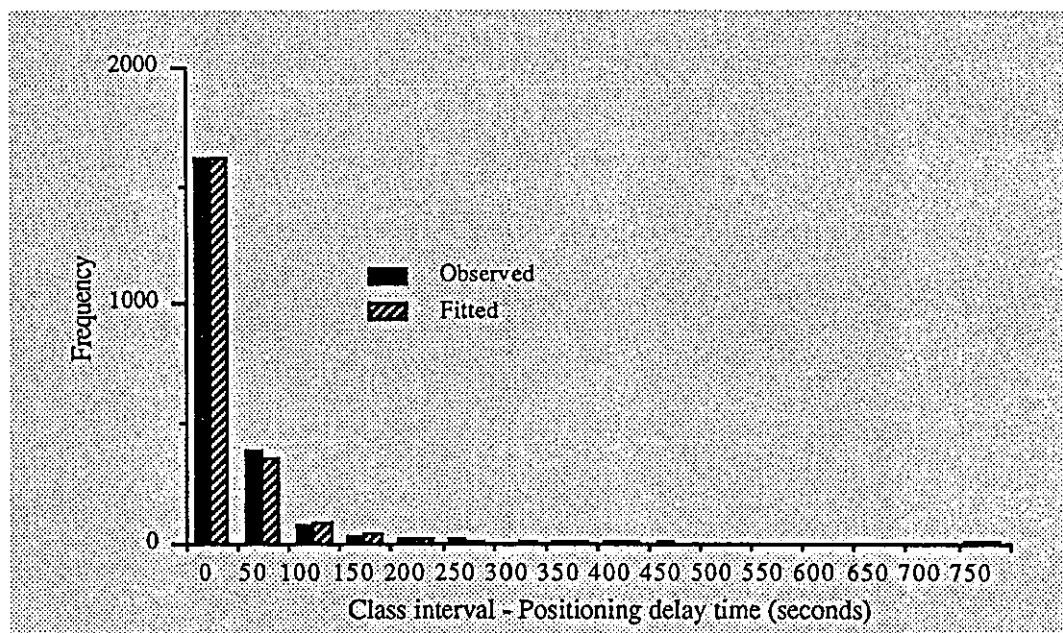


Figure D.9 - Observed and fitted histogram for positioning delay time (no queue at cut with average operational factor, $10.0 + \text{Weibull}[0.4, 7.0, S]$)

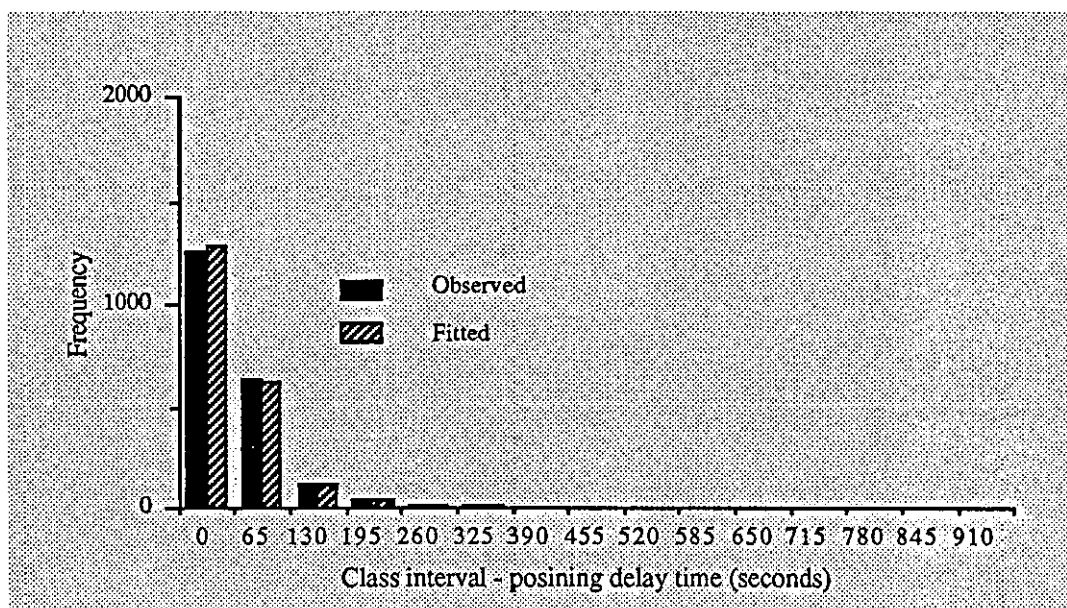


Figure D.10 - Observed and fitted histogram for positioning delay time (queue exists at cut with average operational factor, $20.0 + \text{Weibull}[0.5, 14.3, S]$)

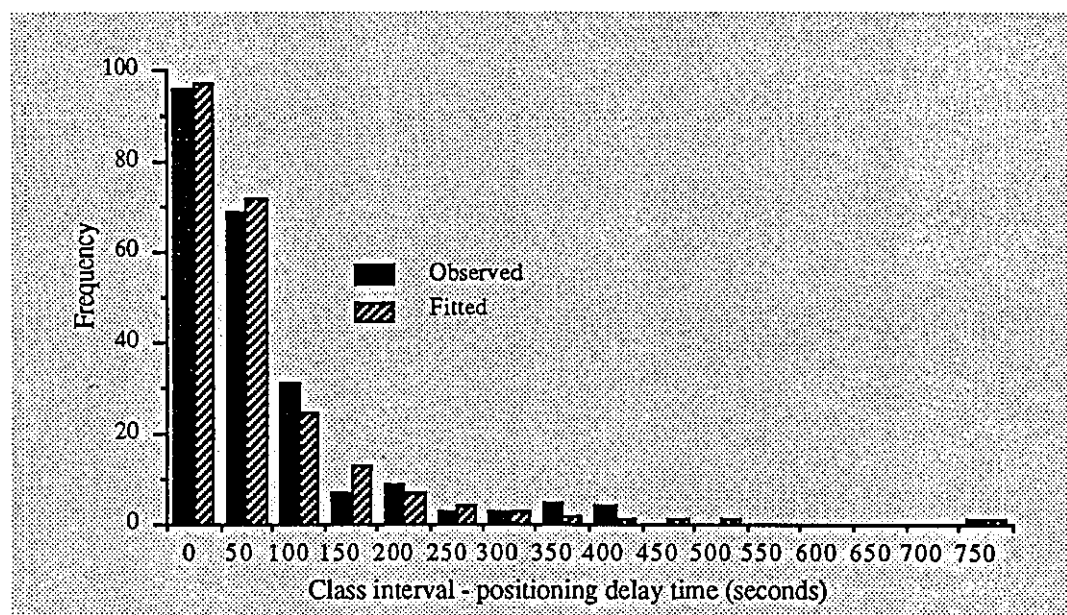


Figure D.11 - Observed and fitted histogram for positioning delay time (no queue at cut with poor operational factor, $10.0 + \text{Weibull}[0.6, 40.2, S]$)

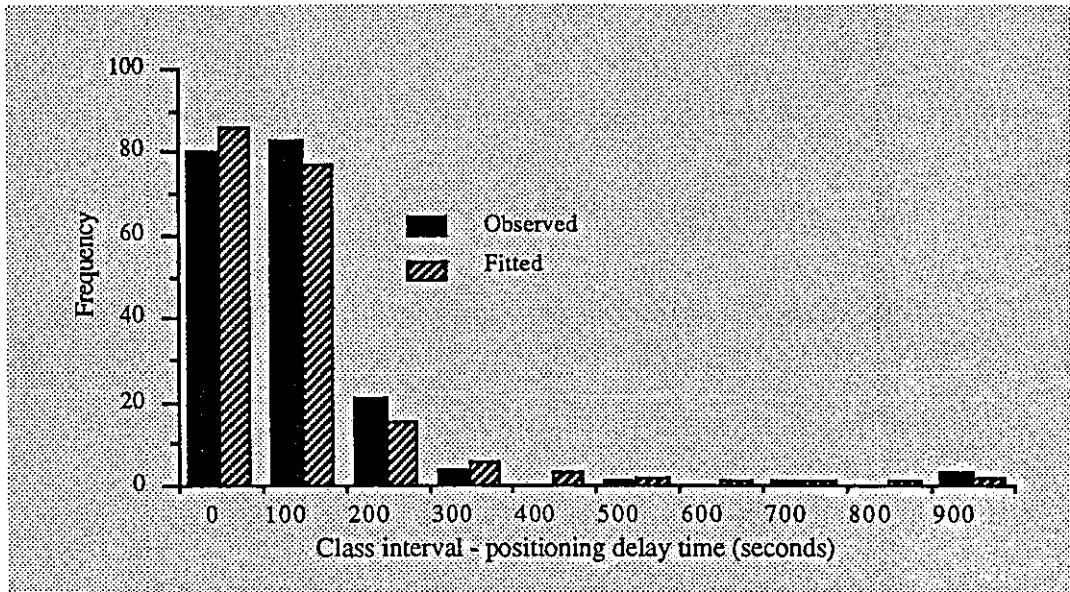


Figure D.12 - Observed and fitted histogram for positioning delay time (queue exists at cut with poor operational factor, $40.0 + \text{Weibull}[0.5, 30.1, S]$)

D.3.2.4 Histogram of return delay time

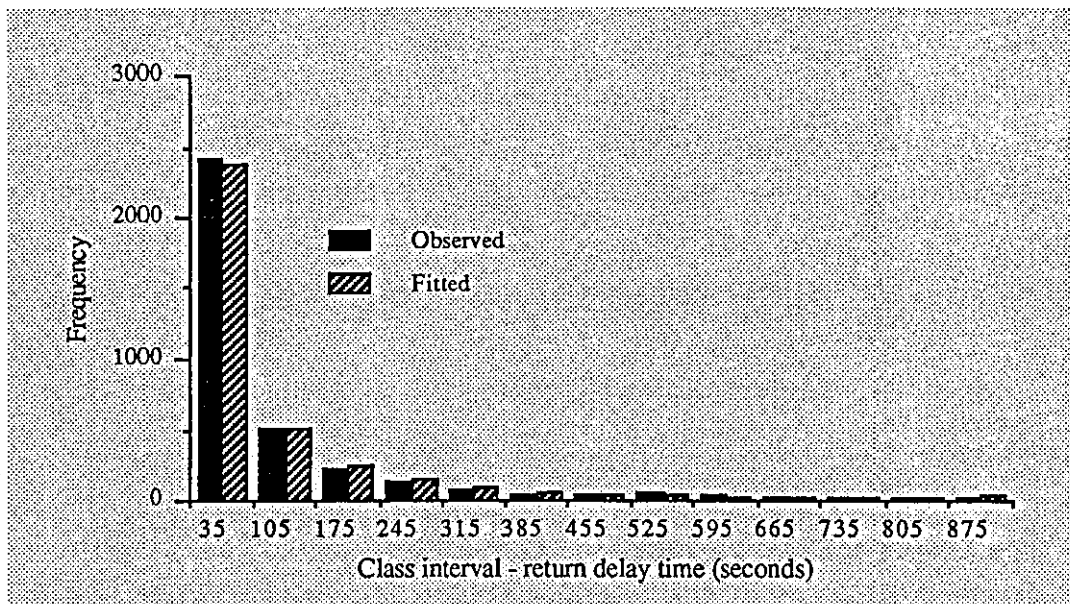


Figure D.13 - Observed and fitted histogram for return delay time, $0.0 + \text{Weibull}[0.6, 63.0, S]$

D.3.2.5 Histogram of hauling delay time

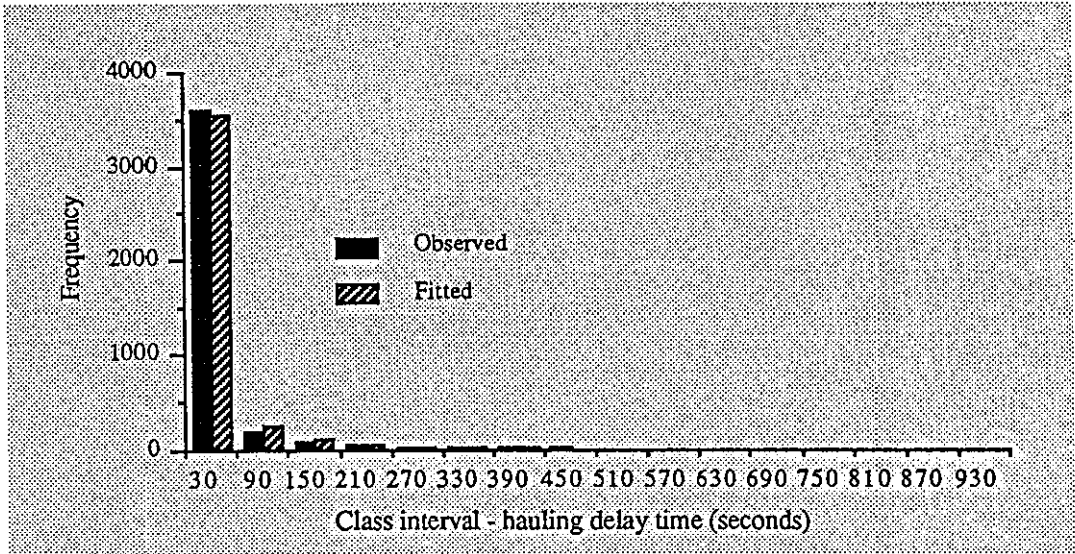


Figure D.14 - Observed and fitted histogram for hauling delay time,
 $0.0+Weibull[0.4,9.2,S]$

APPENDIX E

PROGRAMMER'S MANUAL

- E.1 Introduction
- E.2 Problem Solving Approach
- E.3 Program Logic in Succinct Form
 - E.3.1 Flow diagrams of major modules
 - E.3.2 A brief description of major routines
- E.4 Program Units
- E.5 Program and Data Files Used in the Simulation Model

E.1 Introduction

This appendix provides a brief description of the programming aspects adopted during the development of the simulation model which was carried out using Turbo Pascal version 4.0. It is aimed at providing useful guide-lines to a programmer rather than the model user, and is described in three sections as follows.

1. Problem solving approach
2. Program logic
3. Program units

E.2 Problem Solving Approach

Clearly, the first step in designing a program is the complete and precise specification of the problem. Having done that, the solution process involves many phases, from gaining an understanding of the problem to be solved, through the design of a conceptual solution, to the implementation of the solution with a computer program. A solution typically consists of two components: *algorithms* and *data structures* (Helman 1986). An algorithm is a concise specification of a method for problem solving and data structure is a means of storing a collection of data. When designing a solution the data structures should be so chosen that the data to be operated on easily in the manner required by the algorithm.

The three major tools available in designing a solution process are *top down design*, *data abstraction* and *recursion* (Helman 1986). The top down design approach involves the break down of the task to be accomplished into few big tasks, then decompose each big task into smaller subtasks, then replace smaller subtasks by even smaller subtasks and so forth, until the solution becomes trivial to implement in the pascal language. This process is also called *stepwise refinement*. Data abstraction is a tool that allows each data structure to be developed in relative isolation from the rest of the solution so that the modules which use the associated data structures do not depend on how the data is stored or how the operations are performed. Recursion is another extremely powerful problem solving tool whose basic principle is to obtain a solution to a problem by repetitively solving smaller instances of the same problem.

The above described approach and the following six key issues were carefully observed as far as possible in developing the simulation model. However, it is not intended to provide a comprehensive discussion of the problem solving approach here and such a

description can be obtained from any structured programming book on Pascal (Helman 1988, Savitch 1984).

The six key issues considered were:

- (i) modularity through top-down design;
- (ii) modifiability;
- (iii) user interface;
- (iv) fail safe programming;
- (v) style; and
- (vi) debugging.

E.3 Program Logic in Succinct Form

E.3.1 Flow diagrams of major modules

A conceptualised representation of the simulation model building process was shown in Figure 8.15. The flow diagrams shown in Figures E.1 to E.5 represent a bit more elaborate logical processes involved in major modules of the simulation program and were drawn using the following convention.

- (i) Modules in level 1 - bold phase capital within thick boxes.
- (ii) Modules in level 2 - plain capitals within thick boxes.
- (iii) Modules in level 3 - plain simples within thick boxes.
- (iv) Modules in level 4 - plain simples within ordinary boxes.

The smaller modules below level four are not indicated.

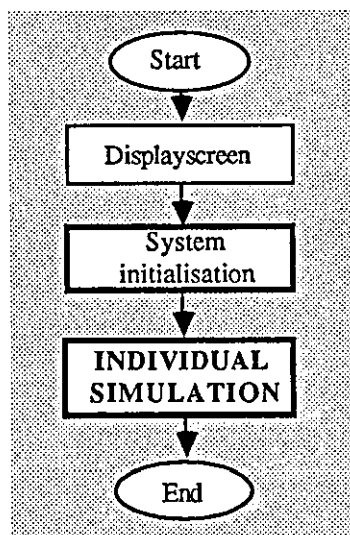


Figure E.1 - Flow diagram of the main program

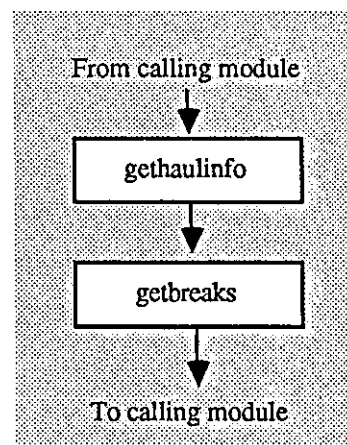


Figure E.2 - Flow diagram of the 'systeminitialisation' module

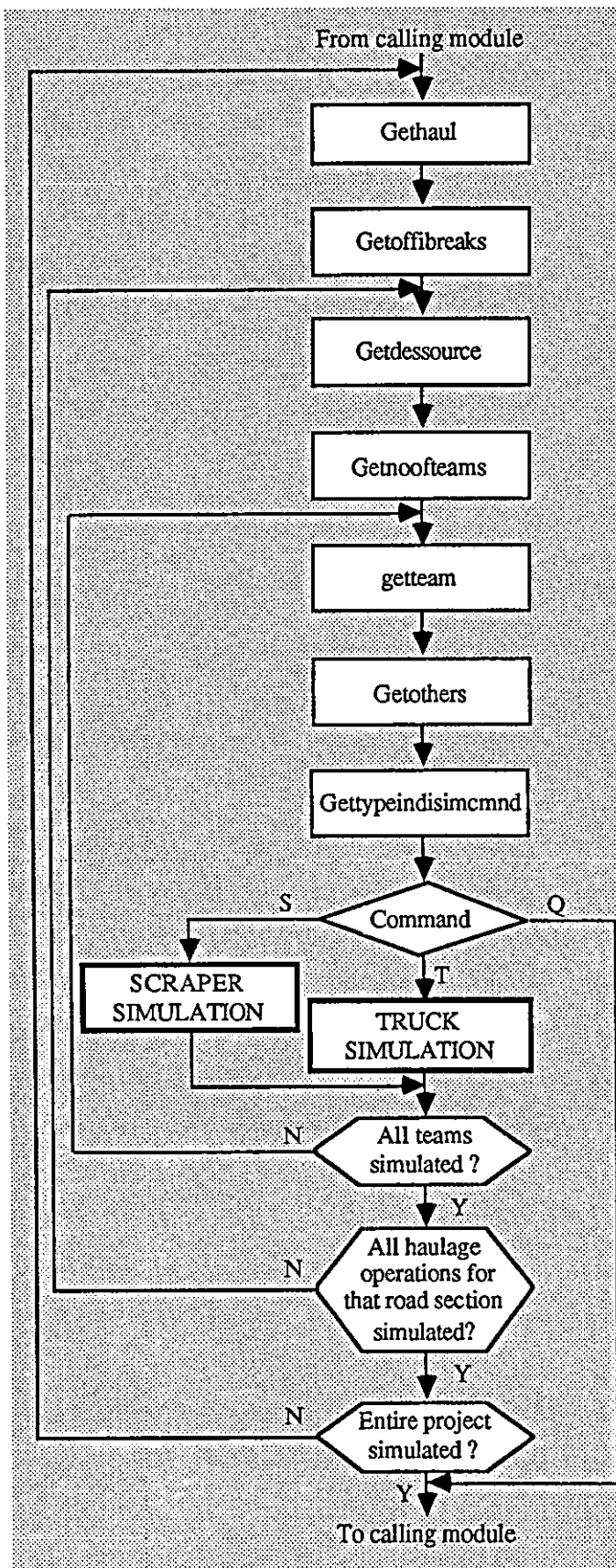


Figure E.3 - Flow diagram of the 'individualsimulation' module

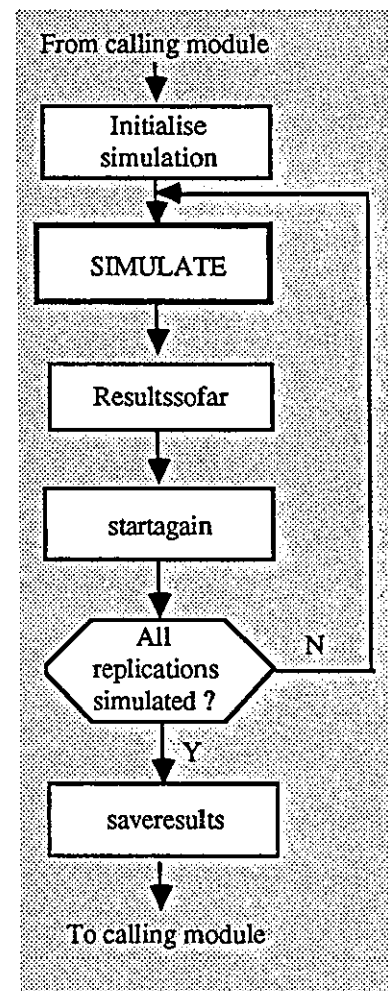


Figure E.4 - Flow diagram of the 'trucksimulation' module

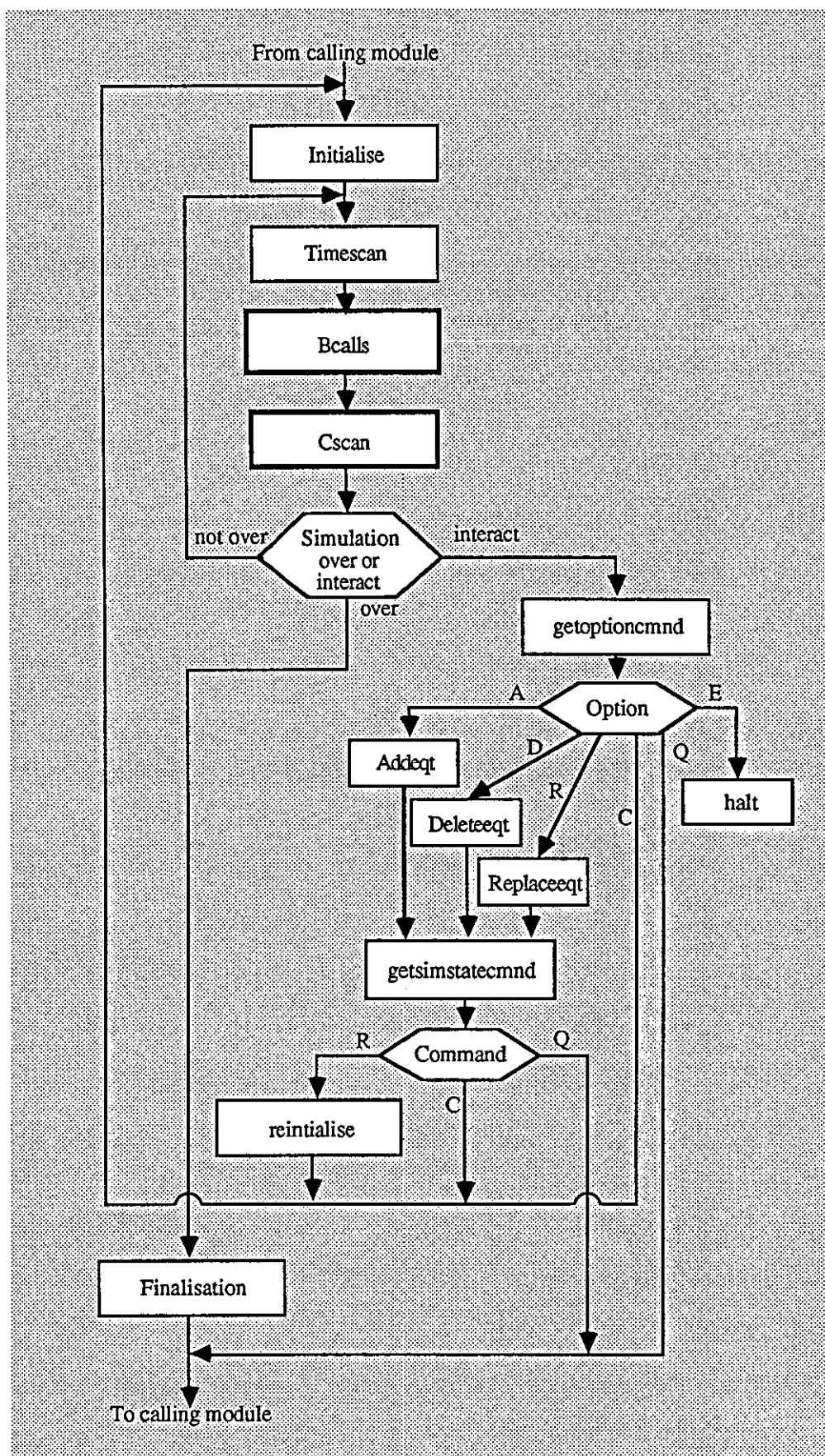


Figure E.5 - Flow diagram of the 'simulate' module

E.3.2 A brief description of major routines

The routines shown in the above flow diagrams are briefly described and listed below in the alphabetical order. They may contain several other subroutines depending on their complexity.

Addeqt : Facilitates to change the equipment team by adding hauling or loading units.

Bcalls : Executes all 'B' activities identified in the 'A' phase as being due when this routine is called.

Cscan : Attempts each 'C' activity in turn and executes those whose conditions are satisfied. Repeats this process until no more 'C' activities are possible.

Deleeteqt : Facilitates to change the equipment team by removing unnecessary or unsuitable equipment items from the current team.

Displayscreen : Introduces the simulation model on entry to the program.

Finalisation : Provides a hard copy of simulated results after each replication. This also includes queue time histogram of hauling units, idle time histogram of loading units and also queue length histogram of hauling units.

Getbreaks : Obtains and saves official break times for later retrieval. These include starting and finishing times of; working day, morning tea, lunch and evening tea.

Getdessource : Retrieves information on the next haulage operation to be simulated corresponding to the selected roadway section. Information includes the identification of destination/source, swell/shrinkage factors, haul/return distances, operational factor and site condition.

Getteam : Obtains and saves a plant team for the selected haulage operation. The plant team should be specified by an id number which if already created, saved, and used earlier is retrieved from two external files. If that team is not previously utilised, models of each equipment item should be specified so that the other specifications on these items can be directly read from external data libraries. In situations where the selected plant item is not in the appropriate data library, required information must be user fed.

Gethaul : Retrieves information corresponding to the next roadway section to be simulated. These include section identification number, whether the section is a cut or fill, soil type, quantity, number of possible haulage operations etc.

Gethaulinfo : For a given road project, obtains and saves details of all possible haulage operations in two different files, to be retrieved one by one during simulation. Information includes identification numbers of roadway sections, all feasible haulage operations to or from different roadway sections, soil types,

swell/shrinkage factors, quantities involved, haul/return distances, operational factors, site conditions etc.

Getnoofteams : Obtains the number of possible plant teams to be tested for the selected haulage operation.

Getoffbreaks : Retrieves all official break times to be used during simulation.

Getoptioncmd : Provides the facility to interact the simulation process to add, delete, replace equipment items or to quit from simulation all together.

Getothers : Reserved routine for other input.

Getsimstatecmd : Facilitates to restart or continue simulation without change with the modified equipment team or quit from simulation altogether.

GetTypeindisimcmd : Provides the opportunity to direct the execution to simulate scraper-pusher, loader-truck operations or exit from the program.

Individualsimulation : See the flow chart shown in Figure E.3 and the corresponding sub modules.

Initialisesimulation : Sets initial values to all variables. This also includes scheduling of hauling units, loading units and other required entities.

Reinitialise : Facilitates to reinitialise the simulation process with a modified plant team.

Replaceeqt : Facilitates to replace hauling or loading units one at a time by another equipment item of the same type.

Resultssofar : Provides a hard copy of mean simulated statistics after each replication calculated using the total number of replication made up to that point.

Saveresults : Saves the simulated results corresponding to each possible haulage operation after the specified replications have been simulated. These results include, the team identification, unit earthmoving cost, production, swell/shrinkage factors, soil types etc.

Scrapersimulation : See the flow chart shown in Figure E.4 for truck simulation and the appropriate sub modules.

Screen1 : Prepares the computer screen for dynamic simulation.

Simulate : See the flow chart shown in Figure E.5 and the appropriate sub modules.

Startagain : This initialises almost all the variables used during simulation and reschedules, hauling units, loading units and other entity classes, to be used during the next replication.

Timescan : Determines when the next event is due and which 'B' activities are due at that time. Moves the simulation clock time to next event time.

Trucksimulation : See the flow chart shown in Figure E.4 and the appropriate sub modules.

E.4 Program Units

The entire simulation program was built using six different program *units* to satisfy both memory restrictions and the modular design approach. A unit is a collection of constants, data types, variables, procedures and functions, and can be considered as a separate pascal program (Turbo Pascal 1987). The units used in the simulation model are:

- (i) *Globals* : This unit has a collection of 36 global data structures used during the simulation model and consists of pointer types, fixed and variant record types, file types and many other structured data types.
- (ii) *Utils* : This unit provides a collection of 18 utility procedures frequently used during simulating a road project. These also include procedures developed to generate random variates for different cycle element times.
- (iii) *Scrapers* : This unit consists of almost all program routines necessary to simulate an individual haulage operation consisting of a scraper-pusher plant team.
- (iv) *Trucks* : This is similar to scrapers unit and provides most of the routines for loader-truck simulation.
- (v) *Indisim* : This unit has a collection of all the procedures required to retrieve the necessary information to simulate different haulage operations, specifications for plant teams and also it builds the framework required to simulate individual haulage operations.
- (vi) *Projectsimulation* : This has a collection of procedures required to initialise the simulation model taking details of the entire project separately for each possible haulage operation, and also to simulate individual haulage operations separately.

How each unit is related to one another is shown in Figure E.6.

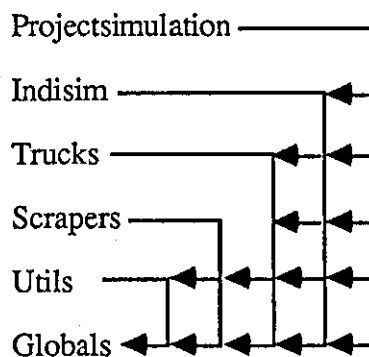


Figure E.6 - Inter-relationships of different units

In this way, the simulation model of RESOM developed using Turbo Pascal version 4.0 consists of about 5500 lines of program code and the main executable file requires 118kb of memory storage.

E.5 Program and Data Files Used In the Simulation Model

The simulation model (stage 1 of RESOM) consists of several program and library files shown in Table E.1. The files created during the execution of the simulation model are also shown in the same table.

Table E.1 - Program and library files used in the simulation model

File name	Description
<u>Program files</u>	
resom.exe	the main simulation model
scspecs.exe	scraper data library creation sub-system
tspecs.exe	trucks data library creation sub-system
dspecs.exe	dozer data library creation sub-system
lspecs.exe	loader data library creation sub-system
<u>Library files</u>	
scspecs.lib	scraper specification library
tspecs.lib	trucks specification library
dspecs.lib	dozer and pusher specification library
lspecs.lib	loader specification library
<u>Files created during execution</u>	
section.dat	stores road sectional information
dessource.dat	stores information on possible haulage operations
interval.dat	stores official break times
ftrec1.dat	stores general plant team information
ftrec2.dat	stores detail specification of selected plant items
sresults.dat	stores final simulation results

APPENDIX F

A SPECIMEN CALCULATION OF REALISTIC PRODUCTION AND ASSOCIATED TRAVEL TIME CHARTS

- F.1 Introduction
- F.2 Travel Time Charts
- F.3 A Specimen Calculation in Determining the Team Production

F.1 Introduction

As a means of partly validating the simulation model, the simulation production obtained on case study 2 : A42 Measham and Ashby By-pass, was statistically compared with that obtained by a realistic estimating procedure suggested by Alkass (1988). This process was carried out in Chapter 9.

This appendix provides the travel time charts suggested by Alkass and also a specimen calculation explaining the steps involved in estimating the team production.

F.2 Travel Time Charts

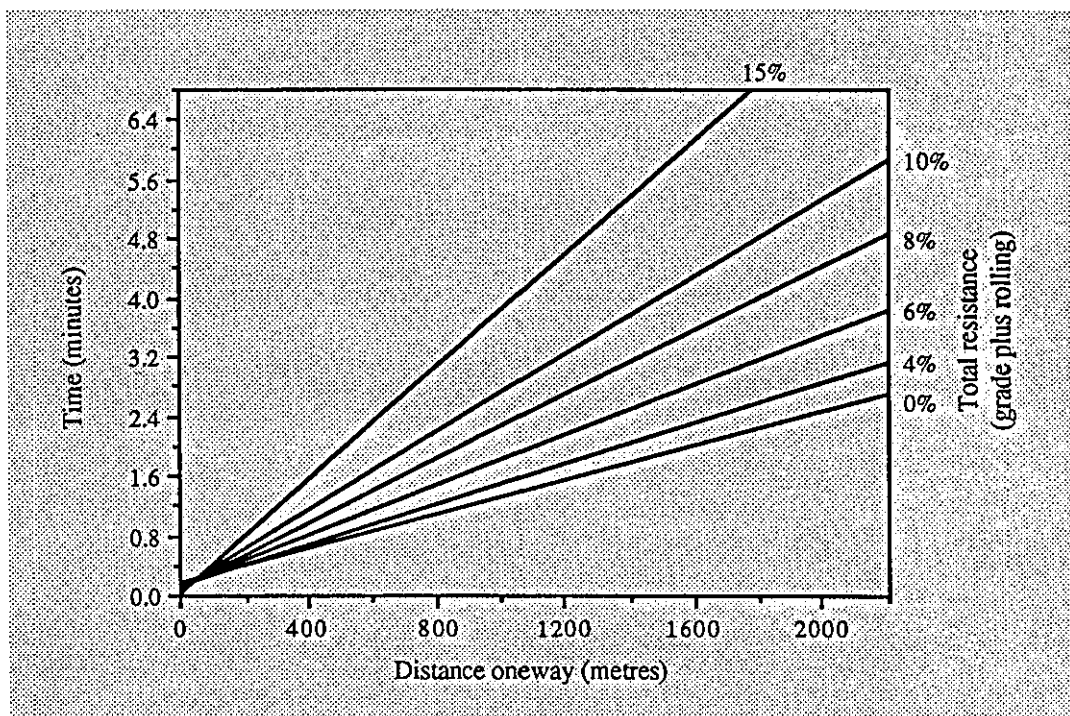


Figure F.1 - Time vs distance : empty truck

Equations for the curves in Figure F.1 (T = travel time in minutes and D = travel distance in kilo metres)

$T = 0.17 + 1.153D$	Grade 0%
$T = 0.16 + 1.355D$	Grade 4%
$T = 0.14 + 1.682D$	Grade 6%
$T = 0.09 + 2.164D$	Grade 8%
$T = 0.09 + 2.625D$	Grade 10%
$T = 0.05 + 3.791D$	Grade 15%

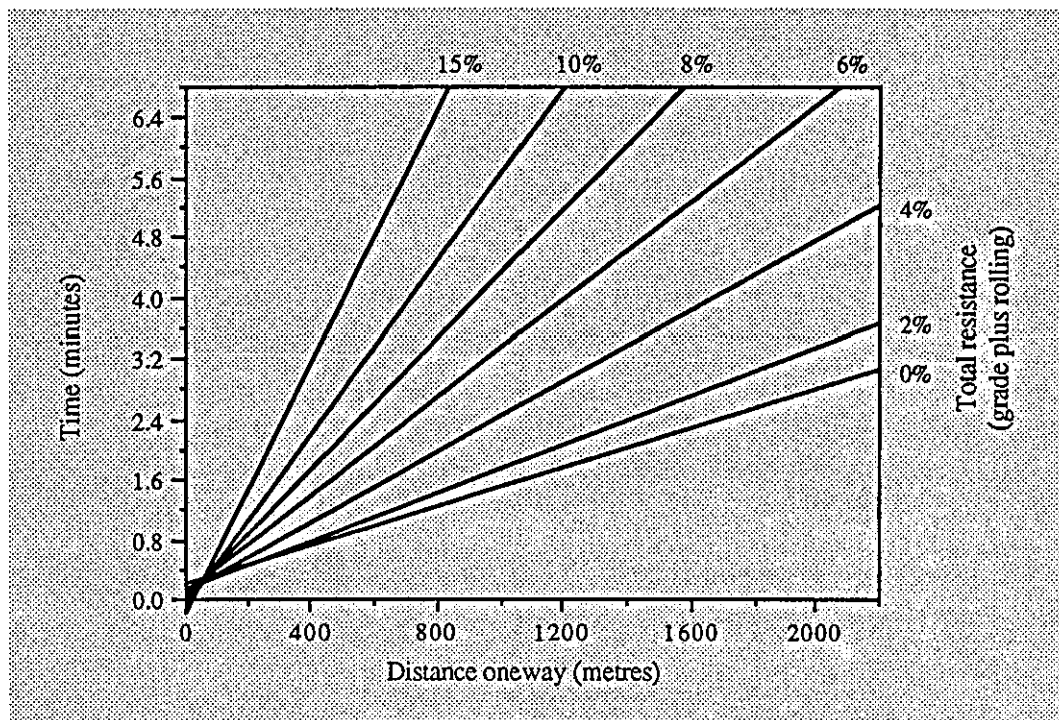


Figure F.2 - Time vs distance : loaded truck

Equations for the curves in Figure F.2 (T = travel time in minutes and D = travel distance in kilo metres)

$T = 0.21 + 1.300D$	Grade 0%
$T = 0.16 + 1.588D$	Grade 2%
$T = 0.11 + 2.330D$	Grade 4%
$T = 0.09 + 3.234D$	Grade 6%
$T = 0.02 + 4.302D$	Grade 8%
$T = -0.06 + 5.688D$	Grade 10%
$T = -0.18 + 8.322D$	Grade 15%

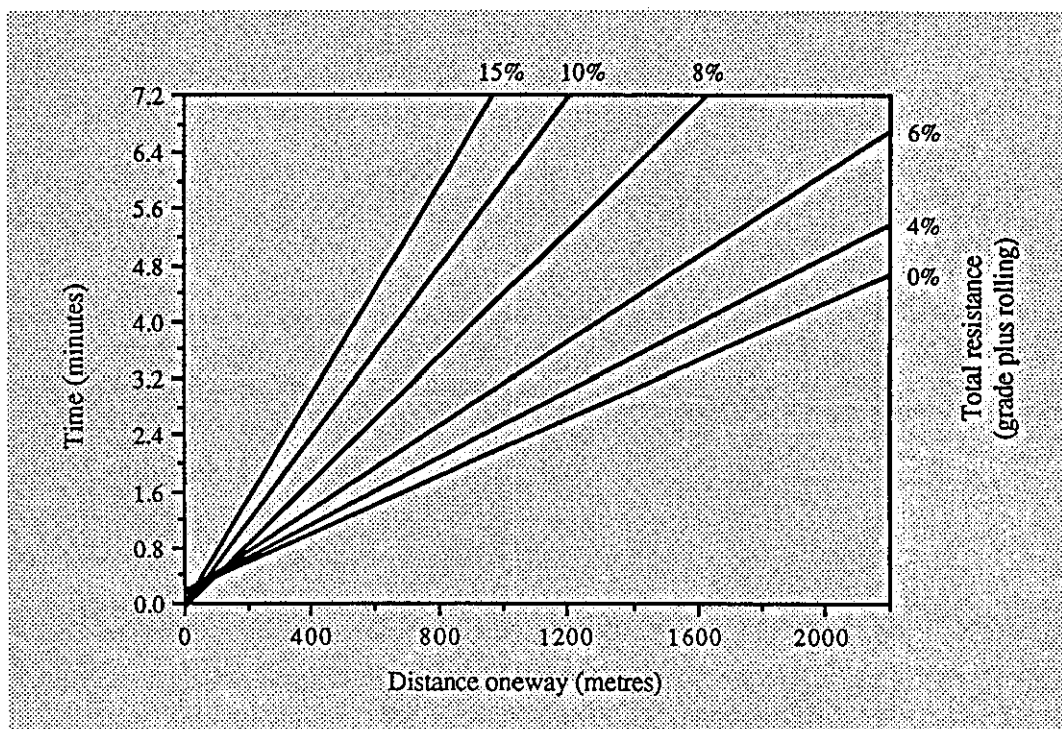


Figure F.3 - Time vs distance : empty scraper

Equations for the curves in Figure F.3 (T = travel time in minutes and D = travel distance in kilo metres)

$T = 0.17 + 2.045D$	Grade 0%
$T = 0.20 + 2.353D$	Grade 4%
$T = 0.15 + 2.988D$	Grade 6%
$T = -0.05 + 4.450D$	Grade 8%
$T = -0.02 + 5.996D$	Grade 10%
$T = -0.01 + 7.433D$	Grade 15%

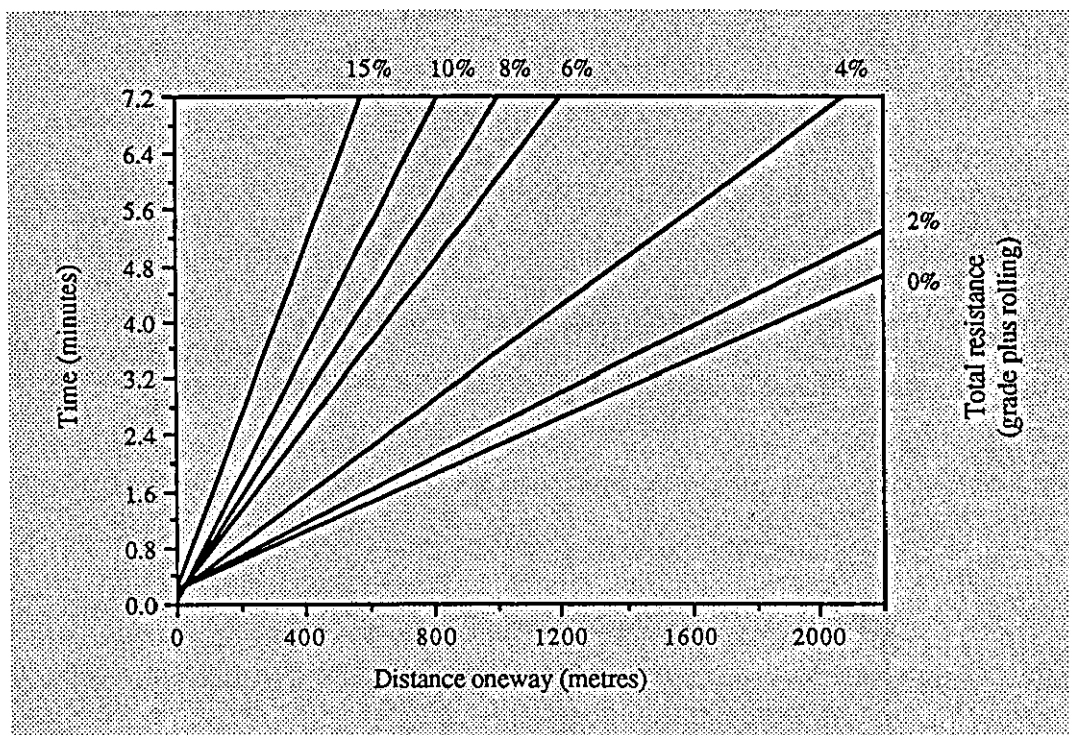


Figure F.4 - Time vs distance : loaded scraper

Equations for the curves in Figure F.4 (T = travel time in minutes and D = travel distance in kilo metres)

$T = 0.23 + 2.025D$	Grade 0%
$T = 0.23 + 2.318D$	Grade 2%
$T = 0.17 + 3.395D$	Grade 4%
$T = 0.16 + 5.866D$	Grade 6%
$T = 0.11 + 7.081D$	Grade 8%
$T = 0.09 + 8.878D$	Grade 10%
$T = 0.27 + 12.145D$	Grade 15%

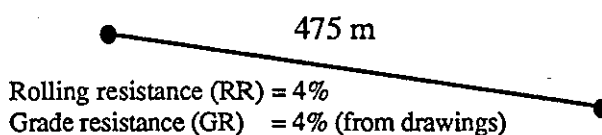
F.3 A Specimen Calculation in Determining the Team Production

The following calculation is applicable to the haulage operation two described in Figure 9.2 and Table 9.4 in Chapter 9 and represents the procedure adopted in determining the team production for similar operations.

Equipment team :

- 4 - 631E wheel tractor scrapers
- 1 - D8N dozer equipped with a push plate

Job layout :



Total effective grade	= RR% ± GR%
Total effective grade during hauling	= 4 - 4
	= 0%
Total effective grade during returning	= 4+4
	= 8%

Determination of the cycle time :

Hauling time	= 1.2 min	(from Figure F.4)
Returning time	= 2.0 min	(from Figure F.3)
Load time	= 0.6 min	(Caterpillar 1987, page 178)
Dump and manoeuvre time	= 0.7 min	(Caterpillar 1987, page 178)
Allowance for unexpected delays	= 1.0 min	(Alkass 1988)
Total cycle time	= 5.5 min	

Check pusher scraper combinations :

Boost time	= 0.10 min	(Caterpillar 1987, page 646)
Return time	= 40% load time	(Caterpillar 1987, page 646)
Manoeuvre time	= 0.15 min	

$$\begin{aligned}\text{Total pusher cycle time} &= 140\% \text{ load time} + 0.25 \text{ min} \\ &= 140\% \times 0.7 + 0.25 \\ &= 1.23 \text{ min}\end{aligned}$$

$$\begin{aligned}\text{Number of scrapers which can be handled by a pusher} &= 5.5/1.23 \\ &= 4.47\end{aligned}$$

Therefore four scrapers can be handled.

Estimate Production :

Total cycles per hour	= 60/5.5 = 10.91
Estimated load	= heaped capacity x load factor = 23.7/1.2 = 19.75 BCM
Hourly unit production	= 19.75 BCM x 10.91 cycles/hr = 215.47 BCM/hr
Adjusted production	= Efficiency factor x hourly production = 0.83 x 215.47 (assuming 50 min hour) = 178.84 BCM
Team production	= 4 x 178.84 = 715 BCM/hr.
	=====

APPENDIX G

SIMULATED RESULTS, LP/IP FORMULATIONS AND LINDO OUTPUTS

- G.1 Introduction
- G.2 LP/IP Model Applied to Case Study 4
 - G.2.1 LP/IP formulation
 - G.2.2 LINDO output
- G.3 RESOM Applied to Case Study 3 for Sensitivity Analysis
 - G.3.1 Case 1 : Average sectional interval = 495m
 - G.3.2 Case 2 : Average sectional interval = 765m
 - G.3.3 Case 3 : Average sectional interval = 936m

G.1 Introduction

Chapter 10 explained the application and experimentation procedure of RESOM by applying it to case study 3 : M40 Banbury By-pass. The same case study was used to test the effect of variation of road sectional interval and plant team selection on the optimum solution. In addition, the advanced use of RESOM was also illustrated using a hypothetical example (case study 4).

This appendix provides some simulated results, LP/IP formulations and LINDO outputs obtained on selected cases of the above case studies.

G.2 LP/IP Model Applied to Case Study 4

A plan and a profile view of the proposed highway, cut/fill quantities and capacity limitations of borrow/disposal sites, contractor's equipment fleet specifications, the proposed equipment configurations for different haul distances and the assumed simulated results given in Chapter 10 are reproduced in Figure G.1, Tables G.1 to G.4 respectively for easy understanding of the formulation. The substituted LP/IP formulation and the LINDO solution obtained with available plant for timely project completion (18 days) are given in the following sections.

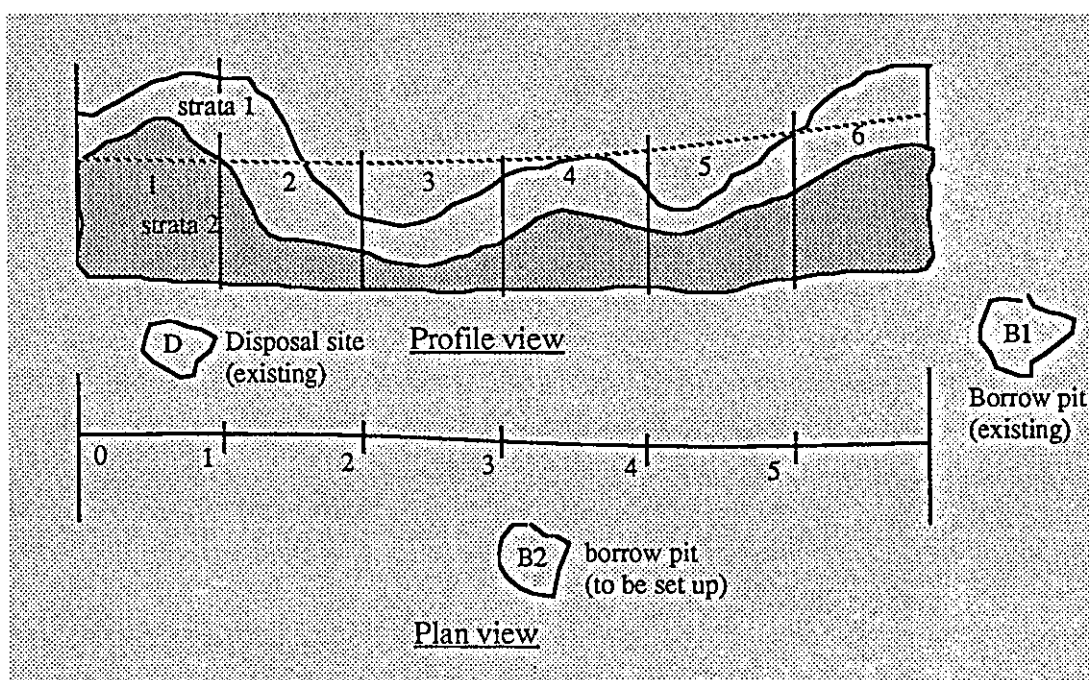


Figure G.1 - Plan and profile views of the proposed highway : case study 4

Table G.1 - Cut/fill quantities and capacity limitations of borrow/disposal sites : case study 4

Cut/fill quantities and capacity limitations of borrow/disposal sites (100m ³)										
Section/location (1)		1 (2)	2 (3)	3 (4)	4 (5)	5 (6)	6 (7)	B1 (8)	B2 (9)	D (10)
cut	Strata 1	748	395	-	-	-	650	2500	1500	
	Strata 2	340	-	-	-	-	-	-	-	-
fill	Subgrade	-	195	600	100	850	-	-	-	7500

Table G.2- Contractor's equipment fleet with specifications : case study 4

Model (1)	Description (2)	Number (3)	Identification (4)
Cat 769C	Off highway trucks with 17.3 m ³ struck capacity	8	T1 - T8
Cat 773B	Off highway trucks with 26.0 m ³ struck capacity	8	T9 - T16
Cat D4H LGP	Bulldozer with straight blade with 2.17 m ³ capacity	1	B1
Cat D6H	Bulldozer with straight blade with 3.35 m ³ capacity	1	B2
Cat 980C	Wheel loader with 4.7 m ³ bucket capacity	1	L1
Cat 988B	Wheel loader with 6.3 m ³ bucket capacity	1	L2
Cat D3B LGP	Bulldozer equipped with push plate	1	B3
Cat 651E	Standard scraper with 24.5 m ³ struck capacity	4	S1 - S4
Cat 825C	Compactors	3	C1 - C3
Cat 14G	Motor graders	2	G1 - G2
Cat D4H	Dozer equipped with power angle and tilt blade	2	B4 - B5

Table G.3- Proposed equipment team configurations : case study 4

Equipment combination (1)	Team identification (2)	Suitable haul distance (m) (3)
T1-T4,L1,B1,B4,C1,G1	1	400 - 650
T1-T5,L1,B1,B4,C1,G1	2	500 - 1000
T1-T6,L1,B1,B4,C1,G1	3	900 - 1500
T1-T7,L1,B1,B4,C1,G1	4	1250 - 2000
T1-T8,L1,B1,B4,C1,G1	5	1750 - 2500
T9-T12,L2,B2,B5,C2,G2	6	400 - 700
T9-T13,L2,B2,B5,C2,G2	7	600 - 950
T9-T14,L2,B2,B5,C2,G2	8	750 - 1300
T9-T15,L2,B2,B5,C2,G2	9	1200 - 1800
T9-T16,L2,B2,B5,C2,G2	10	1700 - 2500
S1-S4,B3,C3	11	400 - 600

G.2.1 LP/IP formulation

Objective function

$$\begin{aligned} \text{Min} = & 5000\text{YSB1} + 28\text{X1} + 32\text{X2} + 30\text{X3} + 35\text{X4} + 33\text{X5} + 40\text{X6} + 34\text{X7} + 42\text{X8} \\ & + 38\text{X9} + 46\text{X10} + 40\text{X11} + 48\text{X12} + 44\text{X13} + 52\text{X14} + 46\text{X15} + 54\text{X16} + 23\text{X17} + \\ & 28\text{X18} + 28\text{X19} + 32\text{X20} + 33\text{X21} + 40\text{X22} + 38\text{X23} + 46\text{X24} + 38\text{X25} + 46\text{X26} + \\ & 33\text{X27} + 40\text{X28} + 28\text{X29} + 32\text{X30} + 45\text{B1} + 53\text{B2} + 38\text{B3} + 46\text{B4} + 33\text{B5} + 40\text{B6} + \\ & 27\text{B7} + 31\text{B8} + 26\text{B9} + 30\text{B10} + 32\text{B11} + 40\text{B12} + 20\text{D1} + 26\text{D2} + 22\text{D3} + 29\text{D4} + \\ & 22\text{D5} + 28\text{D6} + 45\text{D7} + 55\text{D8} \dots\dots\dots(\text{G.1}) \end{aligned}$$

Constraints

Substituting values to equation (4.27) the constraints corresponding to each strata in each cut section are:

$$\text{X1} + \text{X2} + \text{X5} + \text{X6} + \text{X9} + \text{X10} + \text{X13} + \text{X14} + \text{D1} + \text{D2} = 748 \dots\dots\dots (\text{G.2})$$

$$\text{X3} + \text{X4} + \text{X7} + \text{X8} + \text{X11} + \text{X12} + \text{X15} + \text{X16} + \text{D3} + \text{D4} = 340 \dots\dots\dots (\text{G.3})$$

$$\text{X17} + \text{X18} + \text{X19} + \text{X20} + \text{X21} + \text{X22} + \text{X23} + \text{X24} + \text{D5} + \text{D6} = 395 \dots\dots\dots (\text{G.4})$$

$$\text{X25} + \text{X26} + \text{X27} + \text{X28} + \text{X29} + \text{X30} + \text{D7} + \text{D8} = 650 \dots\dots\dots (\text{G.5})$$

Table G.4 - Assumed simulated results of case study 4

Column		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)		
row	fill	cut		1				2		6		B1		B2	
		strata		S1		S2		S1		S1		S1		S1	
1	2	28 40 X1 .9 1	32 55 X2 .9 11	30 38 X3 1 1	35 50 X4 1 6	23 53 X17 .9 1	28 71 X18 .9 11	-	-	-	-	-	-		
2	3	33 39 X5 .9 3	40 53 X6 .9 8	34 36 X7 1 2	42 45 X8 1 8	28 40 X19 .9 2	32 52 X20 .9 11	38 36 X25 .9 4	46 48 X26 .9 9	45 34 B1 .9 5	53 45 B2 .9 10	27 41 B7 .9 1	31 56 B8 .9 11		
3	4	38 36 X9 .9 4	46 48 X10 .9 9	40 33 X11 1 3	48 41 X12 1 9	33 38 X21 .9 3	40 49 X22 .9 8	33 39 X27 .9 3	40 54 X28 .9 8	38 36 B3 .9 4	46 48 B4 .9 9	26 45 B9 .9 1	30 59 B10 .9 11		
4	5	44 35 X13 .9 5	52 46 X14 .9 10	46 31 X15 1 4	54 39 X16 1 10	38 36 X23 .9 4	46 46 X24 .9 9	28 40 X29 .9 1	32 55 X30 .9 11	33 39 B5 .9 3	40 53 B6 .9 8	32 38 B11 .9 2	40 52 B12 .9 8		
5	D	20 48 D1 1.4 1	26 60 D2 1.4 11	22 44 D3 1.3 1	29 57 D4 1.3 6	22 42 D5 1.4 1	28 55 D6 1.4 11	45 38 D7 1.4 5	55 45 D8 1.3 10	-	-	-	-		

Note - Top left, top right, bottom left, bottom right corners and centre of appropriate boxes indicate unit cost (£/100m³), production (100m³/day), swell (shrinkage) factor in compaction, plant team number and the associated variable name respectively.

Substituting values to equation (4.28) the constraints corresponding to each layer in each fill section are:

$$0.9X1 + 0.9X2 + X3 + X4 + 0.9X17 + 0.9X18 = 195 \dots\dots\dots (G.6)$$

$$0.9X5 + 0.9X6 + X7 + X8 + 0.9X19 + 0.9X20 + 0.9X25 + 0.9X26 + \\ 0.9B1 + 0.9B2 + 0.9B7 + 0.9B8 = 600 \dots\dots\dots (G.7)$$

$$0.9X9 + 0.9X10 + X11 + X12 + 0.9X21 + 0.9X22 + 0.9X27 + 0.9X28 + \\ 0.9B3 + 0.9B4 + 0.9B9 + 0.9B10 = 100 \dots\dots\dots (G.8)$$

$$0.9X13 + 0.9X14 + X15 + X16 + 0.9X23 + 0.9X24 + 0.9X29 + 0.9X30 + \\ 0.9B5 + 0.9B6 + 0.9B11 + 0.9B12 = 850 \dots\dots\dots (G.9)$$

Equations (4.29) and (4.30) are not critical since the capacity limitations are greater than the total requirement of the project. For example, the total fill material required to the project (1745 m³) is less than the quantity available at borrow pit one (2500 m³), hence, application of these constraints are not necessary.

Substituting values to equation (4.31) the constraints corresponding to each strata in each borrow pit to be set up are:

$$-1500YSB1 + B7 + B8 + B9 + B10 + B11 + B12 \leq 0 \dots\dots\dots (G.10)$$

Substituting values to equation (4.40) plant utilisation constraints are:

$$X1/40 + X3/38 + X5/39 + X7/36 + X9/36 + X11/33 + X13/35 + X15/31 + \\ X17/53 + X19/40 + X21/38 + X23/36 + X25/36 + X27/39 + X29/40 + \\ B1/34 + B3/36 + B5/39 + B7/41 + B9/45 + B11/38 + D1/48 + D3/44 + \\ D5/42 + D7/38 \leq 18 \dots\dots\dots (G.11)$$

$$X4/50 + X6/53 + X8/45 + X10/48 + X12/41 + X16/39 + X22/49 + X24/46 + \\ X26/48 + X28/54 + B2/45 + B4/48 + B6/53 + B12/52 + D4/57 + D8/45 \leq 18 \dots\dots\dots (G.12)$$

$$X2/55 + X18/71 + X20/52 + X30/55 + B8/56 + B10/59 + D2/60 + \\ D6/55 \leq 18 \dots\dots\dots (G.13)$$

Substituting values to appropriate equations (4.41 to 4.44), sequence of operation and equipment congestion constraints are:

$$X1/40 + X2/55 + X3/38 + X4/50 + X5/39 + X6/53 + X7/36 + X8/45 + \\ X9/36 + X10/48 + X11/33 + X12/41 + X13/35 + X14/46 + X15/31 + \\ X16/39 + X17/53 + X18/71 + X19/40 + X20/52 + X21/38 + X22/49 + \\ X23/36 + X24/46 \leq 18 \dots\dots\dots (G.14)$$

$X5/39 + X6/53 + X7/36 + X8/45 + X19/40 + X20/52 + X25/36 + X26/48 +$
 $B1/34 + B2/45 + B7/41 + B8/56 \leq 18$ (G.15)

$X9/36 + X10/48 + X11/33 + X12/41 + X21/38 + X22/49 + X27/39 +$
 $X28/54 + B3/36 + B4/48 + B9/45 + B10/59 \leq 18$ (G.16)

$X13/35 + X14/46 + X15/31 + X16/39 + X23/36 + X24/46 + X29/40 +$
 $X30/55 + B5/39 + B6/53 + B11/38 + B12/52 \leq 18$ (G.17)

$X25/36 + X26/48 + X27/39 + X28/54 + X29/40 + X30/55 + D7/38 +$
 $D8/45 \leq 18$ (G.18)

G.2.2 LINDO output

LP OPTIMUM FOUND AT STEP 28
 OBJECTIVE VALUE = 77387.4200
 SET YSB1 TO ≥ 1 AT 1, BND= $-.8202E+05$ TWIN= $-.7785E+05$ 41

NEW INTEGER SOLUTION OF 82018.2000 AT BRANCH 1 PIVOT 41

OBJECTIVE FUNCTION VALUE

G.1) 82018.2000

VARIABLE	VALUE	REDUCED COST
YSB1	1.000000	5000.000000
X1	.000000	3.111182

(output continues)

NO. ITERATIONS= 41
 BRANCHES= 1 DETERM= $.937E-7$
 BOUND ON OPTIMUM: 77853.91
 FLIP YSB1 TO ≤ 0 AT 1 WITH BND= -77853.910

NEW INTEGER SOLUTION OF 77853.9100 AT BRANCH 1 PIVOT 41

OBJECTIVE FUNCTION VALUE

G.1) 77853.9100

VARIABLE	VALUE	REDUCED COST
YSB1	.000000	-13948.420000
X1	.000000	5.148014

(output continues)

NO. ITERATIONS= 41
 BRANCHES= 1 DETERM= $.590E-7$
 BOUND ON OPTIMUM: 77853.91
 DELETE YSB1 AT LEVEL 1
 ENUMERATION COMPLETE. BRANCHES= 1 PIVOTS= 41

LAST INTEGER SOLUTION IS THE BEST FOUND

RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

G.1) 77853.9100

VARIABLE	VALUE	REDUCED COST
YSB1	.000000	-13948.420000
X1	.000000	5.148014
X2	.000000	2.060001
X3	.000000	4.517989
X4	.000000	1.022331
X5	.000000	1.817238
X6	176.152000	.000000
X7	73.813530	.000000
X8	207.149700	.000000
X9	.000000	1.822065
X10	.000000	.612409
X11	.000000	.598542
X12	59.036810	.000000
X13	.000000	15.612790
X14	.000000	10.293000
X15	.000000	16.620300
X16	.000000	11.198200
X17	21.249380	.000000
X18	195.417300	.000000
X19	.000000	2.076654
X20	178.333300	.000000
X21	.000000	1.272923
X22	.000000	.132701
X23	.000000	14.243620
X24	.000000	10.183650
X25	.000000	13.817300
X26	.000000	18.655910
X27	.000000	1.474730
X28	.000000	5.556532
X29	.000000	1.258668
X30	650.000000	.000000
B1	.000000	14.285340
B2	.000000	18.938000
B3	45.514660	.000000
B4	.000000	4.838614
B5	92.465870	.000000
B6	201.978600	.000000
B7	.000000	8.346123
B8	.000000	11.235560
B9	.000000	.000000
B10	.000000	3.051498
B11	.000000	12.115680
B12	.000000	12.850920
D1	571.848000	.000000
D2	.000000	5.813223
D3	.000000	1.078761
D4	.000000	5.492182
D5	.000000	8.229368
D6	.000000	13.215170
D7	.000000	54.712900
D8	.000000	61.717920
ROW	SLACK OR SURPLUS	DUAL PRICES
F.2)	.000000	-22.371030
F.3)	.000000	-23.507820
F.4)	.000000	-16.480390

F.5)	.000000	6.717919
F.6)	.000000	-27.888890
F.7)	.000000	-37.846670
F.8)	.000000	-45.734870
F.9)	.000000	-57.078580
F.10)	.000000	12.632280
F.11)	.000000	113.809800
F.12)	4.822224	.000000
F.13)	.000000	93.255840
F.14)	.000000	870.952000
F.15)	4.593206	.000000
F.16)	15.295780	.000000
F.17)	.000000	602.649100
F.18)	6.181829	.000000

NO. ITERATIONS= 41
BRANCHES 1 DETERM.= -.590E -7

G.3 RESOM Applied to Case Study 3 for Sensitivity Analysis

The sensitivity analysis of the average road sectional interval on the total project cost was tested in Chapter 10. This section provides how the road profile was divided, simulated results of possible haulage operations and the optimum material distribution obtained from RESOM corresponding to three different average sectional intervals applied to case study 3.

G.3.1 Case 1 : Average sectional Interval = 495m

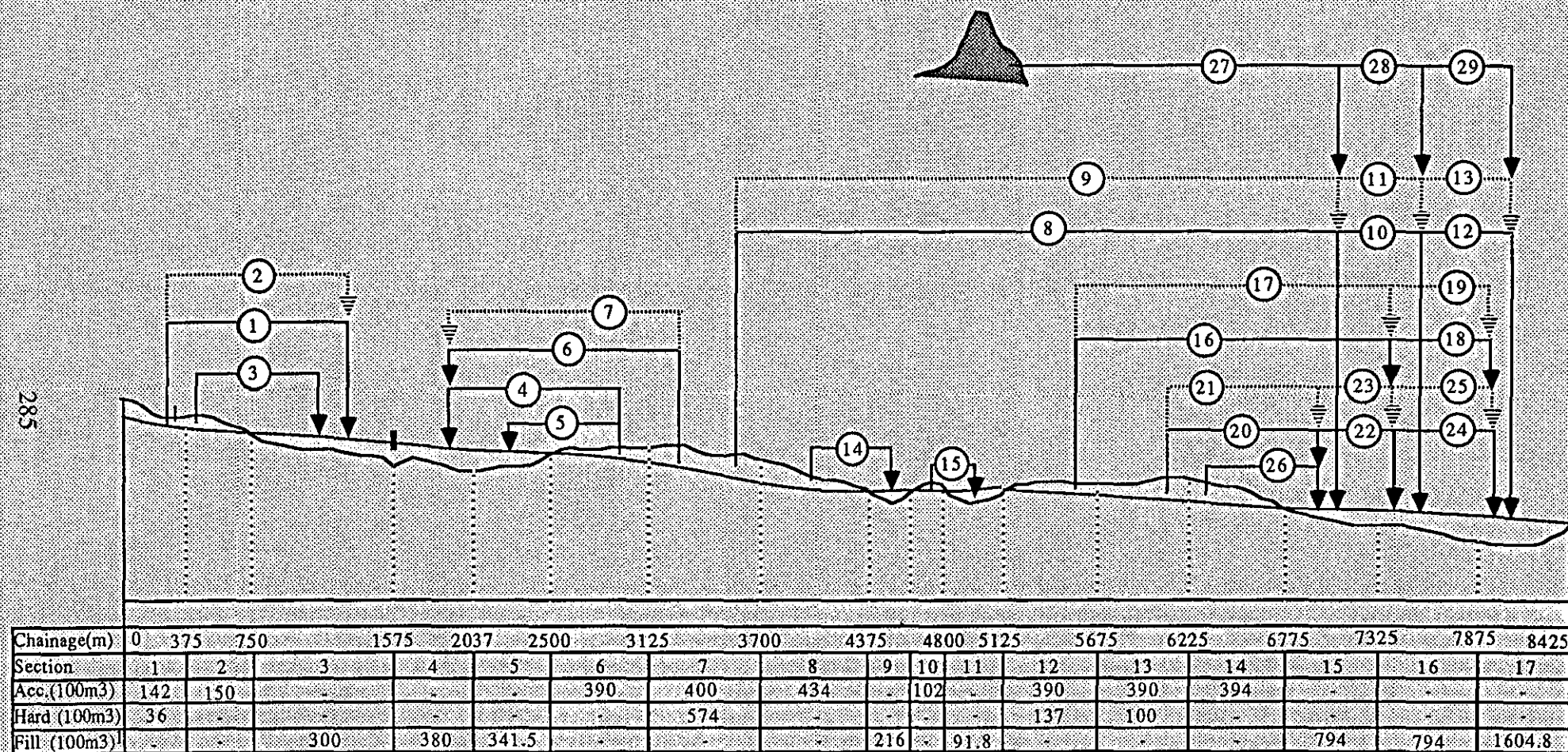
Possible haulage operations tested by RESOM and the corresponding simulated results are shown in Figure G.2 and Table G.5 respectively. Details of all such haulage operations together with the optimum material distribution obtained from LINDO are shown in Table G.6.

G.3.2 Case 2 : Average sectional interval = 765m

Similar to case 1 above, possible haulage operations tested, simulated results and details of each haulage operation together with the optimum material distribution are shown in Figure G.3, Table G.7 and Table G.8 respectively.

G.3.3 Case 3 : Average sectional Interval = 936m

Similar to the above two cases, the required details are provided in Figure G.4, Table G.9 and Table G.10 respectively.



1 - Actual fill quantity measured from drawings

Note - Tag attached to each arrow indicates the haulage operation number

Figure G.2 - Possible haulage operations tested by RESOM : case study 3 - M40 Banbury By-pass : Average sectional interval = 495m (not to scale)

Table G.5 - Simulated results of case study 3 : M40 Banbury By-pass (average sectional interval = 495m)

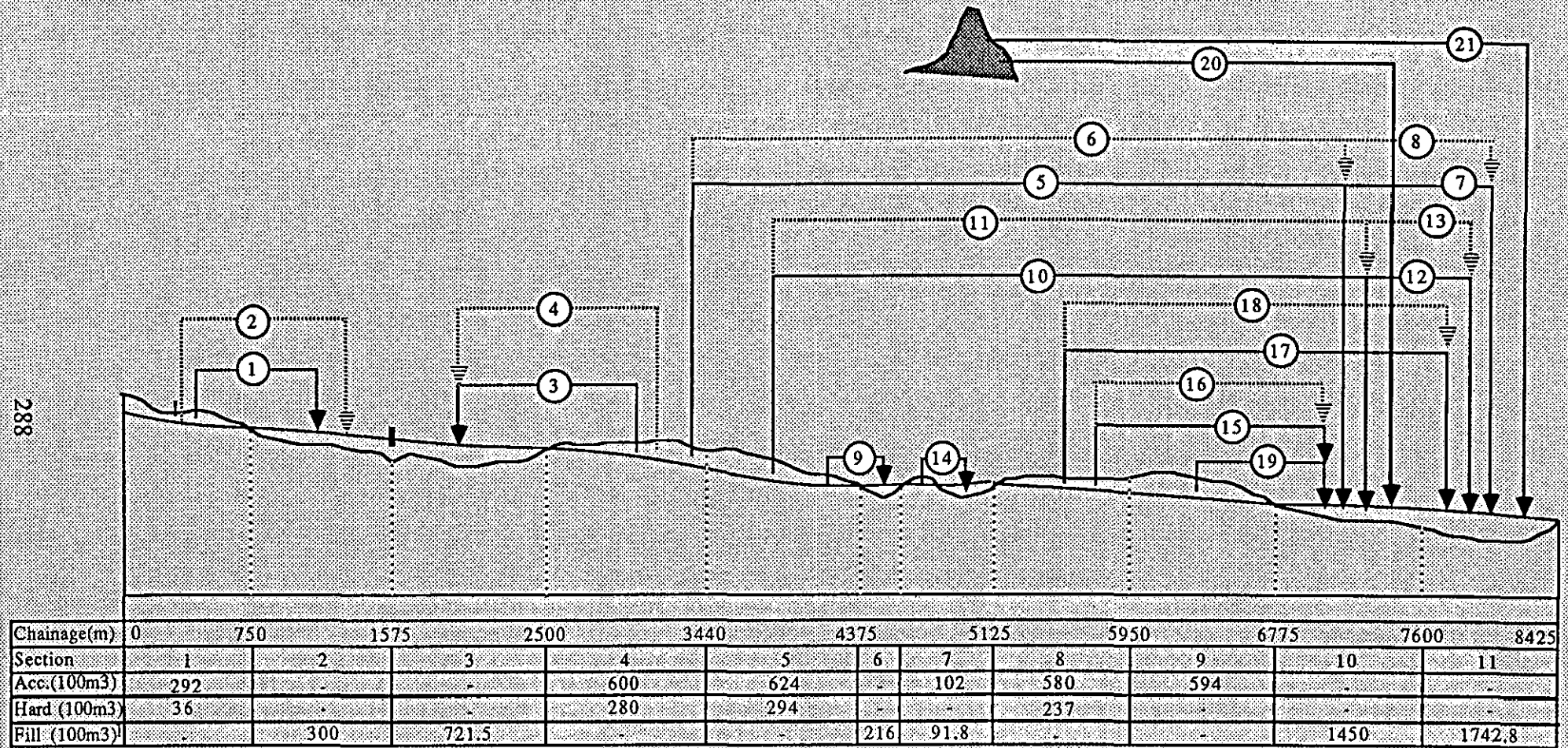
Column		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
row	Cut	1		2	6	7		8	10	12		13		14	B
	strata fill	CE	R	CE	CE	CE	R	CE	CE	CE	R	CE	R	CE	CE
(1)	3	29 67.68 .9 S4	92 15.55 1.1 T4d	27 59.39 .9 S3	-	-	-	-	-	-	-	-	-	-	-
(2)	4	-	-	-	31 65.05 .9 S4	74 59.27 .9 T10	25 13.13 1.1 T5d	-	-	-	-	-	-	-	-
(3)	5	-	-	-	27 59.27 .9 S3	-	-	-	-	-	-	-	-	-	-
(4)	9	-	-	-	-	-	-	26 45.84 .9 S2	-	-	-	-	-	-	-
(5)	11	-	-	-	-	-	-	25 47.22 .9 S2	-	-	-	-	-	-	-
(6)	15	-	-	-	-	81 33.80 .9 T12	131 15.39 1.1 T7d	-	-	-	-	31 65.05 .9 S4	95 15.12 1.1 T4d	30 66.88 .9 S4	243 44.23 .9 HT1
(7)	16	-	-	-	-	89 30.90 .9 T2	143 14.15 1.1 T7d	-	-	62 31.92 .9 T8	115 14.22 1.1 T5d	56 31.77 .9 T7	104 15.62 1.1 T5d	-	250 42.26 .9 HT
(8)	17	-	-	-	-	97 30.36 .9 T13	152 14.61 1.1 T8d	-	-	72 32.62 .9 T10	121 15.17 1.1 T6d	67 32.48 .9 T9	115 14.20 1.1 T5d	-	267 38.61 .9 HT1
(9)	D	7 58.38 1.2 D	10 40.00 1.3 D	7 58.38 1.2 D	7 58.38 1.2 D	7 58.38 1.2 D	10 40.00 1.3 D	7 58.38 1.2 D	7 58.38 1.2 D	7 58.38 1.2 D	10 40.00 1.3 D	7 58.38 1.2 D	10 40.00 1.3 D	7 58.38 1.2 D	-

Note - Top left, top right, bottom left and bottom right corners of appropriate boxes indicate unit cost (£/100m³), production (100m³/day), swell (shrinkage) factor in compaction and plant team number respectively.

Table G.6 - Details of haulage operations and the optimum material distribution : case study 3 - M40 Banbury By-pass (average sectional interval = 495m)

Haulage No.	Sour.-Des.	Mat.type	Haul distance (m)	Plant team	Team id. No.	Optimum quantity (100m ³)
1	1 - 3	CE	1000	D9+4@TS24	S4	142.00
2	1 - 3	R	1000	D8+245+4@M	T4d	33.82
3	2 - 3	CE	600	D9+3@TS24	S3	150.00
4	6 - 4	CE	1100	D9+4@TS24	S4	10.55
5	6 - 5	CE	644	D9+3@TS24	S3	379.44
6	7 - 4	CE	2620	245+10@M	T10	411.67
7	7 - 4	R	2620	D8+245+5@M	T5d	-
8	7 - 15	CE	3325	245+12@M	T12	-
9	7 - 15	R	3325	D8+245+7@M	T7d	-
10	7 - 16	CE	4050	245+12@M	T12	-
11	7 - 16	R	4050	D8+245+7@M	T7D	-
12	7 - 17	CE	4575	245+13@M	T13	182.33
13	7 - 17	R	4575	D8+245+8@M	T8d	574.00
14	8 - 9	CE	412	D9+2@TS24	S2	240.00
15	10 - 11	CE	275	D9+2@TS24	S2	102.00
16	12 - 16	CE	2037	245+8@M	T8	-
17	12 - 16	R	2037	D8+245+5@M	T5d	-
18	12 - 17	CE	2750	245+10@M	T10	390.00
19	12 - 17	R	2750	D8+245+6@M	T6d	137.00
20	13 - 15	CE	1100	D9+4@TS24	S4	390.00
21	13 - 15	R	1100	D8+245+4@M	T4d	-
22	13 - 16	CE	1487	245+7@M	T7	-
23	13 - 16	R	1487	D8+245+5@M	T5d	-
24	13 - 17	CE	2200	245+9@M	T9	-
25	13 - 17	R	2200	D8+245+5@M	T5d	100.00
26	14 - 15	CE	1090	D9+4@TS24	S4	394.00
27	B - 15	CE	5000	235+245+30@18t	HT1	98.22
28	B - 16	CE	5500	235+245+30@18t	HT1	882.22
29	B - 17	CE	6000	235+245+30@18t	HT1	219.56
-	1 - D	R	-	D8	D	2.18

Note - notations are as given in Table 10.1



1 - Actual fill quantity measured from drawings

Note - Notations are as given in Figure G.2

Figure G.3 - Possible haulage operations tested by RESOM : case study 3 - M40 Banbury By-pass : Average sectional interval = 765m (not to scale)

Table G.7 - Simulated results of case study 3 : M40 Banbury By-pass (average sectional interval = 765m)

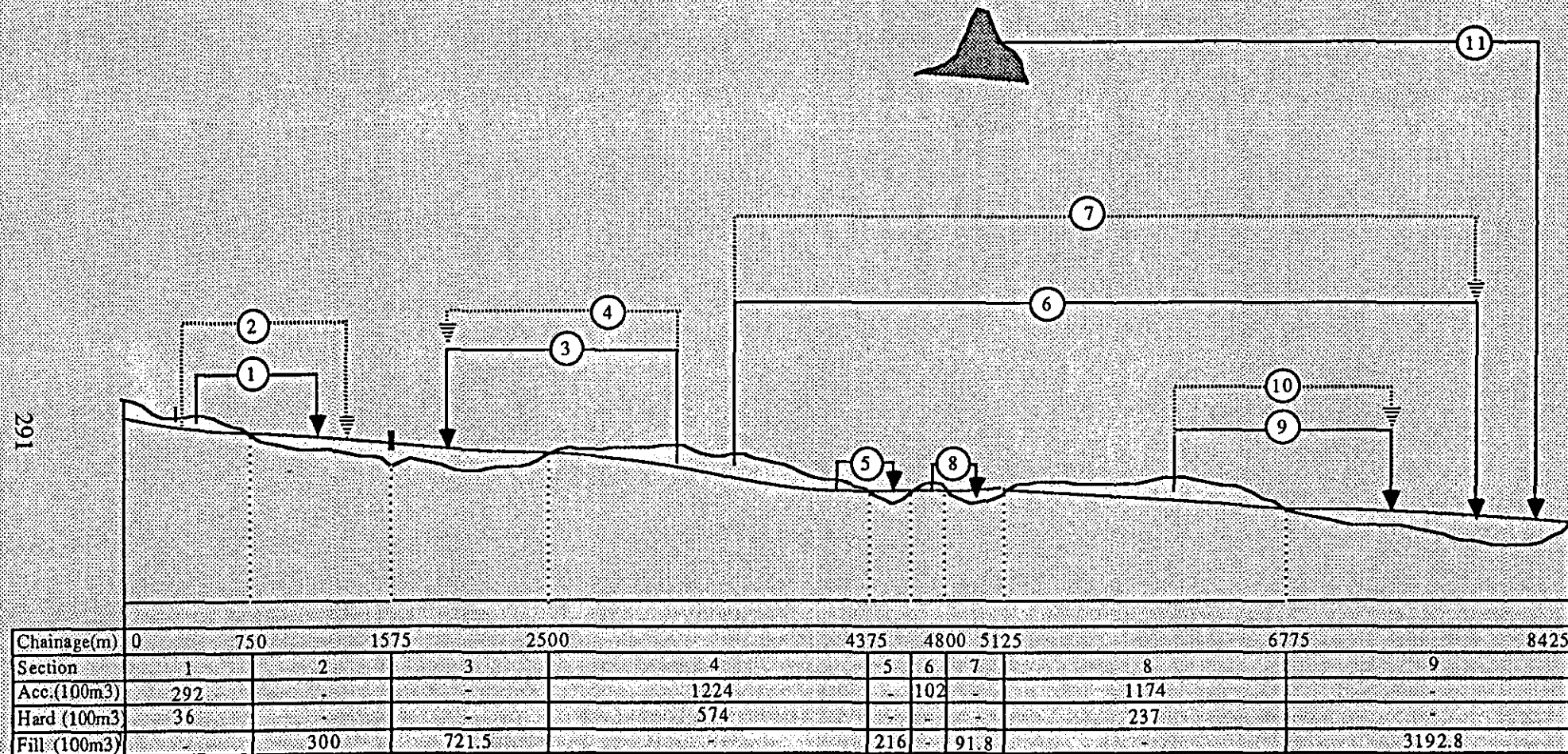
Column		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
row	Cut strata fill	1		4		5		7	8		9	B
		CE	R	CE	R	CE	R	CE	CE	R	CE	CE
(1)	2	28 56.32 .9 S3	92 15.55 1.1 T4d	-	-	-	-	-	-	-	-	-
(2)	3	-	-	28 56.47 .9 S3	91 15.61 1.1 T4d	-	-	-	-	-	-	-
(3)	6	-	-	-	-	26 45.84 .9 S2	-	-	-	-	-	-
(4)	7	-	-	-	-	-	-	25 47.22 .9 S2	-	-	-	-
(5)	10	-	-	92 31.94 .9 T13	147 15.09 1.1 T8d	79 34.55 .9 T12	131 15.39 1.1 T7d	-	34 69.48 .9 S5	105 15.41 1.1 T5d	30 66.88 .9 S4	243 44.23 .9 HT1
(6)	11	-	-	104 30.16 .9 T14	157 15.26 1.1 T9d	91 30.16 .9 T12	142 14.24 1.1 T7d	-	67 32.17 .9 T9	116 14.00 1.1 T5d	-	267 38.61 .9 HT1
(7)	D	7 58.38 1.2 D	10 40.00 1.3 D	7 58.38 1.2 D	10 40.00 1.3 D	7 58.38 1.2 D	10 40.00 1.3 D	7 58.38 1.2 D	7 58.38 1.2 D	10 40.00 1.3 D	7 58.38 1.2 D	

Note - notations are as given in Table G.5

Table G.8 - Details of haulage operations and the optimum material distribution : case study 3 - M40 Banbury By-pass (average sectional interval = 765m)

Haulage No.	Sour.-Des.	Mat.type	Haul distance (m)	Plant team	Team id. No.	Optimum quantity (100m ³)
1	1 - 2	CE	788	D9+3@TS24	S3	292.00
2	1 - 2	R	1000	D8+245+4@M	T4d	33.82
3	4 - 3	CE	800	D9+3@TS24	S3	600.00
4	4 - 3	R	800	D8+245+4@M	T4d	165.00
5	4 - 10	CE	4200	245+13@M	T13	-
6	4 - 10	R	4200	D8+245+8@M	T8d	-
7	4 - 11	CE	5000	245+14@M	T14	-
8	4 - 11	R	5000	D8+245+9@M	T9d	115.00
9	5 - 6	CE	412	D9+2@TS24	S2	240.00
10	5 - 10	CE	3280	245+12@M	T12	-
11	5 - 10	R	3280	D8+245+7@M	T7d	-
12	5 - 11	CE	4100	245+12@M	T12	384.00
13	5 - 11	R	4100	D8+245+7@M	T7d	294.00
14	7 - 7	CE	275	D9+2@TS24	S2	102.00
15	8 - 10	CE	1640	D9+5@TS24	S5	580.00
16	8 - 10	R	1640	D8+245+5@M	T5d	-
17	8 - 11	CE	2335	245+9@M	T9	-
18	8 - 11	R	2335	D8+245+5@M	T5d	237.00
19	9 - 10	CE	1090	D+4@TS24	S4	594.00
20	B - 10	CE	5000	235+245+30@18t	HT1	437.11
21	B - 11	CE	6000	235+245+30@18t	HT1	762.89
-	1 - D	R	-	D8	D	2.18

Note - notations are as given in Table 10.1



1 - Actual fill quantity measured from drawings

Note - Notations are as given in Figure G.2

Figure G.4 - Possible haulage operations tested by RESOM : case study 3 - M40 Banbury By-pass : Average sectional interval = 936m (not to scale)

Table G.9 - Simulated results of case study 3 : M40 Banbury By-pass (average sectional interval = 936m)

Column cut row	fill	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		1	4	6	8	B			
		CE	R	CE	R	CE	CE	R	CE
(1)	2	28 56.32 .9 S3	92 15.55 1.1 T4d	-	-	-	-	-	-
(2)	3	-	-	28 56.41 .9 S3	91 15.68 1.1 T4d	-	-	-	-
(3)	5	-	-	26 45.84 .9 S2	-	-	-	-	-
(4)	7	-	-	-	-	25 47.22 .9 S2	-	-	-
(5)	9	-	-	96 30.64 .9 T13	153 14.50 .9 T8d	-	31 64.96 .9 S4	98 14.76 1.1 S4	25042.26 .9 HT1
(6)	D	7 58.38 1.2 D	10 40.00 1.3 D	7 58.38 1.2 D	10 40.00 1.3 D	7 58.38 1.2 D	7 58.38 1.2 D	10 40.00 1.3 D	-

Note - notations are as given in Table G.5

Table G.10 - Details of haulage operations and the optimum material distribution : case study 3 - M40 Banbury By-pass (average sectional interval = 936m)

Haulage No.	Sour.-Des.	Mat.type	Haul distance (m)	Plant team	Team id. No.	Optimum quantity (100m3)
1	1 - 2	CE	788	D9+3@TS24	S3	292.00
2	1 - 2	R	1000	D8+245+4@M	T4d	33.82
3	4 - 3	CE	800	D9+3@TS24	S3	546.84
4	4 - 3	R	800	D8+245+4@M	T4d	208.49
5	4 - 5	CE	412	D9+2@TS24	S2	240.00
6	4 - 9	CE	4500	245+13@M	T13	437.16
7	4 - 9	R	4500	D8+245+8@M	T8d	365.51
8	6 - 7	CE	275	D9+2@TS24	S2	102.00
9	8 - 9	CE	1200	D9+4@TS24	S4	1174.00
10	8 - 9	R	1200	D8+245+4@M	T4d	237.00
11	B - 9	CE	5500	235+245+30@18t	HT1	1200.00
-	1 - D	R	-	D8	D	2.18

Note - notations are as given in Table 10.1

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