A construction-specific simulation-based framework for earthworks

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Abstract

Construction companies are operating within an increasingly competitive environment. Work often has to be tendered for on a very low profit basis. If the tender is too high, work is lost. If too low the contract may be won, but the job completed at a loss, unless more effective working methods can be found. Plans are used throughout the construction industry to allocate resources and schedule work. Yet, the planning tools used; Gantt chart, PERT and Queuing theory to name but a few, represent jobs as if they are static in duration, which in the complex, dynamic construction environment are clearly inappropriate.

The EPSRC fuelled interest in developing a simulation methodology by suggesting that the construction industry could be considered similar to the traditional manufacturing industry. The manufacturing industry faced similar production dilemmas, work was completed but using inefficient resource configurations, causing bottlenecks, increased work-in-progress leading to higher costs. To reduce number of problems the manufacturing industry sought to utilise and develop a planning technique that had the capacity for modelling the dynamic nature of the industry. Discrete-event simulation enables the problems associated with manufacturing to be anticipated and minimised, as opposed to constantly fire-fighting. Since using simulation has accrued such impressive benefits within the manufacturing industry it is therefore not without credence to believe that the construction industry could also obtain saving from embracing this management tool.

Simulation has been applied to model a number of scenarios within the construction industry. Similarities between the applications were sought and an area for further development was identified. A problem was modeled using the most frequently encountered simulation paradigms found in the manufacturing and construction industries, 'Activity cycle' and 'Process based'. Of the two methodologies, 'Process based' was selected for the development of further models.

A conclusion drawn from the research is that simulation is not being utilized within the construction industry due to the perception that it requires an excessive use of resources. The research project identified that the model building process may be simplified through the development of generic simulation modules. These generic modules enable a simulation model to be developed quickly and easily by a non-simulation practitioner.

The generic modules can be connected to represent the layout of an earthmoving operation. A host of scenarios can thus be modeled with the minimum of time and effort. To ensure that only significant data and process logic was collected and included within the modules the experimental methodology factor analysis was employed. Using this experimental technique, the relationship between and significance of ten different factors were established. Further experiments were performed on the most significant factors establishing an appropriate level of detail for those factors. It was beyond the scope of this thesis to develop modules for every conceivable construction process. Therefore, a methodology is given documenting the development of the chosen construction processes.

Preface

This thesis is submitted to the Schools of Engineering and Construction, at Sheffield Hallam University for the degree of Doctor of Philosophy.

I would like to express my gratitude to my supervisors Dr. D.T. Perera, Dr. P. Stephenson and Mr J. Ridal, for their guidance and constructive criticism throughout the course of this study.

I would like to thank the engineers at Balfour Beatty for their time, without which it would have been impossible to develop simulation models of the construction processes.

The results obtained during the course of this research are to the best of my knowledge original, except where reference is made to the work of others.

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1 Introduction

Projects are tendered for and won based on cost, completion date and quality. Producing accurate plans is therefore vitally important. Current planning tools used within the construction industry are static and hence unrepresentative of the dynamic nature of the industry. These planning tools allow neither variation in process duration, nor alteration of resource configurations to be explored.

Simulation allows the exploration of ideas without the disadvantages of experimenting with the real system. Experimenting with the real system has many disadvantages namely; length of time required to perform an experiment, since the time-base is fixed; the lack of control over environmental factors and hence repeatability of an experiment. Simulation has been successfully used within the manufacturing industry for allocating both time and resources for the completion of various tasks. Since the manufacturing and construction industries can be considered similar, it is hoped that simulation shall be applicable to both industries. Construction personnel have thus far been reluctant to embrace simulation, perhaps because they perceive each construction project to be unique requiring the development of a complex simulation model. Considering each project as a whole, they are unique. Yet, at an operational level, the tasks are often very similar, e.g. one site might require up to 100,000m^3 of material to be excavated while another may require only 1000m^3 of material excavating. Although the quantities differ, the processes remain the same.

It is proposed that the use of simulation in the construction industry can be increased through the development of generic modules that can be joined together to rapidly develop a working simulation model.

1.1 AIMS OF THE RESEARCH

The aims of this research are as follows:

- Identify where simulation has been utilised within the construction industry.
  This research shall be of practical significance to researchers, construction planners and software developers. It will provide a source of reference documenting where simulation has been utilised, and the benefits obtained from applying the technique.

- Establish the reasons for simulation not being widely used in the construction industry outside academia. Propose a solution and select a methodology that shall enable the rapid development of simulation modules for the construction industry.

- Analyse the factors that influence output in a particular sector of the construction industry.

- Develop simulation modules of construction scenarios incorporating the significant factors. The generic modules will enable a large number of scenarios to be modeled without requiring specialist simulation model building skills.

1.2 OBJECTIVES OF THE RESEARCH

The project aims will be achieved through these objectives.

- Undertake a critical review of the literature revealing where simulation has been applied in the construction industry and the type of modelling methodologies employed.
- Develop simulation models of construction processes using the most popular modelling methodologies from both the construction and manufacturing industries.
- Establish a methodology for the development of specific construction activity modules.
- Determine the main effect and interaction between factors using the experimental technique factor analysis.
- Examine the significant factors to determine how Output is affected by modelling a system in varying degrees of detail.
- Develop generic modules for rapid application development and demonstrate the benefit of simulating construction processes.

1.3 STRUCTURE OF THE THESIS

Chapter 1 Introduction

The contents of this thesis are chapter outlined, together with the aims, objectives and scope of the research.

Chapter 2 Literature Review

The variety of planning tools adopted by the construction industry are documented, with the limitations of each outlined. The ability to model complex interactions between resources using simulation enables some of the disadvantages associated with traditional planning tools to be overcome. A number of construction processes have been modeled using discrete event simulation. Commonality between these process characteristics is highlighted with a construction process identified for the application of simulation. The academic community has to a limited extent, explored simulation and demonstrated some of benefits that simulation can bring to the construction industry. Yet, the construction industry has not embraced this technology, the reasons for this are documented.

Chapter 3 Selection of simulation methodology

A few researchers have experimented with applying simulation to the construction industry. The majority of which has been performed using activity cycle methodology, although a small number of papers report on using process based simulation techniques. This chapter explores the difference between results obtained using mathematical and simulation models. Further experiments are performed to determine a suitable simulation methodology for the development of simulation modules for the construction industry.

Chapter 4 Analysis of significant factors

For the construction industry to embrace simulation, it must be easy for an individual, not wholly conversant with the art of simulation, to develop models and assess different resource configurations for a large number of scenarios. Simulation modules that can be joined together is one approach for solving this problem. The significance of each factor, whether it has a main effect or interacts with other factors, is established using factor analysis. Further experiments were performed on significant factors to determine an appropriate level of detail for the modules. This prevented resources from being wasted through including insignificant factors in the modules.

Chapter 5 Development and use of generic modules

Simulation modules can be developed once a simulation methodology is identified, the significant factors are established and an appropriate level of detail determined. For each generic module, a communicative model is described. The programming logic for each module is explained and an animated front-end illustrated. To transform generic into site specific modules, data needs entering. A typical example of the type of data that might be entered is given with prompts illustrating the range of suitable data that may be entered. At the end of each module, concluding remarks specify the limitations of each module. The chapter concludes with a practical example of how the models are assembled to model a particular scenario.

Chapter 6 Conclusions and recommendations

The suitability of using simulation to plan road construction earthworks has been determined. The feasibility of developing simulation modules of construction operations and the significance of each factor has been established. To increase the number of construction scenarios that may be modeled using the modules it is recommended that additional modules be developed using the methodology presented within this thesis.

1.4 SCOPE AND LIMITATIONS OF THE RESEARCH

It is not the objective of this thesis to enable all conceivable earthmoving scenarios to be modelled using generic modules, as this would require an excessive use of resources. Modules are developed to enable the most frequently encountered problems to be quickly and easily modelled.

2 Literature Review

2.1 INTRODUCTION

This literature survey contains a review of papers, books and thesis relating to planning of construction activities. It examines how construction projects are currently planned and controlled. The drawbacks of using static planning tools are highlighted, together with the advantages of using a dynamic planning tool such as discrete event simulation.

There are only a few documented applications of simulation within the construction industry; these are examined later within this chapter. Hence, it was necessary to examine other industries that have benefited from using discrete event simulation to establish what modelling techniques are employed.

Simulation may reduce the number and magnitude of delays. This chapter contains a general review of simulation identifying where it has been applied within the construction industry. The characteristics of these activities are noted enabling new operations within the construction industry to be identified.

2.2 PLANNING TECHNIQUES.

Within the construction industry, project planning is vitally important. A good plan provides the opportunity for contracts to be won in the knowledge that the project can be completed on time, safely, within budget and to an agreed quality.

"The results of a well planned carefully monitored and controlled contract reflect directly on the profitability of the contract and the company." Wijesundera (1989).

If the accuracy of planning construction operations can be improved, then all concerned with the project shall benefit. The current economic climate necessitates the submission of tenders on a near zero profit basis. Hence, any unexpected delay significantly undermines the viability of the project necessitating the investigation of planning techniques within the construction and other similar industries.

2.2.1 TYPES OF PLANNING TOOLS.

It is difficult to consider all of the possible construction sequences through which a building may be erected without the aid of a suitable planning tool. To assist in the management of construction projects there are several tools currently available; Bar-Chart, Critical Path Method (CPM) and Line Of Balance (LOB) to name but a few.

A survey carried out by Aouad (1994) identified the Bar-chart and CPM as two of the most commonly used tools for planning construction operations with LOB and PERT being used to a lesser extent, Figure 1. The large number of companies using the Bar-chart can be accounted for because of its simplicity, but it was not until the advancement in computer technology in the early 50's that planning tools other than the bar-chart were developed and adopted.

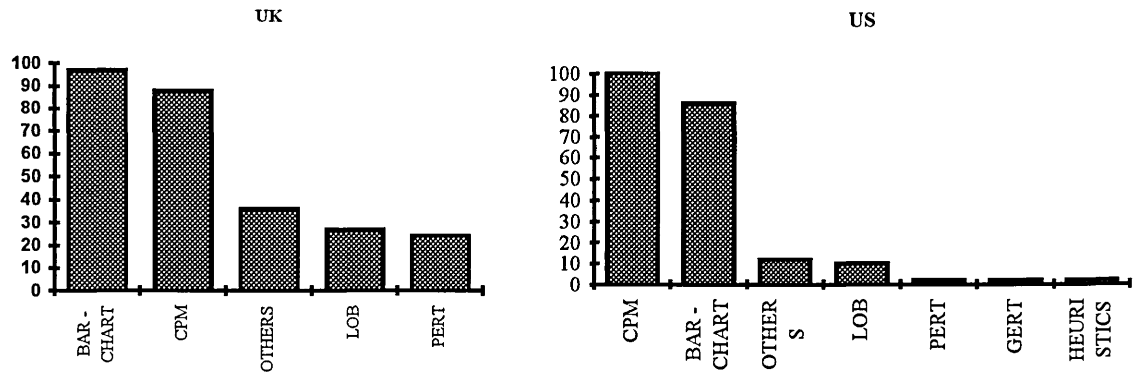

Figure 1 Planning techniques used by contractors in the UK and US.
Source: Aouad (1994) .

2.2.2 GRAPHICAL MODELS:- THE GANTT (BAR) CHART.

The Gantt chart, more commonly known as the bar-chart, was developed by Henry Gantt around the 1900's. A Gantt chart consists of a list of activities recorded against a time scale with both start and end dates given for each activity. The duration of which is usually given in terms of half-days, days or weeks and is represented by a continuous bar. An example of a typical bar-chart is given in Figure 2.

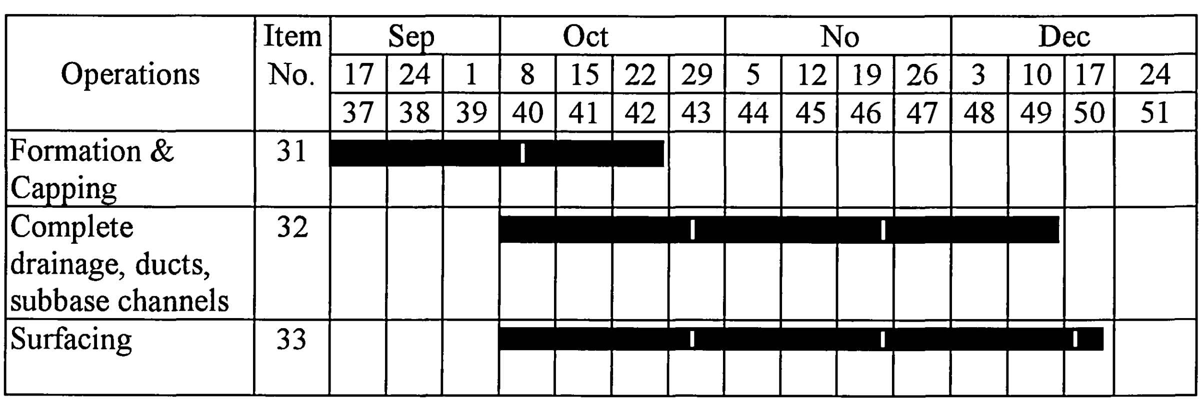

Figure 2 Typical Bar chart

The main advantage of the bar-chart is its simplicity as a communication tool, enabling managers to obtain an overview of construction processes, facilitating tighter planning and control. Figure 2 shows that drainage should start after the formation and capping operation has started. However, the interdependencies of activities are not explicitly defined, i.e. could drainage start any earlier, if so, by how much and would starting drainage earlier reduce the overall project duration? To enable questions like these to be answered linked bar-charts can be used.

2.2.3 LINKED BAR CHARTS.

Linked bar charts Archibald (1967) were developed to establish which processes/activities must lead or follow one another. This enabled activities that were critical and those with float to be identified so that the effect of completing a given sequence of activities late could be anticipated.

Another adversary of the bar-chart, Archibald (1967) stated that bar charts are seriously flawed; 'the inability to reflect uncertainty, or tolerances, in the duration times estimated for the various activities. In contemporary management this deficiency can be critical.'
However, it should be born in mind that Archibald was a champion of both Critical Path Method (CPM) and Program Evaluation and Research Technique (PERT).

McCaffer (1984) argued that despite the advancement of the tool, major problems that are inherent to the bar-chart still remain, namely, activities are not typically broken down into small steps. This can create problems especially if the project is complex.

2.2.4 NETWORK MODELLING TOOLS

The advent of powerful computers in the mid 50's and the increased desire to complete projects on time and within budget led to a new generation of planning tools.

- Critical Path Method (CPM) was developed in 1957.
- Project Evaluation and Review Technique (PERT) were developed independently, but around the same time as CPM.

Kelly developed one of the first network modelling tools, CPM, originally to improve the planning and scheduling for the construction and maintenance of chemical processing plants.

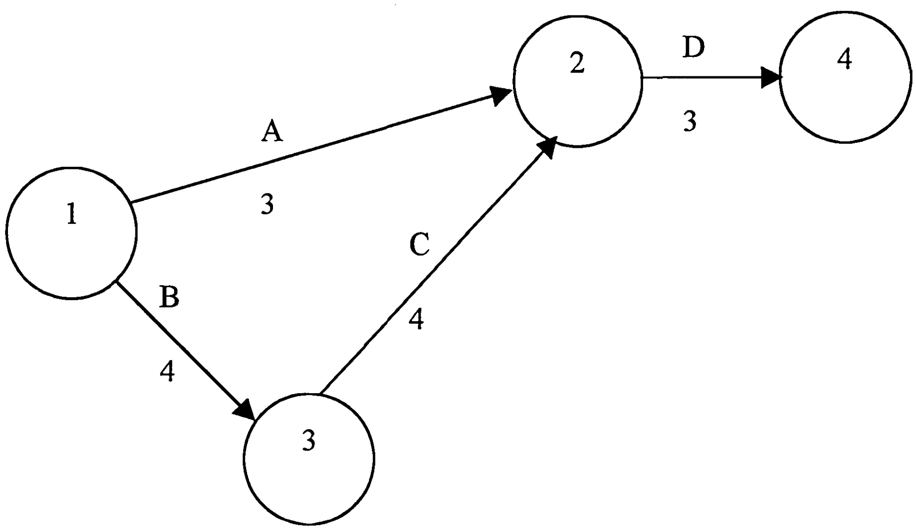

Figure 3 Example network

The network shown in Figure 3 consists of; activities, their durations and how they are associated. For example, the duration of activity 'A' is 3 weeks; activity 'C' takes 4 weeks but cannot start until activity 'B' is completed. With this information, a planner has the necessary information to determine those paths that are and are not critical. Activities 'B', 'C' and 'D' are critical, while 'A' is not and could start up to 5 weeks behind 'B' without affecting the overall completion time of the project.

Clearly, CPM is an improvement upon the bar-chart when there is a requirement for activities that are critical to be determined. However, Adrian (1973) states that the duration of activities recorded in CPM are deterministic and hence inappropriate. It is clearly inappropriate to consider activities as possessing durations that are deterministic, since activity durations are dependant upon many factors including; weather, labour availability/experience and equipment reliability. It would be more realistic to assume that the durations of activities are variable (stochastic). A PERT model assumes that activity durations are stochastic.

2.2.5 PERT

In 1957, management consultants Booz, Allen, and Hamilton developed PERT for the US Navy Special Projects Office. The aim of project PERT (Program Evaluation Research Task) was to develop a tool that would provide its management with: -

- *Information on the progress* to date and the outlook for accomplishing the Fleet Ballistic Missile (FBM) program,
- *Measure of the validity of established schedules* for the optimum accomplishment of total program objectives,
- *Predict* the impact of actual or proposed changes in plans on total objectives.

The duration of each activity in a PERT model is based upon past experience. A minimum, maximum and mean duration is obtained for each operation and incorporated into the model in the form of a stochastic, typically triangular, distribution.

Despite the widespread acceptance of CPM and PERT, schedule overruns continue to be a major problem. One possible reason is that network schedules calculated with CPM or PERT do not provide adequate information regarding the potential for schedule overruns. That is, CPM gives only a single number, which is intended to be the duration of the project. PERT is but a slight improvement in that it attempts to evaluate the probability of a project's duration by giving the expected completion time. Additionally, the PERT method sums the variance of the activities along the path used to calculate the expected completion time in order to express a measure of risk to the project duration.

'Although PERT introduces elements of probability into the calculations, PERT consistently underestimates project duration. The principal cause of this underestimation is a condition known as "merge event bias." Briefly, merge event bias occurs when several paths converge on a single node.' Halpin (1992).

Kavanagh (1985) summarised the findings of Ashley (1980), Birrel (1980) and Peer (1974). 'CPM/PERT places emphasis on minimising the total duration of a project and therefore makes the fundamental, unrealistic assumption that resources are unlimited and centrally controlled. The contractor, however, is primarily interested in minimising the resource input and maximising resource utilisation.'

CPM and PERT are not used exclusively by the construction industry; indeed the manufacturing industry has used these techniques for many years. However, the drawbacks inherent to these techniques have led to the investigation of other planning tools. One of the more successful tools for planning complex processes in the manufacturing environment is simulation.

2.3 WHAT IS SIMULATION?

2.3.1 SIMULATION AND MODELLING PHILOSOPHY

Simulation and modelling are widely used to describe a whole manner of applications from finite difference analysis to flight simulators. The first stage in this research project is to define precisely what is meant by the terms discrete event simulation and modelling. The Oxford English dictionary does very little to clarify the meaning of these terms.

Discrete; -	Discontinuous, consisting of distinct parts.
Event; -	Anything which happens, any incident, occurrence or result.
Simulate; -	Pretend to be, have, or feel; Imitate or counterfeit; Reproduce the conditions of (a situation etc.); Produce a computer model of (a process).
And to model; -	Representation in 3D of an existing person or thing of a proposed structure, esp. on a smaller scale; Simplified description of a system etc., to assist calculations and predictions; Figure in clay, wax etc., to be reproduced in another material; Particular design or style, esp. of a car.

When reading the literature on simulation it became apparent that the word simulation means different things to different authors. The Author of 'Cranes, Concrete, Construction...& Computers', Tarricone (1992), believed simulation to be that of 3D visualisation, Lansley (1981) used simulation as a gaming tool for modelling management strategies. While McCahill (1993) believed that simulation provides us with a tool for optimising a particular performance parameter by adjusting the configuration of available resources. Both are totally valid interpretations; however in this thesis, it is the models documented by Dennis McCahill rather than Paul Tarricone that are considered as discrete event simulation.

Construction and manufacturing have many similar operational characteristics. However, best practices; 'Just in Time' and 'Material Requirement Planning', developed in manufacturing have rarely been used in the construction industry. Among the many best practices that exist, Halpin (1993), argued that computer simulation would provide an excellent opportunity to improve output, reduce cost and shorten lead times in the construction industry. For example, at present, conventional project planning tools are used to plan and manage construction projects. These 'static models', however, do not consider the dynamic nature of construction processes with resources allocated to activities on an aggregate basis. These over-simplified models often provide less accurate performance data hence managers and planners make ill-informed decisions. Consequently, project targets may be missed and additional expense incurred.

In contrast, 'dynamic models' such as computer simulation can take account of time variations (as occur in real construction projects) with the utilisation of resources more accurately represented. These models enable realistic 'what-if' analysis to be performed providing a planner with detailed performance data, thus improving the quality of decisions made.

2.3.2 WHY SIMULATE?

Nunnally (1981) and Halpin (1992) indicated that one particular reason for applying simulation in construction was because of the limitations of current planning tools, stating that "because of the complexity of interactions among units on the job site and in the construction environment, queuing models can be applied to only a limited number of special cases." Thus simulation, through its ability to model the dynamic characteristics of operations as evident in manufacturing, offers the potential to be an improved planning technique over existing tools, particularly where the processes are repetitive.

The benefits of undertaking simulation exercises in the manufacturing industry are widely publicised, Banks (1995) and the Simulation Study Group (1991). A well designed and executed simulation project can prove invaluable for understanding how a system really operates as opposed to how it is perceived to operate, thereby reducing the cost and risk of implementing change. New situations, about which we have limited knowledge or experience, can be manipulated in order to prepare for theoretical future events, simulation's greatest strength lies in its ability to let us explore the dynamics of a system through asking "what if" questions. Pegden (1990). Discrete event simulation is a tool that enables one set of input parameters to be compared with another set so that the most desirable level for each parameter can be established.

One could of course perform the majority of desirable experiments on the real system rather than incur the cost of generating a computer model, but in doing so there are many dangers to overcome. Robinson (1994) gave several reasons for this.

- Cost: to assess the impact of utilising additional machinery would necessitate incurring the cost of renting and installing machinery not to mention the cost of training operators.
- Repeatability: a particular phenomenon may seldom occur, perhaps only when several separate conditions are present, however the condition may seriously affect the operation of the facility.
- Control of the time base: activities seldom occur at an appropriate speed to allow detailed analysis. The operation may be performed too quickly in the case of a bottling facility, or too slowly when examining the possible throughput of a car paint spray booth. A computer model allows the speed of the activity to be performed at a user-defined rate allowing closer analysis of the system.
- Legality and safety: experiments are performed remote to the system eliminating disruption to the facility, confusion and associated reduction in safety that changing work patterns can cause.

Of course, a system could be represented using a mathematical model, however the dynamic and transient effects, non-standard distributions, and interaction of random events can not be determined, Robinson (1994).

Even though the application areas are diverse, simulation models are generally developed for one or more of the following reasons: to assess resource utilisation, reduce delays/bottlenecks or reduce costs.

2.4 ACTIVITY CYCLE, EVENT VS PROCESS BASED SIMULATION

2.4.1 INTRODUCTION

Although simulation is an appropriate tool for modelling construction activities, there are only a few documented applications, in comparison to the manufacturing industry where many applications have been documented. Where simulation has been applied within the construction industry, it has been done so using the activity cycle methodology where as the manufacturing industry tends to utilise process based methodology. Thus the following section discusses the various simulation methodologies available.

2.4.2 SELECTION OF MODELLING METHODOLOGY

There are three main types of modelling methodologies or 'word views' Activity, Entity and Process based. Each of which represents a compromise between how well the real world can be modelled, the ease of model building or their computational efficiency, Carrie (1988).

2.4.3 ACTIVITY CYCLE METHODOLOGY

The activity cycle methodology is most commonly used for modelling construction operations. With academics; Oloufa (1992), Ioannou (1992), Vanegas (1994) and Huang (1994) each developing their own simulation packages based on this methodology.

Activity-based simulation models are constructed from the point of view of each entity's lifecycle and the interactions between other classes of entity. When drawing an activity cycle diagram there are five conventions to observe:

- 'Each type of entity has an activity cycle
- The cycle consists of activities and queues
- Activities and queues alternate in the cycle
- The cycle is closed
- Activities are depicted by rectangles and queues by circles or ellipses', Carrie(1988).

Thus the simple activity of excavating and hauling material may be represented as Figure 4.

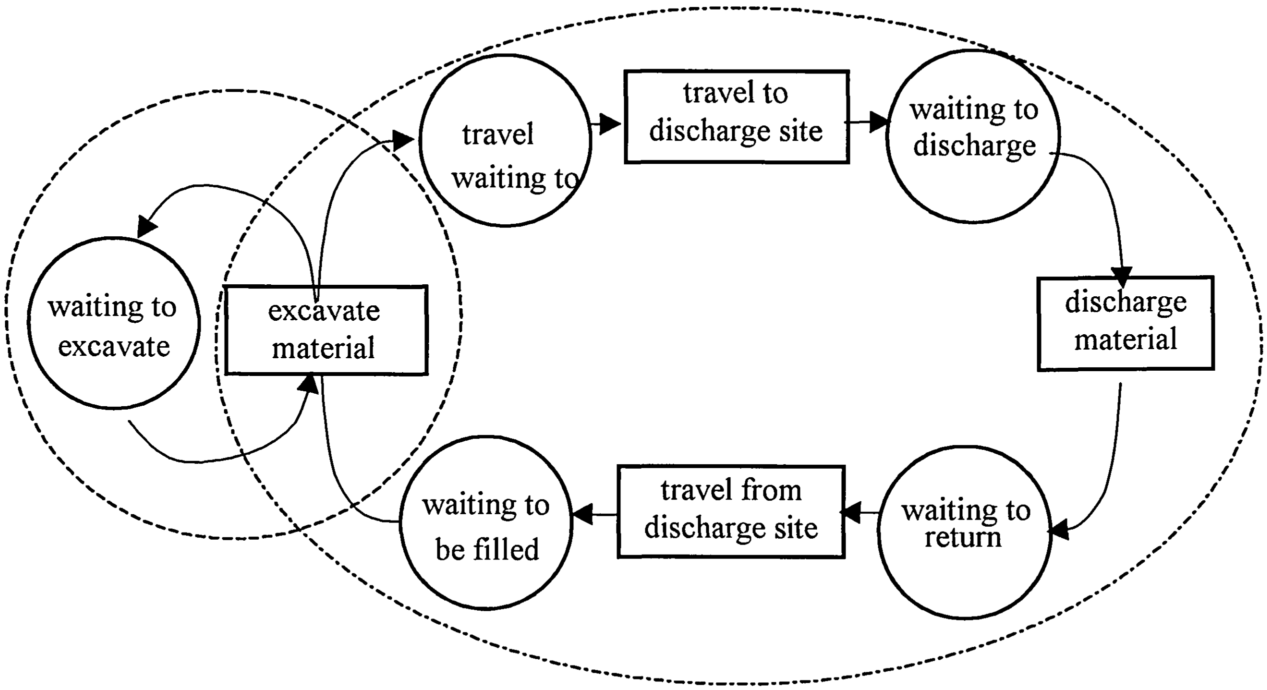

Figure 4 Activity Cycle diagram of excavator and single truck type.

A circle is used to represent an idle state with a rectangle to represent a busy state. Thus the excavator can either be idle, waiting for a truck or busy filling it. Whereas a truck can be waiting for the excavator, being filled, waiting to travel to the discharge site, travelling to the discharge site, waiting to discharge the material, discharging the material, waiting to return or travel back to the excavator to complete the activity cycle.

Although it is considered to be conceptually easier to develop activity cycle diagrams, Pidd (1994) commented that 'the main advantage of this approach [activity cycle] is that it supports rapid program development. The main snag is that, without considerable effort, it is very difficult to model complex systems.'

2.4.4 EVENT-BASED APPROACH

Event based simulation packages, such as SEE-WHY and GASP consist of event routines, where an event routine describes the operations in which entities engage when the system changes state, such as the beginning or the end of an activity. As an example, take the event of an articulated truck arriving at an excavator and joining a queue on a first in first out basis, in an event based model there are two stage changes:

- The arrival of the truck
- The end of service, i.e. the departure of the truck.

With an event based approach, each event requires an event routine, Figure 5.

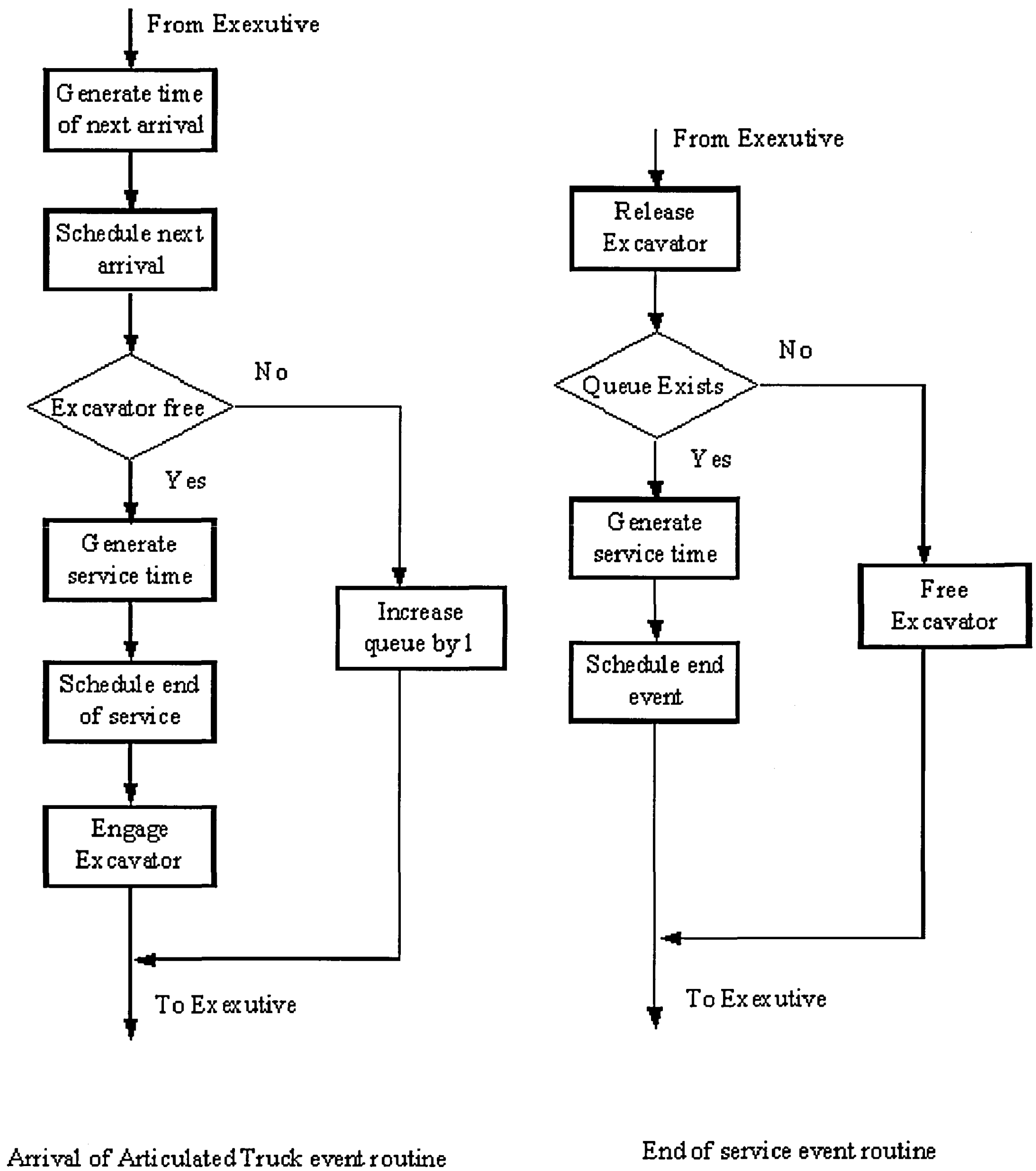

Figure 5 Event based truck arrival and departure routines

Arrival of next articulated truck: if the excavator is free and no queue exists, it is immediately loaded. Otherwise the truck joins a queue.
End of service: the truck leaves the excavation area. The excavator serves the next truck if there are any waiting in the queue. If there are non waiting, the excavator becomes idle.

Of the two simulation methodologies, activity and event based, Pidd(1984) commented that it is easier to write activity based programs because:

- They tend to produce smaller program segments for activities than would be the case for events.
- An analyst need not be too concerned about the sequence of activities at each event – since this is sorted out by the executive in the activity scan.

Hence the approach to programming is more structured making it easier to modify existing models, which is particularly important when developing large and complex simulation models.

2.4.5 PROCESS BASED

The third simulation methodology is the process based approach, which "views the simulation in terms of the individual entities involved, and the code written describes the 'experience' of a 'typical' entity as it 'flows' through the system." Law (1991, p. 13). Thus in earthmoving, the entity is the material and the experience is the processes that the entity is exposed to, e.g. the method that is used to excavate, haul or discharge the material. This differs from activity cycle simulation where the focus is on the use of resources in order to perform a sequence of activities.

In process based simulation the progress of each entity continues until it is blocked or delayed for some reason. Generally two kinds of delay are considered.

Unconditional delays, e.g. excavation time. In these, the entity remains at the same point in its process until the pre-determined excavation time has elapsed.

Conditional delays, the entity remains at that point until a condition allows it to move. For example, the truck remains in the queue until the excavator is free and the truck is at the head of the queue.

Thus the simple activity of excavating material may be represented as Figure 6.

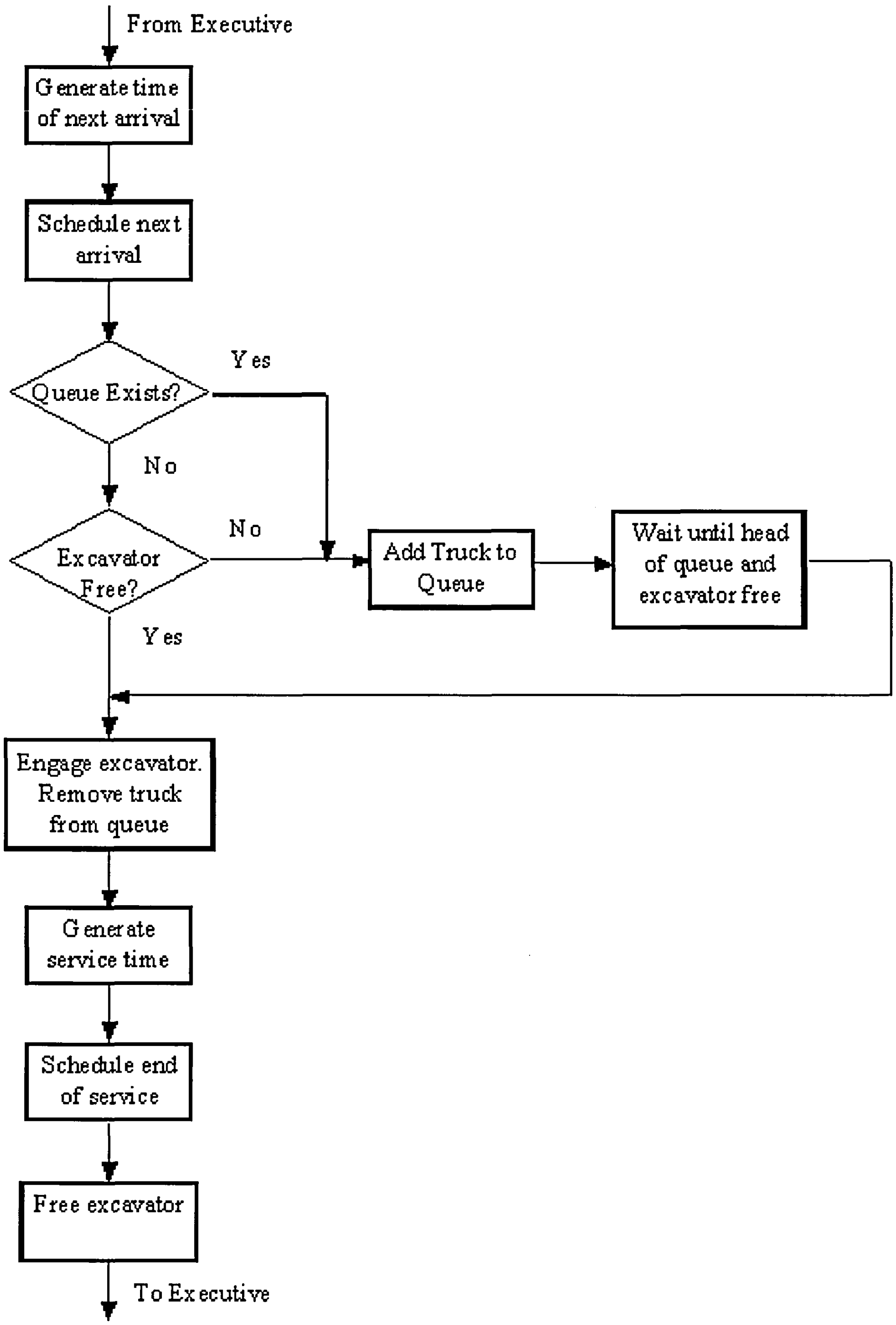

Figure 6 Simple queue: truck process

An articulated truck arrives in the excavation area. If there is a queue then the truck joins it and conditionally waits for the excavator to become available. When the excavator becomes available the truck engages it and is unconditionally delayed while it is filled. Once full the truck leaves the excavation area freeing the excavator.

2.5 COMPARISON OF METHODOLOGIES

Although it is easier to develop a simple simulation model using activity cycle as opposed to the process based approach, as the complexity of the model increases it becomes increasingly difficult to model using activity cycle methodology, and 'in most cases they cannot include the full complexity of a system being simulated', Pidd (1989).

Sergen (1995) observed that 'activity cycle diagrams only contain a few symbols, they cannot, in most cases, fully represent the complexity of the system being modelled. It is difficult to express the logic and the rules of the system, sometimes called process strategies, without using dummy cycles.' Pidd (1992) concurs with this view stating that; "There are systems which do not easily fit the activity cycle notion - though enthusiasts would argue that they can be made to fit. One such type of system is where the interruption of an active state may occur before it reaches its scheduled termination." This is similar to what can happen to a truck as its progress may be interrupted by congestion of traffic lights or even roundabouts.

Pidd(1984) also suggests that the length of time required for a programmer to produce a working program should be considered when choosing a simulation methodology. He observed that there is a trend for the cost of computers to keep falling where as the cost of skilled labour shows no sign of dropping. Hence, it would seem appropriate to concentrate on methods that reduce the length of time to produce a working, valid simulation model by easing the task of the programmer.

Finally, the results attained through modelling a given system should be the same irrespective of which methodology is employed and what ultimately maters is the ease with which a model can be constructed, and that is dependant upon the software employed, which is examined in section 3.3.

2.6 OVERVIEW OF WHERE SIMULATION HAS BEEN USED IN CONSTRUCTION

When simulation has been applied to construction processes, it has been documented almost exclusively by academics. This could be because academics document and publish substantially more than their industrial counterparts, or that the construction industry views simulation as an abstract tool, only to be undertaken as an academic exercise and bearing little relevance to the outside world. Alternatively it could simply be explained by the fact that industry does not yet appreciate how to exploit the potential of simulation.

The majority of the research into using discrete event simulation within the construction industry emanates from North America. This is principally because the most noticeable champion of simulation in the construction industry is Professor D. W. Halpin who is based at Purdue University, West Lafayette. His studies began with the 'investigation of the use of simulation networks for modelling construction operations' for which he obtained his PhD in 1966.

Halpin realised that the construction industry considered process-based simulation to be an abstract tool with little correlation between its modelling elements and construction processes and consequently developed CYCLONE. He considered the activity cycle based methodology, upon which CYCLONE is based, to represent construction activities more closely than process based simulation. Later Lluch (1981) under his guidance developed a microcomputer-based version of CYCLONE, called MicroCYCLONE. More recently a windows based animated front-end was developed called DISCO, Huang (1993).

Another of Halpin's researchers AbouRizk, supervised Sawhney (1994) and the development of the AP^3 modelling methodology, which recommends that the method of simulating construction processes could be simplified if a model environment was develop consisting of eight basic components:

1. A database to store resource attributes.
2. An atomic model library that includes all types of resources for a specific type of construction project.
3. A user interface that allows the user to specify required resources, project related resource attributes, and other project information.
4. A module to convert physical site conditions to simulation information, e.g. computing the duration of a construction process from the physical site conditions.
5. An atomic model generation module which can combine resource attributes and project-related information with atomic models in the library to produce project specific atomic models.
6. A knowledge-based module which can identify and generate proper linking structures to suit the atomic models.
7. A module that can assemble all atomic models with linking structures to generate a working simulation model.

8. An interface which can call the selected simulation language and allow the user to experiment with the generated model.

Shi (1994) also proposed the development of atomic models consisting of resources and operating processes which are stored in model libraries using object oriented representation technologies. However, in order to develop the libraries he considered that several issues need to be resolved including defining and designing the atomic model to be included in the libraries, together with the mechanism for assembling models from the atomic elements. From his research he also concluded 'that for equipment intensive applications such as earthmoving, simulation can be applied at very little cost if the modelling environment is consistent with the way planners model their systems.'

Ioannou (1996) also recognised the limitations of the simulation packages available and adapted and enhanced MicroCYCLONE to produce a simulation-modelling package called Stroboscope. Stroboscope differs from its predecessor by allowing the use of attributes, which are extremely useful. They enable the characteristics of say, excavated material to be retained. Making it possible to change the amount of material that may be compacted depending upon the type of material excavated. Ioannou demonstrated the functionality of Stroboscope by developing models of and establishing which of two bridges would be the most cost effective to purchase.

One of the more unusual pieces of research was undertaken by AbouRizk (1993). Unlike previous academics, where the applications were theoretical and documented to publicise the development of new simulation software, AbouRizk developed a simulation model for industry to reconcile the differences of opinion between Alberta Transportation and Utilities

(ATU) Bridge Engineering Branch, and Northern Steel Inc. (NSI). The disagreement stemmed from a complexity claim accruing to additional labour amounting to $236,000. A simulation model was built to compare the original working method with that of the required proposal, caused by an amendment to the design specification. The model was a success, with the output considered unbiased and as such, it was deemed that a justifiable excess claim should be between $124,523 - $130,549.

Hajjar (1997), also appreciated that there was a gap between simulation tools and the abilities of construction planners to use simulation and suggested the development of simulation models could be simplified using a visual object-oriented environment. To this end special purpose simulation tools; AP2-Earth, Hajjar (1997) and CRUISER, Hajjar (1998) were developed using object-oriented techniques. Object-oriented techniques simplify module development through the notion of encapsulation. Where all of an entity's properties are set within the definition of the object, Joines (1998). With one object communicating with another by passing messages. Thus additional modules can be created without requiring an original object to be modified.

Although early researchers used activity cycle methodology, e.g. Halpin (1973), recently some research has been performed using process based simulation Gonzalez-Quedo (1993) and Hajjar (1997). The following chapter therefore investigates the suitability of each methodology for modelling a particular construction scenario.

Summary of the simulation packages used for modelling construction operations and the modelling methodologies employed are given in Table 1.

Tools	Modelling Methodology
MicroCYCLONE	Activity cycle
DISCO	Activity cycle
STROBOSCOPE	Activity cycle
CIPROS	Activity cycle
SLAMII	Process Based
AP2-Earth	Object oriented
CRUISER	Object oriented

Table 1 Simulation packages used to model construction operations.

Even thought the application areas appear to be diverse, upon closer inspection it became apparent that previous simulation research typically falls into one of two categories, earthmoving or placement of concrete. These two categories possess particular characteristics that make them suitable to be modelled using simulation.

- Systems are modelled at an activity level, involving the allocation and utilisation of resources.
- The processes are repetitive, usually lasting several hours,
- The equipment used or material handled is expensive,
- The type of machinery used and their processing times are predicable.

Not only is it important to consider how and where simulation has been applied in the construction industry but also to establish activities that have either been infrequently modelled or wholly overlooked.

Applications involving manual labour are seldom modelled. To model humans accurately is theoretically possible, but the interactions between and the characteristics of people make modelling these processes difficult. Assuming that it is technically possible; the cost of collecting, validating and analysing the data is prohibitive. When modelling processes that are heavily dependent on humans, the duration of the task can vary

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Applications involving manual labour are seldom modelled. To model humans accurately is theoretically possible, but the interactions between and the characteristics of people make modelling these processes difficult. Assuming that it is technically possible; the cost of collecting, validating and analysing the data is prohibitive. When modelling processes that are heavily dependent on humans, the duration of the task can vary significantly from one day to another. An employee will work at different rates depending upon, fatigue, lengths of the day, weather, morale and of course the operatives' ability and willingness to perform the task. The advantage of accurately estimating the time required to complete small tasks involving complex interactions are currently outweighed by the time required to develop a useful model.

It is however possible to model alternative methods of construction, establishing the most efficient equipment configuration. As the accuracy of the data required for a comparative study is significantly less than that required for accurately predicting production duration, Shannon (1992).

In comparison to the manufacturing industry where there are hundreds of applications documenting the use of simulation, there are relatively few examples within the construction industry. Indeed, when Shannon (1992) addressed that year's Winter Simulation Conference the construction industry was noticeably absent from the application domains listed within his paper.

2.6.1 USE OF SIMULATION WITHIN THE CONSTRUCTION INDUSTRY

The majority of the articles reviewed in the literature survey were written by academics, to demonstrate how simulation could in theory be used within the construction industry. Only a few industrial applications of where simulation has been applied have been sighted.

"Though discrete-event simulation has been around for many years and is well suited to model construction operations, this technique has not gained widespread use in industry", Tommelein (1994), Aouad (1994) also endorsed this view.

The lack of documentation supporting the hypothesis "simulation is utilised within the construction industry" led to the supposition that this industry does not use simulation. However, industrial practitioners seldom have the time, or the inclination to document their use of a particular management tool, therefore it was necessary to consult various employees within construction companies to establish whether simulation is being utilised. To this end a preliminary questionnaire was devised, delivered and the results evaluated.

Preliminary Questionnaire

It was considered that a questionnaire would enable a large number of construction companies to be contacted not only to assess which, if any used simulation, but also those that might wish to develop and enhance the planning and allocation of resources. It was anticipated that companies receive numerous requests for assistance from researchers, students and school children. Thus, to increase the response rate the questionnaire was directed towards an individual, rather than speculatively to a department within an organisation. Also, the number of questions posed was kept to a minimum and contained within two pages.

Aim of each question

Although the role of the planning engineer is to determine the duration and cost of performing a sequence of operations, it is a site-based manager that has to work within the parameters set by the planner. Thus it is important to establish the site-based beneficiary of improving the planning and allocation of resources.

Understanding whether planners perceive material to arrive in the correct location in the correct quantities, indicates whether they are content with their method of planning and allocating resources, and hence their willingness to investigate an alternative method. One of the benefits of simulation is that it facilitates experimentation. If planners consider altering such a fundamental factor as the material schedule impossible, then it is unlikely that they would be willing to alter other parameters, thus, the benefit of simulating a system would be reduced.

As stated earlier, it is quite possible that simulation is being utilised within the construction industry without the outcomes of their study being publicised. Thus the respondents were asked whether they were aware of simulation being utilised, if so how and where.

Selection of respondents

To obtain an indicative answer to each question, a random sample of thirty construction companies were alphabetically selected from a construction design and build journal. To maximise the response rate, each company was contacted by telephone to obtain the full name and address of the chief planning engineer. Of the thirty companies contacted twelve questionnaires were completed and returned. An additional eight responses were solicited through telephone interviews.

Questionnaire Results

	Yes	No	Other	Don't Know	N/A
Is the Site Manager responsible for materials management?	75%		25%		
Does the Site Manager decide where material is located?	75%		25%		
Do you ever consider fixing material upon delivery?	84%	8%			8%
When buying in bulk, is it possible to stagger delivery?	100%				
Does staggering delivery eliminate double handling of the material?	84%	8%			8%
Does the Site Manager determine the delivery schedule?	84%		(Site staff 8%,Site agent 8%)		
Does your company use a central material store on site?	50%	50%			
Does the location of material significantly affect the cost of storage?	50%	25%		25%	
Do you use intermediate stores?	33%	67%			
Are there any specific problems in relation to material handling/location that you feel should be addressed?	67%	25%		8%	
Does you company utilise simulation in any manner?	8%	92%			
Is the storage of material currently simulated to minimise double handling ?	8%	84%		8%	

Table 2 Questionnaire Results

Conclusions drawn; preliminary questionnaire

The vast majority of the respondents considered the site engineer to be responsible for scheduling and allocating materials. Since it is the site engineer that will ultimately benefit from being able to experiment with different resource configurations, he shall be contacted in the first instance both to demonstrate the benefits of simulation and to obtain data.

The full potential of simulation can only be realised if it is possible to alter the operation of a facility to maximise certain performance parameters. It would appear from the responses that it is possible to alter performance parameters, specifically the arrival of material, hence it is possible that output may be improved through the application of simulation.

Sixty-seven percent of the respondents consider that the planning and allocation of material could be improved. Had the respondents considered the planning and allocation of material could not be improved then there would be little reason for an alternative planning tool to be developed as it would probably never be used.

Two of the respondents claimed that the company they were employed by utilised simulation. To ascertain where and how the respondents were contacted by telephone. In each case when pressed, it transpired that they either perceived simulation to mean 3D visualisation/animation, or they had heard that simulation was being employed but were unable to ascertain how or where within their organisation.

Conclusion

The respondents acknowledge that the planning techniques currently employed within the construction industry provide a less than optimal solution for planning the allocation of material. However the high response rate of sixty percent does indicate a desire within the construction industry to develop and improve the methods of planning currently employed.

The results of this preliminary survey indicate that simulation is not being used within the UK construction industry. These finding concur with those of Aouad, when he surveyed the top 100 contractors in the UK and the top 400 contractors in the US. Aouad (1994) also concluded that simulation has not received greater attention because:

"
- it is too sophisticated and inaccurate
- there are too many variables in output and weather
- there is insufficient time available to build models
- planning a contract is an individual operation
- computer models require large amount of data input
- they are too costly."

Gonzalez-Quedo (1993) also gave reasons for the less than popular acceptance of simulation claiming that it is due to the quantity of learning involved, coupled with the "lack of confidence in the results of unproved techniques" and the "failure of academic researchers to provide practitioners with accurate, easy-to-use, and proven techniques".

To overcome some of the perceived and actual complexities involved in developing simulation models, thereby increasing the utilisation of simulation, it is proposed that a series of standard modules are developed. It envisaged that these modules may be connected together to form a working model requiring little validation and testing before experiments are performed and results obtained. However, before standard models are developed a suitable area within the construction industry must be sought.

2.6.2 PROPOSED APPLICATIONS OF SIMULATION.

There appears to be a requirement for a flexible tool that is capable of overcoming the problems associated with the complex, uncertain and highly volatile construction environment by assisting the decision maker, through making it possible to generate and analyse different courses of action and their likely outcomes. It is generally believed that computer-based simulation can provide such a solution. Both Ibbs C.W. (Ed)(1985) and Tommelein (1994) endorsed this view.

Ghassan Aouad and Andrew D.F. Price (1994) ascertained nine areas where expert systems and simulation techniques could be applied to assist in planning construction processes.

- Standard works (i.e. warehouses, factories)
- Small development and temporary works
- Large contracts with a large number of subcontractors
- Different cranage applications and use or re-use of formwork could be modelled
- "What if?" scenarios are easy to assess
- Problematic scheduling areas can be modelled
- Activity breakdown structure
- Manpower analysis
- Better approximation of actual conditions and procedures.

Simulation can be an extremely useful tool providing useful results can be obtained without requiring the input of excessive quantities of information and the cost is justifiable.

2.6.3 USE OF SIMULATION IN ROAD CONSTRUCTION.

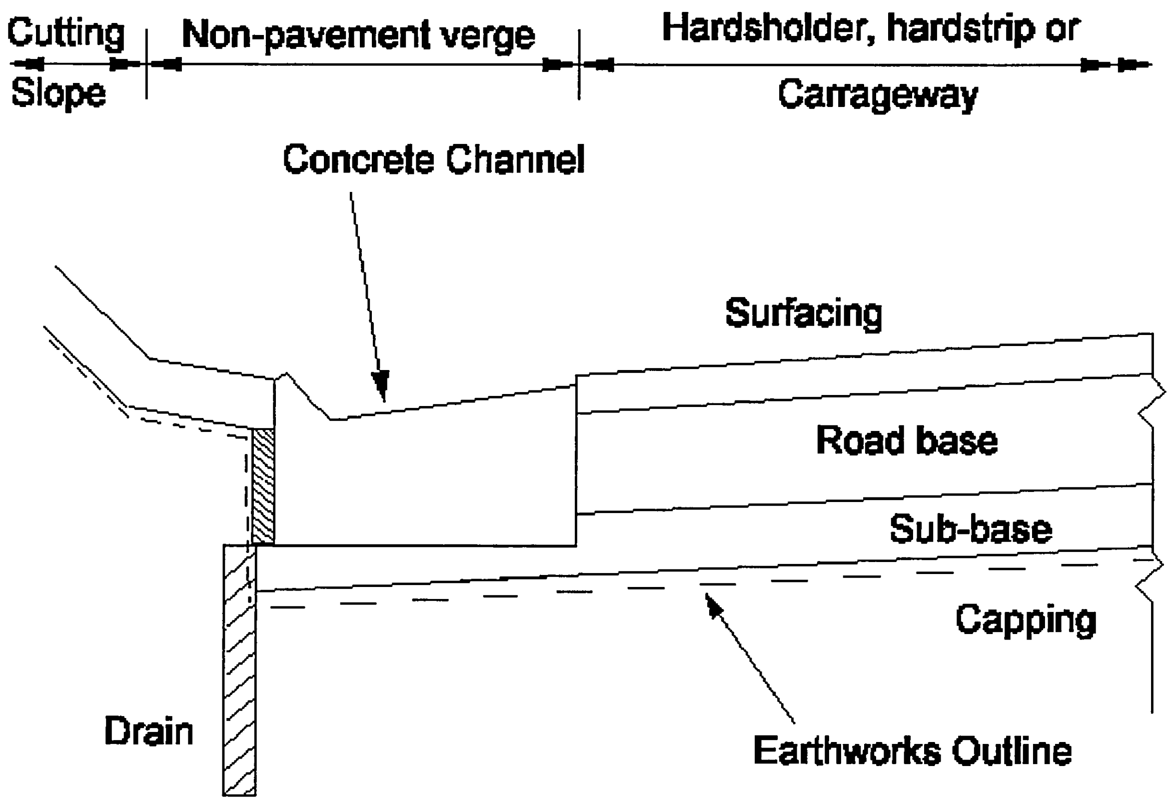

Figure 7 Pavement details

The construction of roads requires the co-ordination of many activities, Figure 7. Each of these activities: clearing grubbing, grading, capping, drainage, sub-base and road base, and surfacing utilises machinery. For a more in-depth discussion of construction processes see Peurifoy(1985).

One of the most resource intensive and hence expensive operations are earthworks. Earthworks concern the operations surrounding the removal of material generally referred to as cut, or its placement, which is generally referred to as fill. Excavators or scrapers tend to be used to remove material with trucks or motor-scrapers used to haul the material while discharged material is compacted using bulldozers or vibrating rollers. The performance of each operation is influenced by many factors. Excavation rate may vary depending upon the characteristics of the material being excavated or the conditions along the haul-road, such as congestion or bridges may impede the transportation of material. Hence several researchers have attempted to apply simulation to the construction industry to increase the quality of estimates and resource utilisation.

Huang (1994) investigated transient behaviour in earthmoving using simulation. From his experiments he ascertained that the maximum effect of transient behaviour was to reduce output by 1.3%. However, the scenario modelled was extremely simple involving minimal interaction between resources, and no congestion along the haul road.

Alkoc (1993) simulated the placement of concrete, however the model had its limitations. Although the movement of the distance the trucks must travel increases, the software was unable to model this as a continuous process. To increase the distance that material was hauled the model had to be stopped, the distance amended and the model re-run. This created the possibility that the difference found between modelling concrete over a static or dynamic haul distance could be due to the warm-up period and not the changing length of the haul road. Also the quantity of material laid at each chainage was constant thus the advancement of the paver was uniform, which is unlike earthworks where the quantity of material excavated from each chainage alters.

In 'Automated construction-simulation optimisation' AbouRizk (1994) used simulation to automatically optimise several performance parameters: production unit cost, production rate, and resource utilisation. However, the models were aimed at mining and were unable to optimise all three parameters simultaneously.

Good communication is paramount if the maximum benefit can be obtained from simulating construction processes. Communication 'can be greatly enhanced if the building elements describing the model are not generic but rather a graphic representation of the resources used at the site', Oloufa (1992). Models consisting of circles and boxes are more abstract than a map with realistic pictures. 'Cyclone model uses generic icons that are unfamiliar and hard to understand for the members of the construction team.' Oloufa (1992). This iconic representation limits the communication of a simulation model and restricts its value.

Amir Tavakoli (1985) appreciated that there was scope for using simulation within road-construction and recognised that industry would not use simulation unless models can be quickly and easily be developed by none simulation practitioners. To this end, he developed three models based on the MicroCYCLONE simulation package. These models allowed the effect of different combinations of equipment to be analysed.

The three models were:

- Face shovel, loaders, haul trucks and a dozer,
- Scraper, pusher, excavation crane and truck dozer,
- Crane, trucks, and spreader unit.

However, the models could not be easily modified to incorporate other factors and hence are inappropriate for modelling other sites.

In parallel to the research undertaken and documented within this thesis, researchers at the Universities of Michigan, Alberta and Edinburgh have developed software for the construction industry.

Ioannou (1996) developed STROBOSCOPE based on the activity cycle paradigm and demonstrated its application for moving large quantity of material in the construction of a dam. The software is abstract using iconic symbols not representative of the construction site. No account is made for congestion along the haul road, this is especially important since two different types of trucks are made available. Two years later Martinez (1998), co-author of the above paper stated that STROBOSCOPE demands "a level of training that is beyond the scope that which can be found in most current practitioners." Hence, Martinez developed 'Earthmover' to overcome some of the limitations of STROBOSCOPE by creating a visual front end using VISIO. Earthmover and STROBOSCOPE were developed for modelling large-scale earthmoving in the quantities found in dam construction and thus do not necessarily include all the factors required to successfully model road construction.

Shi (1998) developed a simulation platform enabling models to be constructed from a set of predefined modules. His work was again specifically aimed at developing a simulation package for large-scale earthmoving founded upon the modelling methodology documented by AbouRizk (1995). In essence, the methodology aims to develop a simulation model based upon selecting the required equipment and project information for the operation.

The simulation models that are developed are constructed in several stages. An activity cycle diagram is constructed, equipment is selected from a database, project specific data is entered, R-processes are generated and finally the model is generated. Although the end product of both pieces of research is similar, the methodology for reaching the goal is very different. Within his research the factors that have been included have been selected by intuition rather that experimentation. Detailed analysis of the factors has not been undertaken; specifically the significance of changing haul duration during excavation has not been examined.

Smith (1995a) undertook the only research focusing specifically on road construction. Smith (1995a) within his research, six factors affecting earthmoving for road construction were examined; number of trucks, passes per load, mean and variability on load time, mean and variability on travel time. A simulation model incorporating those factors was developed. However, by his own admission excavation could only take place using a single excavator and a single class of truck. Further examination of his thesis identified that the haul road was always simple in nature, with the transportation of material never hindered by obstructions such as traffic lights, bridges, or other trucks. Therefore, the significance of several factors, which occur in practice, has not been established.

2.6.4 JUSTIFICATION OF CURRENT WORK

Traditional planning techniques are often inadequate. They neither provide information on critical path variation nor critical activities. The value of factors, e.g. rolling resistance, may change over time and affect the programme of work. Therefore, any planning tool must be quick to use and the results easy to interpret.

It has been observed that 'there has been a substantial increase in the number and magnitude of delays in the construction of highway projects' Herbsman (1985).

AbouRizk (1994) stated that "simulation has great potential in advancing construction planning; however, more research needs to be done to make it an easy-to-use tool for the practitioner."

Simulation was selected because it has a proven record for benefiting the manufacturing industry. It is hoped that by both demonstrating the benefits of applying the technique and providing a framework for implementation the construction industry may reap the rewards already experienced within the manufacturing industry.

The majority of the models have been developed using the activity cycle methodology, however this does not imply that the activity cycle methodology is always the most appropriate modelling methodology since a significant number of the applications have been documented by either Professor Halpin or one of his students. In which case the students may have been biased towards a particular methodology. Since the construction industry has not embraced this methodology, the suitability of three simulation methodologies were examined; activity-cycle, event and process based simulation. From the literature it appears that process-based simulation is better suited for modelling the complex interactions between the resources found on construction sites.

It is also apparent, from the literature, that simulation is most often applied in areas that are resource intensive, repetitive and cyclic. However, models involving a significant number of interactions between humans tend not to be developed.

Earthworks for road construction and mining have many similarities; these together with the differences are discussed later. Road construction and mining involve activities that are resource intensive, repetitive and cyclic, with the focus of any plan being around the equipment rather than the labourers. It should therefore be possible to accurately simulate earthworks for road construction.

The aim of this thesis is to determine which factors are significant and whether the process of simulation model development can be simplified through the creation of generic modules. The research undertaken thus far has been focused on applying simulation to large-scale earthmoving. Thus, the factors that are specific to earthworks for road construction have not been examined.

For example: -

- Congestion.

  Congestion can occur for any one of a number of reasons: -

    Utilising more than one type of excavator or trucks,

    Obstructions along the haul route, such as traffic lights, bridges or other traffic.

- Variable Haul length.

  Unlike mining where the location of the cut and fill is static, in road construction the location of each often changes, affecting the distance material is hauled.

Using the concepts of modularization and experimentation the factors that are significant to road construction shall be examined and incorporated into a simulation model designed specifically for road construction earthworks.

Construction operates within a dynamic environment, where decisions are often made 'off the cuff' with little analysis to backup 'gut feel'. Simulation is useful and can be used to experiment with different scenarios to establish the impact of resources being unavailable, e.g. the removal of a truck. Establishing the factors that have the greatest impact on performance parameters will not only enable significant factors to be included within the modules but also, enable site foremen to focus their attention on controlling the most appropriate factors. Currently understanding which factors to observe and control is obtained though experience, trial and error.

2.6.5 PROBLEM STATEMENT

Through undertaking a review of the available literature and discussions with contractors, it is apparent that there is the desire within the construction industry to improve the scheduling of materials and the allocation of resources.

Current planning tools do not take into account the dynamic nature of the construction site. The time allocated to complete a construction activity is often considered deterministic, which clearly does not accurately represent the nature of the construction site, and where the duration of the same job will tend to differ depending upon environmental factors. A preliminary discrete event simulation model incorporating the main factors for a simple excavation, haul and discharge should be developed to establish that the dynamics involved in earth-moving affect the production rate, and hence whether it is necessary to model road earthworks as a stochastic process.

With the acceptance that simulation has potential for modelling the dynamic nature of the construction process one must decide upon the most appropriate methodology, i.e. activity cycle or process based simulation. The majority of work originates from North America and has been performed on Cyclone or one of its derivatives. Taking the factors involved in the handling of material, the two methodologies are analysed in the subsequent chapter, with the most appropriate highlighted so that future models can successfully be developed.

To facilitate greater acceptance and utilisation of simulation, standard modules are developed reducing the level of skill and time required to build and validate a construction site simulation model.

It is acknowledged that in a constantly changing, dynamic construction environment, decisions are often made on a trial and error basis without the aid of computer tools.

One of the advantages of using simulation is that it provides an efficient experimental platform, facilitating greater understanding of construction processes. Through performing factor analysis, not only will factors be identified that have the greatest influence upon the system but also how each factor interacts with other factors. If heuristics can be found it would provide the site-foreman with the necessary information to enable resources to be effectively allocated. Simulation allows the planner to make the right decision first time most of the time.

3 Planning earthmoving: Comparison between mathematics, activity-based and process-based simulation.

3.1 INTRODUCTION

Chapter 2 established discrete event simulation as a planning tool capable of modelling construction processes. Typically the activity-cycle methodologies is employed, although a number of recent models have been developed using process-based simulation.

Chapter 3 consists of two central themes, demonstrating that discrete-event simulation can successfully be applied for planning earth-moving and, selection of a simulation package that will enable the complexities involved in planning earth-moving for road construction to be modelled.

Currently, the planning and allocation of resources in earthworks is undertaken through the development of a simple mathematical model. Although this can approximately determine production rate, the complex dynamics found in earth-moving often leads to an overly optimistic assessment of the actual completion date. With the aid of a suitable simulation package, the dynamics present in the system can be incorporated into a simulation model enabling resources to be allocated effectively.

A simple earthmoving operation is described, detailing how the number of trucks required is currently determined. A brief discussion of what simulation is and how it can be utilised for allocating resources is given. To illustrate the potential benefits that simulation can offer a number of simple earth-moving operations were observed, with production rates recorded. Comparisons are draw between observed, mathematically calculated and simulated production rates.

Within this chapter the software available is examined with one selected as the platform for the development of simulation within the construction industry.

3.2 PLANNING EARTH-MOVING

To enable a road to be constructed at the desired level, large quantities of material often have to be excavated, hauled and discharged. This is usually done with the aid of an excavator and a number of articulated dumper trucks. Figure 8 illustrates a typical site layout, with the material being hauled 1000m.

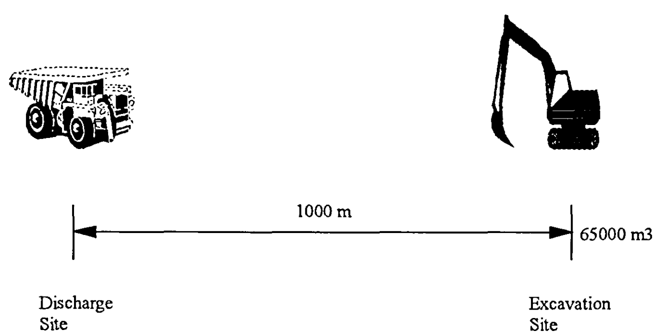

Figure 8 Diagrammatic representation of the excavation scenario.

Mathematical and simulation models are typically developed to answer two questions. How long will it take, and what are the resources required to excavate and transport a quantity of material?

3.2.1 METHOD OF EXCAVATION

Excavation can only commence when both an excavator and a dumper truck are at the excavation site. At the A1-M1 link road, one of the largest construction projects underway at the time within the UK, construction processes were observed. As each Volvo articulated dumper truck was positioned, one bucketful of material was excavated. The material was discharged as soon as the dumper truck stopped moving. Once full, the dumper truck proceeded to the discharge site where sufficient machinery was available to spread and compact the discharged material, without causing undue delay to the articulated dumper trucks. Hence, the spreading and compacting equipment used at the discharge site is not included within this model. With the material discharged, the dumper truck returns to the excavation site where the whole process is repeated until all material has been excavated, transported and discharged.

The 'Volvo's BM Articulated Performance manual' Volvo (1995) states that the number of trucks required to keep the excavator working at maximum capacity is a function of the trucks' work cycle.

A work cycle is a sequence of operations that are repeated continuously throughout the day. A trucks' work cycle comprises of: Loading, Travelling loaded, Manoeuvring for dumping, Dumping, Travelling unloaded and Manoeuvring for loading, Figure 9.

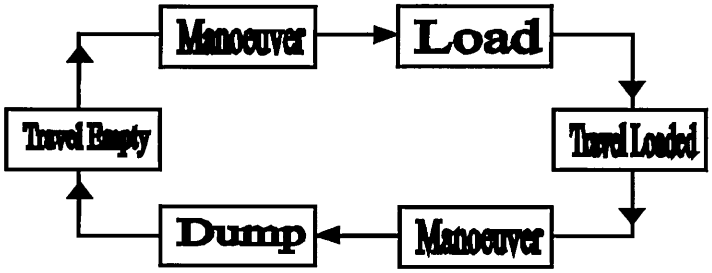

Figure 9 Articulated trucks' work cycle.

Example from the A1-M1 link road at Leeds:

Loading

It was observed that a D400 articulated dump truck took on average 21 seconds to position ready for loading. A further 128 seconds was required for the excavator, a Cat 350, to fill each 17m^3 dumper truck with material using a 2.2m^3 bucket.

Travel time

The time required to travel to and from the dumpsite is dependent upon distance and terrain over which a truck has to travel. Factors such as gradient, ground conditions and rolling resistance each affect the duration of the journey. N.B. What amounts to a positive gradient when travelling too the dump is negative when travelling from the dump. Factors such as bridges, bad weather and other machines each play their part in increasing the journey time.

Manoeuvring and dumping material.

The amount of time spent manoeuvring is dependant upon the nature of the fill. The nature of the observed discharge site was such that it was possible to drive up to and discharge material with very little time spent manoeuvring.

Hence, the complete work cycle for the truck = Manoeuvre and Load + Travel Loaded + Manoeuvre and off load + Travel Empty

Equation 1 Articulated Truck's work cycle.

Manoeuvre and Load	21 sec + 128 sec	= 149 sec.
Travel Loaded	1100 m @ 4.86 m/s	= 226 sec.
Manoeuvre and off load		= 30 sec.
Travel Empty	1100 m @ 10.55156 m/s	= <u>104 sec.</u>
	Total Work Cycle	= 509 seconds

With the truck's work cycle known it is possible to calculate the number of trucks to correctly balance the output of the excavator with that of the trucks.

Number of trucks required	=	truck work cycle / time to load truck
	=	509 s / 149 s
	=	3.4

Equation 2 Number of trucks required.

Obviously to utilise a fraction of a truck is infeasible, unless the truck can be shared between two or more excavators. This is seldom the case, because of the additional supervision required on site. As such, the number of trucks required is typically rounded up or down to the nearest integer.

Production rate is calculated by multiplying the maximum excavation rate against the number of available trucks, divided by the ideal number of trucks.

E.g.

Excavator Output	=	number of seconds in one hour/ time to load a truck
	=	3600 / 149
	=	$410.7 m^3/hr$
Hence the output with 3 trucks	=	Excavator Output * (number of trucks available / number of trucks required)
	=	410.7 * (3 / 3.4) $= 360.36\ m^3/hr$

And with 4 or more trucks the production rate $= 410.7\ m^3/hr$

Equation 3 Output calculation.

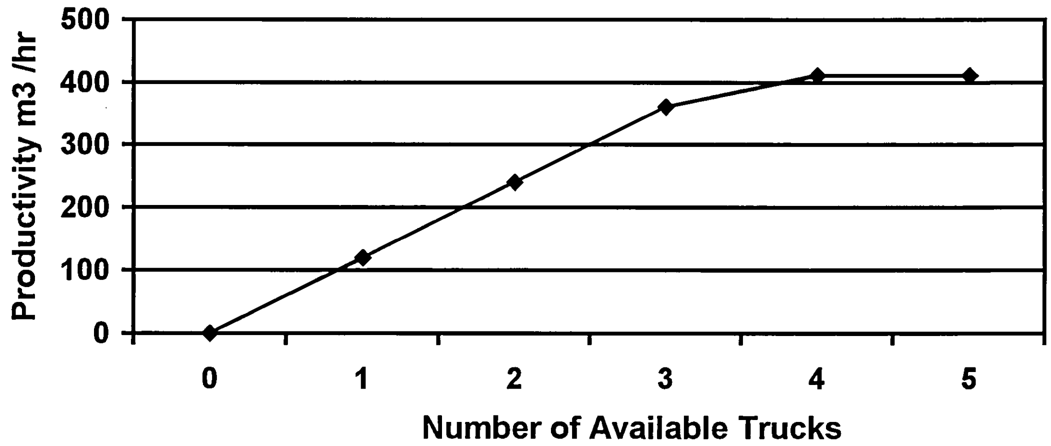

Figure 10 Achievable output for a given number of trucks

3.2.2 SUMMARY

The mathematical model shown above is restricted in that the time required to complete each task is considered deterministic, and because of this does not take into account how the production rate may be affected by variations in either the excavation or transportation duration. In comparison, variations in process times can easily be incorporated into the simulation models, enabling production rate and idle times to be predicted with a greater degree of certainty.

3.2.3 MICROCYCLONE SIMULATION MODEL

Halpin, understanding the benefits of applying simulation in the manufacturing industry for improved planning, sought to develop a simulation methodology that was appropriate to construction. To this end, Halpin (1972) developed *Cyclone;* an activity scanning based simulator. He and his students consider activity scanning methodology suitable for modelling construction processes because it closely represents site activities.

Originally, activity cycle diagrams were drawn using only two symbols, active [Normal] and idle [Queue], represented by a ‘rectangle’ and ‘Q’ symbol respectively. To connect these symbols a line is used with an arrow at one end depicting the direction of movement. However, this did not allow even the simplest of tasks to be truly represented. Hence Halpin developed three additional modelling elements: the combi, consolidate, and counter, represented by a rectangle with a diagonal line across the top left hand corner, a circle, and a circle with a flag on the top. As shown in Figure 11.

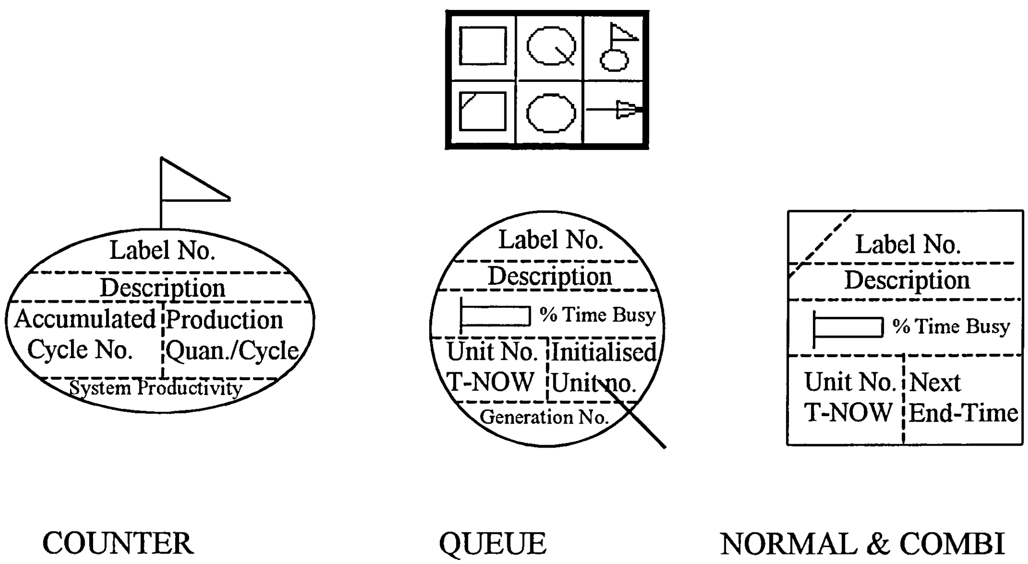

Figure 11 Modelling elements used in MicroCYCLONE

The function of the Normal is to delay the passage of a token a predetermined length of time, and is activated as soon as a token arrives. Whereas a Combi requires at least two tokens, one from each of its two inputs before the element can be activated. Before a Combi, a Queue is required where a token can wait until the combi has the right combination of tokens before proceeding.

Figure 12 is an activity cycle diagram of the same excavation, haul and discharge processes as was mathematically modelled in Equation 1. The activity cycle diagram is developed using MicroCyclone to predict the time required to excavate material from a single chainage, with an excavator and single type of truck.

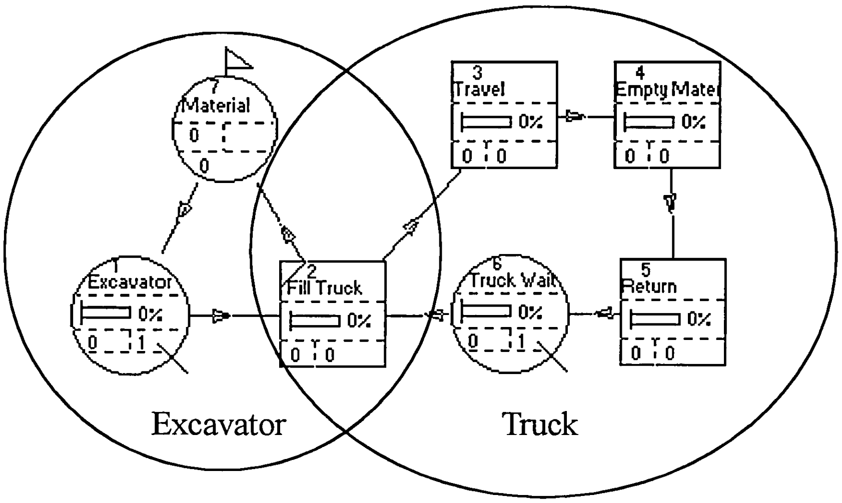

Figure 12 Activity Cycle diagram of the excavation process.

Explanation of the simulation model

Activity based simulators pass tokens around in a cyclic manner. The tokens are delayed a predetermined length of time by each activity before proceeding to the next activity or queue in the loop. As with the mathematical model it is assumed that there is sufficient equipment at the discharged site to handle the discharge of material without impeding the progress of the trucks.

3.2.4 HOW THE RESULTS WERE OBTAINED

Experiments were performed on the simulation model to determine the length of time and the correct number of trucks required for excavating and transporting material in an efficient manner. The duration of each activity was entered into the model with a normal distribution reflecting the variability inherent to each process. The models were run for ten replications to ensure that any variability between the results was due to the randomness of the process and not the effect of using a pseudo-random number stream.

Construction is a terminating process. Operations typically commence at dawn and end at dusk. At the start of a shift, there is a period of time where material is excavated and lorries filled but no material is discharged. This period of time reduces the average output of the system. Hence each replication lasted the equivalent of 8-hrs simulated time.

3.2.5 COMPARISON OF RESULTS.

Figure 13, illustrates the percentage difference between predicting output using simulation as opposed to using a mathematical model. The primary reason for over estimating output using mathematics is its inability to incorporate process variability.

Had the model been run for an extended period of say 120hrs as opposed to 8hrs then the effect of the transient period would have been less pronounced with a difference between the results of approximately one-percent. The length of time that is required for a model to reach steady state is a function of the variability within the system. This variability cannot be included within a mathematical model. Later, in chapter 4 section 4.3.1 the effect of the transient period on output is examined.

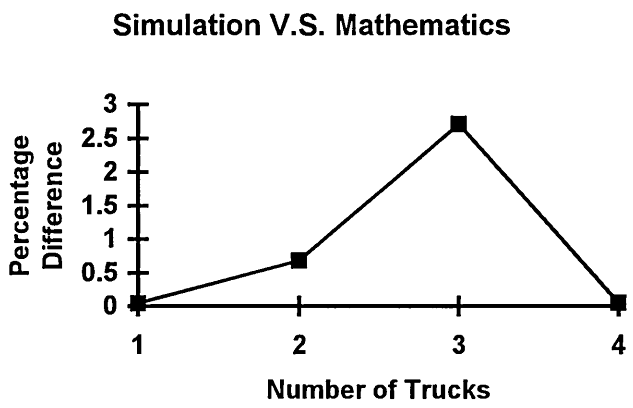

Figure 13 Percentage difference in estimated production rates, simulation versus mathematical model.

One advantage of using simulation is that it is possible to determine the cause of a particular phenomenon. For example, it has been demonstrated that production increases proportionally to the number of available dumper trucks. However, once the critical number of trucks is reached then no matter how many more trucks are available there is no significant increase in output. This can be demonstrated from examining the utilisation of this resource, Figure 14. It is prudent to examine the utilisation of the excavator, as this is the bottleneck resource. In addition to monitoring the utilisation of the excavator, confirmation that the correct number of trucks are utilised can be obtained from looking at the utilisation of the dumper-trucks.

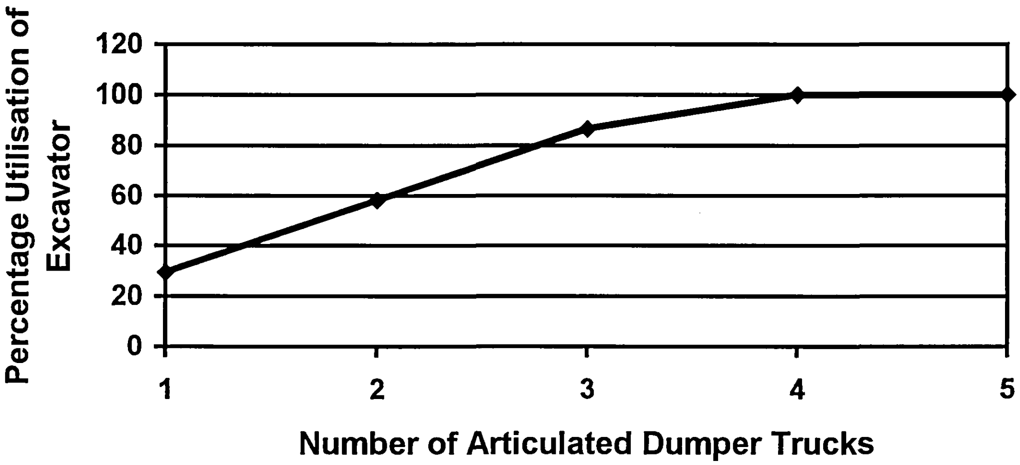

Figure 14 Utilisation of Resources

Even in this very simple queuing system production rate is over estimated. The static mathematical model does not take into account the dynamic nature of this simple excavation process. There is a significant difference between the results derived through simulation and mathematics. Had, as is often the case, the contractor been unable to use identical haul trucks, the amount of time the excavator would spend waiting for trucks and the length of time the trucks were left queuing waiting for the excavator would increase. Since traditional mathematical models do not take queuing into account, the difference between simulation and mathematics would further increase.

The models developed so far in this chapter are simple and do not truthfully represent either the variety of equipment utilised, nor the obstacles often encountered on major haul roads. Therefore, the following chapter investigates how the complexities often encountered in planning road haulage operations affect the trucks work cycle time and hence production rates.

Although the length of time the trucks spent queuing and the excavator waiting, was in this case minimal, it could not have been estimated using the traditional mathematical approach. Though contractors consider using trucks with different characteristics (e.g. capacities) undesirable there are occasions when is unavoidable. Using hauling equipment whose output does not balance that of the excavator may increase cost through reduced output. With the aid of simulation different resource configurations can be explored and there effects determined.

3.2.6 COMPARISON OF RESULTS: OBSERVATIONS VERSUS SIMULATION VERSUS MATHEMATICS.

Comparisons between observed, mathematics and simulation are drawn to highlight that simulation can be successfully be utilised to estimated production rate in earthworks. The sites selected by Smith (1995a) were simple in nature with little or no congestion along the haul-road. At these sites Smith observed and recorded the excavation, travel times and production rates for various combinations of trucks and excavators.

No. of Excavators	No. of Trucks	Bucket Volume	Buckets per load	Swing (Sec)	Dump (Sec)	Spot (Sec)	Travel (Sec)	Observed Qty (m^3)	Mathematical Qty (m^3)	Simulation Qty (m^3)
1	2	1.85	6	19.4	90	41	178	158	164.04	163.46
1	3	2.04	6	16.7	90	40	254	224	235.64	233.10
1	3	1.95	6	29.8	90	43	175	163	182.81	182.97
1	4	1.95	5	19.8	90	32	191	265	263.04	263.18
1	4	2.18	5	19.8	90	29	129	274	302.22	302.44
1	6	2.19	5	15.4	90	45	509	271	279.34	269.93
1	10	1.95	6	16.3	90	27	878	315	323.50	307.84
2	11	2.07	6	24.1	90	35	505	442	479.23	479.26
2	11	2.02	6	19.6	90	42	676	418	441.46	432.58
2	12	2.01	6	23.7	90	40	630	427	456.53	454.91
2	13	2.04	6	16.4	90	34	916	423	425.45	420.37
2	14	2.04	7	21.9	90	41	1272	384	390.88	383.92
2	15	1.9	7	18.1	90	37	1107	440	445.78	432.65

Table 3 Comparison of Production Rates

With the duration of each process known, production-rates are calculated using the method described previously, enabling comparisons between actual, mathematical and simulation to be drawn.

Utilising the same simulation model as presented earlier, activity durations were entered into the simulation model.

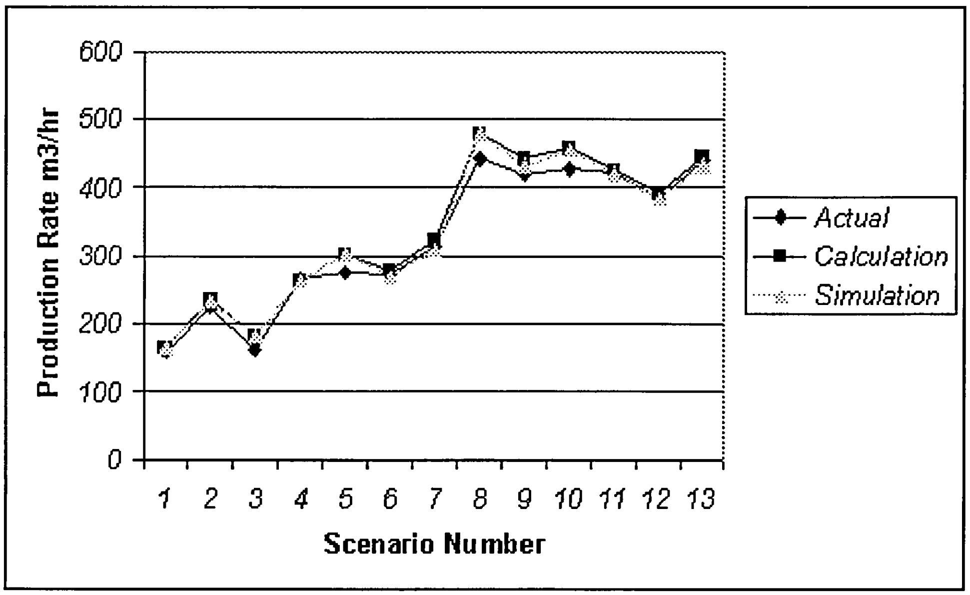

Figure 15 Comparison of Observed, Mathematical and Simulated production rates.

It is apparent from the above, that production rates predicted using simulation and mathematics reflect closely those found on site. To enable direct comparison between mathematics and simulation it was assumed that the systems were operating under steady state conditions. If as is the case in the real world, the output from the transient period had been recorded during the simulation run, it would be reasonable to assume that output would have been reduced. Thus, the difference between actual output and that predicted using simulation would have been less. The extent to which the transient period reduces output is investigated later in the thesis, section 4.3.1.

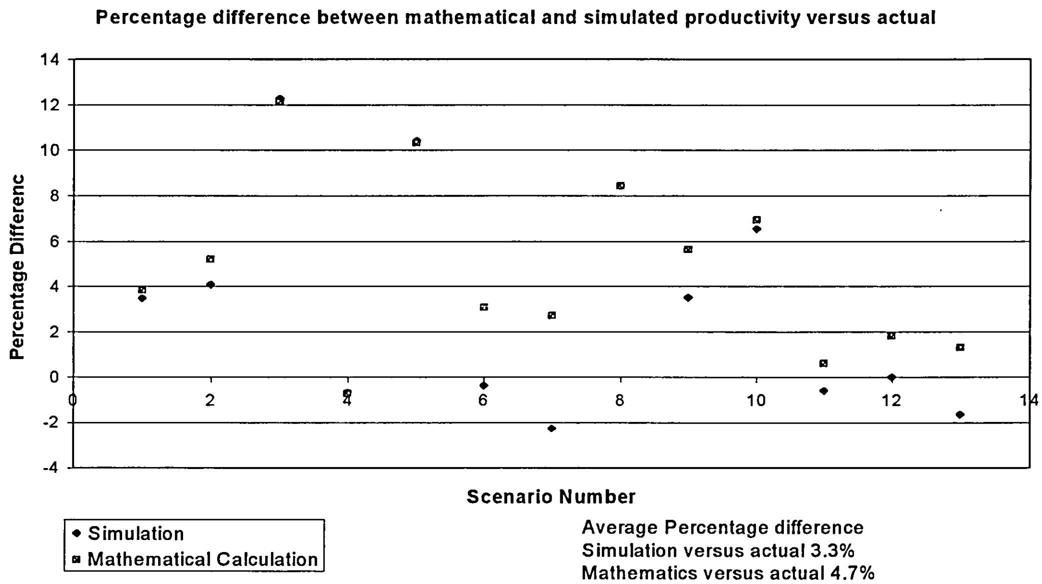

Figure 16 Percentage difference between mathematical and simulation when the results are compared against actual.

The percentage difference between the results obtained using simulation versus observed, and mathematically versus observed are shown in Figure 16. The closer each point is to the x-axis the more accurate the prediction is in comparison to the observed. Over the thirteen scenarios simulation on average, provides a better estimation of actual than is feasible using mathematics. Although in these scenarios there was very little difference between simulated and mathematically calculated results, this was principally because of the simple nature of the sites. The trucks were identical with little in the way of obstructions along the haul road to create variability in process times.

There are of course many other factors which influence the number of trucks required; mean time between failure, space available both at the excavation site and discharge area, congestion and quality of the haul road. Simulation models are developed later within this thesis to analyse some of these factors.

3.2.7 SUMMARY; MATHEMATICAL VS SIMULATION VS ACTUAL OUTPUT

It has been demonstrated through example that it is both feasible and accurate to model the excavation process using simulation. The improved accuracy is achievable because the timing and sequencing of tasks can be more accurately modelled using simulation than with a mathematical model. Hence, greater insight into process interactions can be gained than would be achievable using the traditional approach.
At present, conventional project planning tools are used to plan and manage construction projects. These 'static models', however, do not take into account the dynamic nature of construction processes, hence resources are allocated to activities on an aggregate basis. These over-simplified static models often provide less accurate performance data; hence managers and planners can make ill-informed decisions. Consequently, project targets may be missed and additional expenses incurred.

In contrast, 'dynamic models' such as computer simulation can take time variations (as in real construction projects) into account and the use of resources can be more accurately represented. Simulation models provide detailed performance data, improving the quality of decisions made. Using simulation models, realistic 'what-if' analysis can also be carried out.

Simulation is most beneficial when the problem is cyclic/repetitive and the data are quickly and easily available. Road construction is an expensive repetitive process, requiring the use of large machinery. Typically roads must be constructed with close time constraints, incurring heavy financial penalties when projects overrun. In the light of the above findings, the current planning process based upon calculating completion times using static deterministic production times, provide completion times that are substantially shorter in duration than those obtained through using simulation. Since some construction projects overrun or require the use of unplanned additional resources, perhaps the method of planning rather than the method of construction requires a more thorough investigation.

3.3 SOFTWARE SELECTION

To enable simulation models to be developed simulation methodologies were investigated in chapter 2 section 3. Here a simulation package is selected. Ideally a number of simulation packages would have been evaluated, however in practice the choice of software within an academic environment is largely dictated by what is available. Within the Schools of engineering and construction two simulation packages were available, MicroCYCLONE and ARENA. MicroCYCLONE is the most commonly used activity based simulation package for modelling construction operations while ARENA the predecessor of which 'Simon Cinema' was the most commonly used process based simulator within the manufacturing industry, Simulation Study Group (1991).

Although it may be easier to represent a simple construction process using the activity cycle methodology, MicroCYCLONE the package available has been developed within academia to assist in teaching simulation and consequently lacks functionality. ARENA on the other hand is a very flexible commercial package with a history of being widely used to solve complex problems, but requires considerably greater training to use effectively. From Table 4 it is apparent that ARENA possesses all of the features available within MicroCYCLONE with some additional functionality. Namely the ability to assign attributes to entities, model equipment breakdowns and develop a library of reusable modules.

Aouad (1994) criticises simulation stating that the time required to build a simulation model is too great. Stating that each contract is unique requiring individual plans to be drawn which necessitates the development of a new simulation model. The ability to develop a series of standard modules incorporating production logic would reduce the time required and simplify model development for the naive programmer without loosing the functionality of a commercial package. ARENA consists of templates that include basic building blocks. A special release, the 'professional version', of ARENA allows users to build their own templates.

At this stage of the research project the degree of complexity to be incorporated into the models is as yet unknown. Other researchers, Sergen (1995) and Pidd (1992) observed that it is easier to model complex systems using a process based simulator as opposed to an activity based simulator. Of the two packages available ARENA is a process simulator and possesses all of the functionality required to develop simulation models within the construction industry.

Desirable features	Disco/ MicroCYCLONE	ARENA		Disco/ MicroCYCLONE	ARENA
General Features			**Validation**		
Animation	✓ (Limited)	✓	Interactive Debugger	✓	✓
On-line help	×	✓	Model validation test	✓	✓
Data Acquisition					
Distribution fitting	×	✓	**Model execution**		
Input from an external source	×	✓	Interrupt and resume execution	✓	✓
			Rule based stopping condition	✓	✓
Model development			Automated animation	✓	✓
Library of reusable modules	×	✓	Background execution	✓	✓
Graphical model development	✓	✓	Vary animation speed	✓	✓
Access to simulation code	✓	✓			
Model equipment breakdown	×	✓	**Output Statistical Analysis**		
Define attributes to entities.	×	✓	Graphs to the screen	✓	✓
			Output to file	×	✓

Table 4 Comparison of features, DISCO versus ARENA

3.3.1 CONCLUSION TO THE CHAPTER

As stated earlier, simulation has rarely been applied within the construction industry. The planning and allocation of resources for the excavation and transportation of earth prior to the construction of a road is at present performed through the development of simple mathematical models. Since each resource possesses unique characteristics variations in process duration's is inevitable. The greater the variations in these characteristics the greater the difference between mathematical and actual. Although mathematics can approximately determine production rate, the complex dynamics found in earth-moving often leads to an overly optimistic assessment of the actual completion date.

The available simulation packages were compared, with ARENA a process based simulation package selected for the further development of simulation models.

Aouad (1994) criticises simulation stating that the time required to build a simulation model is too great. Each contract is unique requiring individual plans to be drawn, necessitating the development of a new simulation model. If a series of standard modules incorporating production data could be developed the time required to build a model would not only be reduced but the models could be reused. It is anticipated that, with the aid of a process-based simulator standard modules could be developed. These modules could be connected together enabling solutions to a number of common earth-moving problems to be quickly found.

4 Analysis of significant factors

4.1 INTRODUCTION

The previous chapter involved selecting an appropriate methodology for developing future simulation models. This chapter investigates the level of detail required, and the amount of data that needs to be collected.

Deciding whether a model contains sufficient detail is a difficult and largely subjective task. A simulation model must contain sufficient detail to provide accurate and credible results. Too little detail and the results are inaccurate, too much and the cost in terms of both time and resources is too great. Factor analysis is a unique experimental methodology. It increases the experimenter's understanding of the system, highlighting not only the main effects, but also the extent that factors interact with each other. Understanding the significance of each factor enables the model builder to focus resources on collecting the most important data thereby, minimising the time and energy spent developing a simulation model.

With the main factors and interactions between factors identified, further experiments are performed on the most significant factors to develop greater understanding of the system ensuring that modules are developed with an appropriate level of detail.

A series of simulation models are presented, investigating how modelling the significant factors in different levels of detail affect production rate. The traditional approach when planning earthworks is to consider the system as though it operates at steady state. In the past both mathematical and simulation models have made this assumption. Factor analysis is used to establish whether this assumption is valid.

The main difference between earthworks and mining is the nature of the haul road. The length of this in mining is relatively static, while in road construction the length of the haul road changes as the location of the cut or fill changes. Factor analysis is used to identify whether the length of the haul road is significant in determining output. Therefore, further experiments are performed to assess the level of detail required when modelling the haul road.

The results of these experiments enable conclusions to be drawn so that both the appropriate data can be collected and the significant factors included in a set of generic simulation modules.

4.2 FACTORIAL ARRANGEMENT

Previous chapters have concentrated upon experimenting with one parameter and assessing the impact that a parameter has on a single output or response. However, this is a very laborious and incomplete experimental method since factors often interact with others, varying output by different amounts dependant upon the level of another factor.

It is usual to focus on factors that are controllable, but uncontrollable ones such as the number of daylight hours may also be of interest. Factor analysis enables the significance of each factor to be identified. Those that are insignificant can either be fixed at a given level or perhaps even ignored. Understanding the significance of each factor enables the model builder to focus on the significant factors.

The site foreman will also benefit by alerting him to the factors that he needs to observe closely. It may well be that factors that are currently ignored are of great value and visa versa. The modules developed in the subsequent chapter incorporate these important factors.

Keppel (1973) states that not only are the interactions between factors calculated from fewer experiments but also the main effects are calculated from fewer experiments and with greater accuracy than a single factor experiment.

4.2.1 PROBLEM

Although all earthworks differ in both the equipment used and the nature of the haul route they all share similar characteristics. Each site typically consists of an excavation area, a haul road and a discharge site. The main difference between one earthmoving site and another is often the configuration of the haul road. The haul route may differ simply because of the distance the material has to be hauled or there may be obstructions such as bridges, traffic lights or roundabouts impeding the movement of trucks.

Law (1981) stated that when developing simulation modules it is important to consider; factors that change over time, environmental factors and those that drift to low performance. Thus through discussions with various personnel at Hemsworth and the A1M1 construction sites a list of more than 30 factors was developed, appendix.

A full factor analysis on thirty factors would require (2^{30}) over a million experiments to be performed. This is obviously far too many. To reduce the number of factors to a manageable quantity, secondary factors were grouped with primary. If altering a primary factor has no effect on output then it is unlikely that secondary factors will have any effect. Thus for a preliminary investigation only primary factors are considered. Velocity is a primary factor, while weather and method of paying drivers are secondary factors. Since both factors have the same effect of creating a variance on mean velocity if variance is insignificant then there is little benefit in investigating the other factors further. It was considered that over the course of a shift factors, such as wear and tear on equipment, have a minimal drift to low performance and are therefore omitted.

Discussions with site personnel led to factors being grouped or omitted until a list of 10 primary factors was established. This requires some, 2^{10}, 1024 experiments to be performed. A fractional analysis would have reduced the number of experiments to 2_{III}^{10-6}, 16, but this would have reduced the reliability of the results. Since the conclusions drawn from the experiments form the basis of the generic modules, it was considered worth the additional time and effort required to perform a full factorial design.

Each of the ten factors must be set at two levels, a high and a low, or as is the case with operating policies, policy A or B. The Caterpillar handbook recommends that articulated trucks should be used to transport material within the range 500m to 3500m. The number of trucks required was estimated as 5 for 500m and 23 for 3500m. Depending upon the nature of the material a D350 excavator typically takes between 19 and 30 seconds to excavate a single bucket-full of material. Thus the time required to position and fill a D300 varies between 126.59 and 177.59 seconds and 116.2 to 237.6 seconds for a D400. The Volvo (1995) handbook recommends using discharge times between 15 and 39 seconds depending upon the size of the discharge area. Thus, a complete list of variables is presented in Table 5.

	Low (-)	High (+)
Length of the haul road	500m	3500m
Number of trucks	5	23
Total Rolling resistance	4	10
Variance on Velocity	10%	20%
Nonterminating or terminating	25200 sec.	252000 sec.
Type of truck	D300	D400
Material type	Easy	Difficult
Variance on excavation cycle	10%	20%
Discharge time	15 sec.	39 sec.
Variance on discharge time	10%	20%

Table 5 Response levels for factor analaysis

A construction shift is typically determined by the number of daylight hours. Assuming that there are ten hours of daylight this equates to 25200 seconds. The quantity of material available is often greater than can be excavated over the course of a shift thus length of the experiment was increase tenfold to 252000 seconds. The model could have been simulated for longer but since there was no difference between average production rate for times greater then ten days it was considered unnecessary.

4.2.2 EXPERIMENTAL DESIGN

A grid was constructed of positive and negatives, abbreviated version is presented in Table 6 for full table, see appendix A. The low level of each factor was substituted for the negative sign and the high level for the positive. This enabled the configuration of each experimental run to be determined so that the desired information could be obtained from the minimum number of experiments.

	Length of Haul-Road	Number of Trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on Excavator cycle	Discharge time	Variance on Discharge time
	1	2	3	4	5	6	7	8	9	10
1	-	-	-	-	-	-	-	-	-	-
2	+	-	-	-	-	-	-	-	-	-
3	-	+	-	-	-	-	-	-	-	-
4	+	+	-	-	-	-	-	-	-	-
..	..	..	..	..	..	..	..	..	..	..
..	..	..	..	..	..	..	..	..	..	..
1021	-	-	+	+	+	+	+	+	+	+
1022	+	-	+	+	+	+	+	+	+	+
1023	-	+	+	+	+	+	+	+	+	+
1024	+	+	+	+	+	+	+	+	+	+

Table 6 Experimental Grid (Complete table given in the Appendix.)

For each of the 1024 experiments the value of each factor is entered in the simulation model as per the above grid. Each experiment was replicated five times with the average response taken as the production rate under those conditions.

4.2.3 RESULTS

For each experiment output is recorded. The individual experimental results are combined to form main effects and interactions between effects.

The main effect of each factor is calculated from the change in response when the factor is taken from its low level (-) to its high level (+), while all other factors remain constant. The average response of factor 1, increasing the length of the haul road from 500m to 3500m, was calculated by taking the average response of each factor.

	Production rate m^3/hr
1	357.69
2	131.86
3	323.51
4	314.41
..	..
..	..
1021	247.3
1022	62.91
1023	243.23
1024	240.81

Table 7 Experimental results

Thus the main effect of factor 1 is calculated from the summation of;

$r_2 - r_1$	=	131.86 - 357.69	=	-225.829
$r_4 - r_3$	=	314.41 - 323.51?	=	-9.1
$r_{..} - r_{..}$	=	.. - ..	=	..
$r_{1024} - r_{1023}$	=	240.81 - 243.23	=	-2.42786

Main effect of Length of Haul road = $((r_2 - r_1)+(r_4 - r_3)+\ldots+(r_{1024}-r_{1023}))/512$

= -113

Therefore, the average effect of factor 1, increasing haul distance, is to reduce output by approximately 50%.

The main effects of each of the remaining factors are similarly calculated. Before main effects can be interpreted, the interaction between factors must be examined.

4.2.4 INTERACTION EFFECTS

The advantage of using a factorial design is that interactions between factors can be assessed to determine how production rate varies by different amounts depending upon the level of another factor, i.e. does increasing haul road length reduce output by different amounts depending upon the number of trucks?

The interaction between factors one and two is calculated by multiplying the sign of each factor together. Thus, the interaction between one and two becomes Table 8.

	Length of Haul road	Number of trucks	Interaction between factors
	1	2	1&2
1	-	-	+
2	+	-	-
3	-	+	-
4	+	+	+
..	..	..	..
..	..	..	..
1021	-	-	+
1022	+	-	-
1023	-	+	-
1024	+	+	+

Table 8 Interaction between factors one and two.

Collapsing the table gives the value of the interaction.

Interaction between factors 1 and 2 = $((r_1 - r_2)+(r_4 - r_3)+....+(r_{1024}-r_{1023}))/512 = -81.04$

Similarly, interactions between factors 1, 2, and 3 are calculated by multiplying the sign of each factor and collapsing the table.

A graph plotting the value of the main effects and each interaction is presented in the appendix with a summary of main effects and secondary interactions presented Figure 17.

4.2.5 CALCULATION OF ERROR TERM

Although one must use judgement to determine whether a factor is significant, a statistical test should be used to ensure that the perceived significant factors are actually statistically significant.

Figure 17 illustrates the main effects and interactions between different factors. It can be seen that the magnitude of the interactions declines the higher the order of the interaction. It was considered that fifth and higher order interactions are negligible with their responses principally due to noise or variance between replications. Therefore, these higher order interactions were used to determine an error term. For a detailed discussion of the error term see Box (1978, pp327-328).

Source	Effect	Degrees of Freedom	$Effect^2$
1*2*3*4*5	1.34097	1	1.79819943
1*2*3*4*6	0.875936	1	0.76726406
1*2*3*4*7	0.908403	1	0.82519533
...	...	...	...
...	...	...	...
1*2*3*4*5*6*7*8*10	-1.007649	1	1.01535706
1*2*3*4*5*6*7*8*9*10	-1.215029	1	1.47629619
	Sum	55	40.813624

Table 9 Calculation of Error Term

Variance of an effect = 40.813624/55 = 0.74206589

The estimated standard error of and effect is therefore

$\sqrt{0.74206589} = 0.86143246$

Hence, to have confidence in the results each must be greater than $\pm 3\sigma$.

Thus, for each effect to be statistically significant it must be greater or less than ± 2.58

4.2.6 INTERPRETATION OF RESULTS

Analysis of the graph reveals that five of the main factors: 1, 2, 3, 5 and 7 are significant while five are comparatively insignificant. However, factors 4,6,8,9 and 10 cannot be immediately ruled out from inclusion in further models unless interactions between them and other factors are insignificant at higher order interactions. Examination of two-way interactions reveals that factor 6 does interact with factors 1, 2, 3, 5 and 7. Thus factor 6 is significant and therefore must be included in future models. The largest main effect is for the factor 'length of the haul road'. This is not surprising since the length of the haul road determines the number of trucks necessary. However, the effect of the 'length of the haul road' can not be interpreted in isolation since it interacts with other factors.

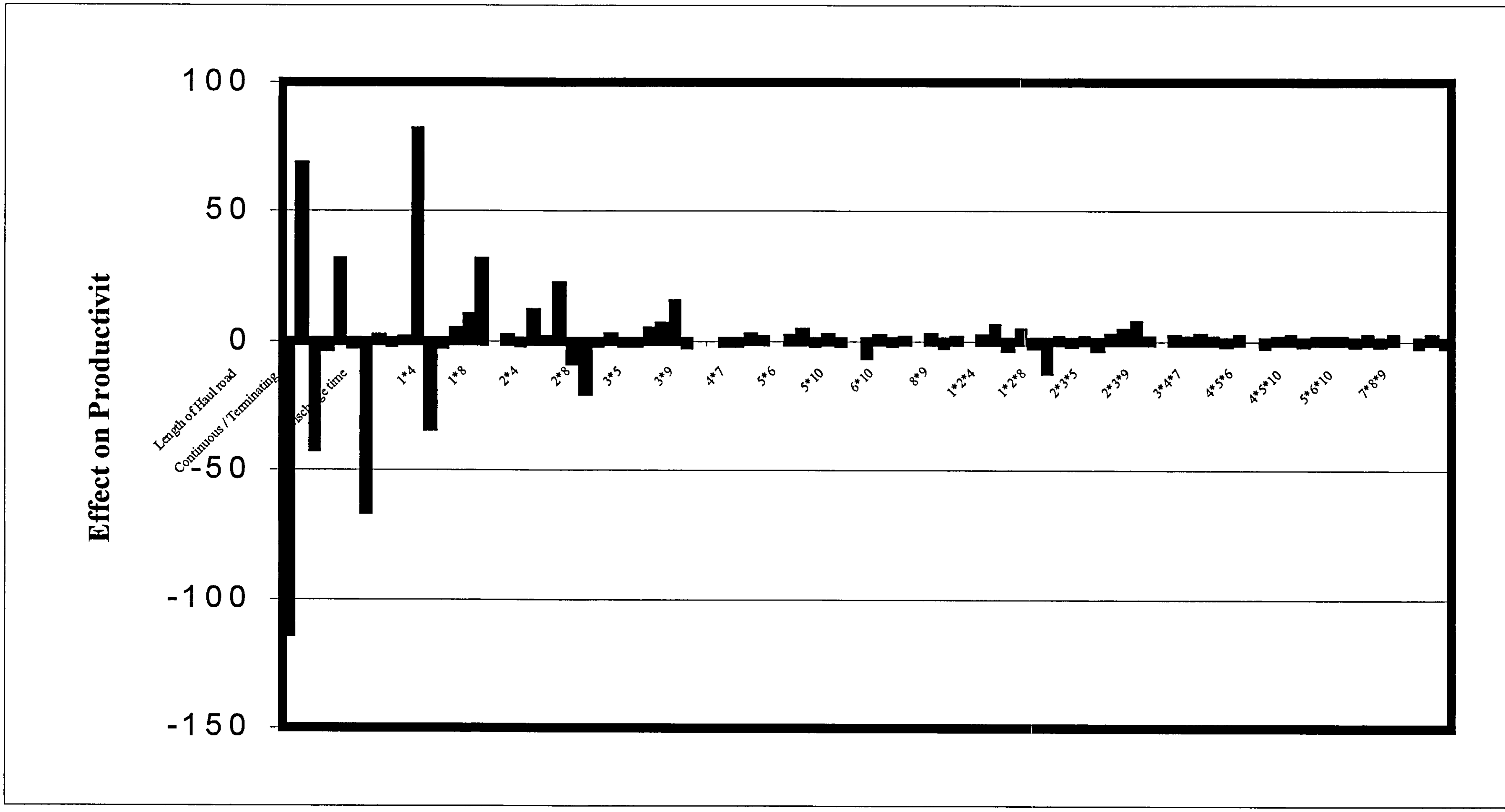

Figure 17 Main effects and interactions between factors

Factor 1; 'length of haul road' has a two-way interaction with factors 2, 3, 5, 6 and 7. A three-way interaction with factors 2, 3 and 2, 7 and four-way interactions with factors 2, 3, 6 and factors 2, 3, and 7. Thus to establish the effect of 'length of the haul road' one must first consider higher order interactions.

Taking the four-way interactions between factors 1, 2, 3, and 6 first.

Increasing the length of the Haul road, Factor 1.
Increasing the number of trucks, Factor 2.
Increasing rolling resistance, Factor 3.
Using larger trucks, Factor 6. All of which increases output.

Increasing the length of the haul road does indeed lower the output attainable. As the length of the haul road increases so does the spacing between each truck. Hence the excavator spends more time waiting for a truck to discharge material. However, if there is a corresponding increase in the number of trucks, then the effect of factor 1 can be counteracted. Bad weather or lack of maintenance to the haul road will increase the rolling resistance thereby lowering output. Increasing the number of trucks will also counteract the reduction in output (shown by the interaction between factors 1,2 and 3). Although it is probably more cost effective to maintain the quality of the haul road rather than keep increasing the number of trucks as the condition of the road deteriorates. Using the slower, larger D400 articulated trucks increased output.

Factor 2. The main effect of increasing the number of trucks is to increase output. This rule holds for interactions with 'increasing total rolling resistance', or if the system is modelled as a 'nonterminating or terminating system'. Surprisingly when factor 2 interacts with factor 6, (using D400's as opposed to D300's) there is a reduction in output. The length of time required to fill a truck is dependent upon the size of the excavator's bucket and the capacity of the truck. Filling the D400 truck to capacity requires a fraction of a bucket of material to be excavated. Assuming that each excavation cycle takes the same length of time irrespective of whether a whole or fraction of a bucket is excavated, then it is apparent that the additional loading time reduces output. Thus, it is recommended that when an excavator cannot fill a truck using complete bucketful's the additional final cycle should only take place when the subsequent truck has not yet arrived at the excavation site.

Factor 3. Increasing the total rolling resistance reduces output. This is understandable. Increasing the total rolling resistance increases the truck's cycle time thereby reducing the time that the truck is available at the excavation site. Increasing the number of trucks counteracts this. Factor 3 has a two-way interaction with factor 7. If both the total rolling resistance and the difficulty in excavating the material increase then the cycle time of the excavator and the trucks will remain balanced with one adverse effect cancelling out the other and productivity does not diminish.

Factor 4. Increasing the limits on variance on velocity from ±10% to ±20% causes neither a main effect nor interaction between factors. It shall therefore be included as a constant within the modules.

Factor 5. Simulating road construction as a nonterminating versus terminating system. This factor has a strong main effect and a significant interaction with factor 2. Output increases if road construction is modelled as a nonterminating system and the number of trucks available is increased. In earthworks for road construction, the quantity of material requiring excavating often exceeds what can safely be accomplished in one day.

Traditional planning of earthworks uses constant output to estimate the number of hours necessary to complete the task. With the number of hours divided by the number of hours per working day to estimate the number of days. The results clearly demonstrate that simulating a system for the equivalent of ten hours produced lower average output than if the system was simulated for one hundred hours. Further experiments are performed to establish the cause of the difference in output and whether using different number of working hours per day produces different productive rates.

Factor 6. The main effect of changing from D300 to D400's is negligible. However, this factor does interact separately with both factors 1 and 7. The interaction with factor 1 was described earlier as was the four-way interaction with factors 1,2, 3 and 6. Factor 7 increases loading time. When a larger D400 is used, its loading time per m^3 increases therefore there is a reduction in the maximum output per hour.

Factor 7. Has a very significant main effect. Understandably as material becomes more difficult to excavate the system output is reduced. One exception is when factor 7 is combined with 1, 2, and 3. This is surprising since, when factor 7 is considered in isolation to the other factors, output would be reduced if harder material were excavated. A possible explanation for the slight improvement in performance is; because the level of the other factors are altered the balance between the work-cycles is maintained. Hence, congestion does not increase and output is maintained, even though it takes longer to excavate the material.

Factors 8, 9 and 10, (variance on excavation time, discharge time and variance on discharge time), have neither main effects nor interactions with other factors. Hence these are either included as a constant or excluded from the modules.

4.2.7 CONCLUSIONS TO FACTOR ANALYSIS EXPERIMENTS

It is clear that a number of factors interact, because of this it would be extremely difficult to develop a mathematical model capable of predicting output under all situations.

Analysis of the graph reveals that there are six significant factors: 1, 2, 3, 5, 6 and 7 and four insignificant factors 4, 8, 9 and 10. The significant factors shall be included as variables within the modules while the insignificant are either omitted or set as constants.

Haul route length, the number of trucks and modelling the operation as a nonterminating or terminating system were identified as the most significant factors.

The significance of the factor 'length of haul road' is illustrated by the size of the bar in relation to the other factors. This is not surprising since it is used to estimate the number of trucks required. It is thus important to accurately determine the length of the haul road when calculating production rate. Simulation models of mining operations typically consider the length of the haul road to be static. This is valid considering the quantity of material excavated at or about a single location. Road construction on the other hand requires the cut and fill of material from many locations. With the length of the haul road often changing. Therefore, simulation models are developed to compare the difference between simulating the haul road as a static or dynamic entity.

The difference between modeling a system as a nonterminating or terminating simulation is apparently large. Therefore, it was considered important to examine this factor in more detail to identify the cause of the difference and the accuracy that the length of the day needs to be entered into the model.
Whether the magnitude of the statistically significant effects carries any practical significance is a mater of judgement.

Main effects are relative to the current design and levels of factors and cannot be extrapolated beyond this unless there are no interactions.

4.3 FURTHER INVESTIGATION OF SIGNIFICANT FACTORS.

The previous section of this chapter concerned the identification of the most significant factors to affect earthmoving. In this section, two of those factors, "nonterminating or terminating" and "single or multiple chainages", are investigated further to assess how output varies at different levels of detail.

Traditionally output is estimated as if the system operates at steady state, both queuing theory and mathematical models make this assumption, as have simulation practitioners, AbouRizk (1994), Huang (1994) and Smith (1995b). However, earlier in the chapter we identified that this assumption may be invalid, since modeling the system under steady state conditions produced higher output than attainable when simulated as a terminating system.

4.3.1 TERMINATING VERSUS NONTERMINATING SIMULATION

We have seen, from factor analysis, that simulating a system as a nonterminating process produces output rates that are greater than when simulating the system as a terminating process. This is because of the warm-up or transient period.

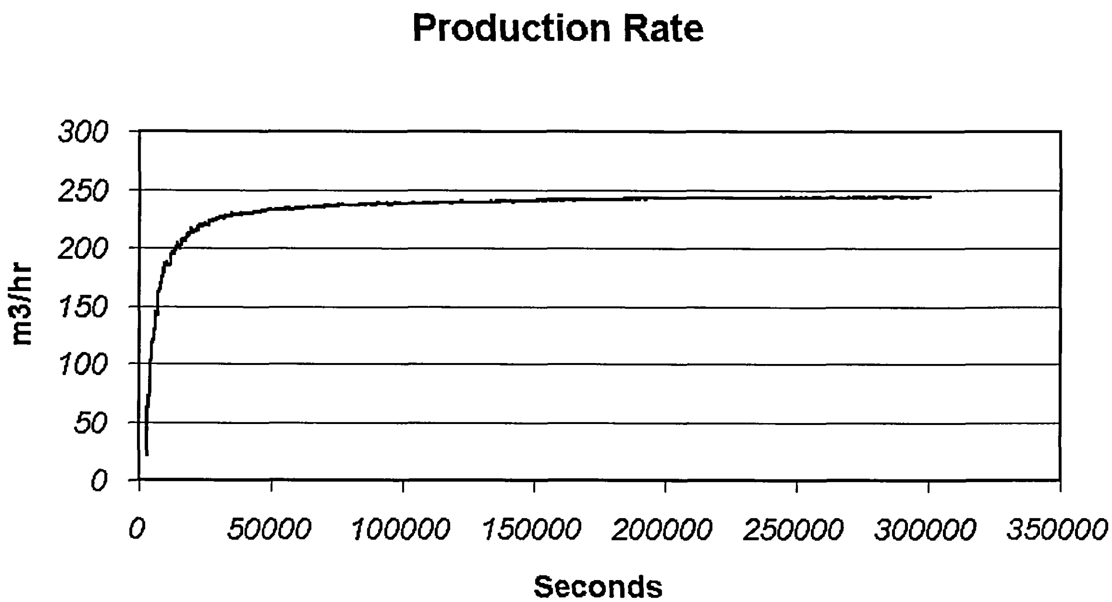

Figure 18 Production rate

The warm-up or transient period, shown in Figure 18, is the length of time required for the system to reach steady state. Transient behavior can be caused by the system warming-up or by the introduction of irregular delays causing the bunching of resources. The transient period lasts from 0 to approximately 50,000 seconds with the steady state from then until the end of the experiment.

The effect of the transient period is to reduce output per day. A series of experiments were performed to determine whether the length of the haul road affects the length of the transient period. The length of the haul road was defined as 500m and 4000m. In both cases the number of trucks was increased until the utilisation of the excavator reached 98% under steady state conditions. Thus the number of D400 articulated trucks for the short and the long haul was 4 and 25 respectively. Plotting the output per hour for both experiments reveals that constant output is reached much earlier for the short than the long haul, Figure 19.

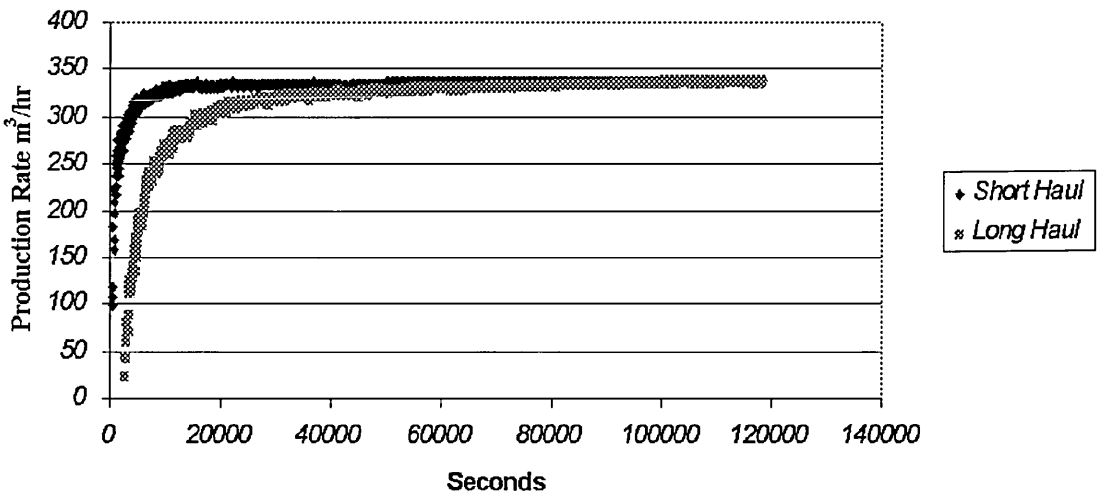

Figure 19 Comparison of Output per hour for short and long haul.

One hour into a days production approximately 303m^3 of material has been excavated, hauled and discharged for the short haul and 121m^3 for the long. After 5 hours output becomes 330m^3 and 297m^3 for the short and long hauls respectively. The percentage difference between the results gradually diminishes, Figure 20. After six and a half hours, the equivalent of working 9 till 5 with 1½ hours for breaks the percentage difference between the models decreases to 6%. Working an extra two hours further reduces the difference to approximately 4%. The difference continues to diminish becoming ever more insignificant as the length of the simulation experiment increases.

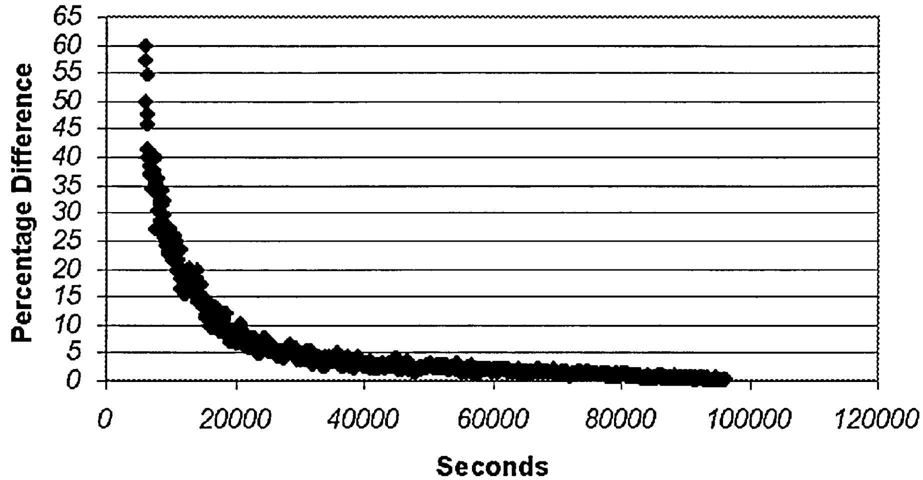

Figure 20 Percentage difference in output.

Thus when using simulation to calculate the number of hours required for excavating, hauling and disposing of a quantity of material it is not only important to accurately determine the length of the haul road but also the length of each working day.

We have seen that there is a significant transient period at the beginning of each shift. Transients may also result from the introduction of irregular delays. These delays affect the spacing of resources. In comparison to the duration of the trucks work-cycle, rest and meal breaks are comparatively infrequent. It is therefore considered necessary to investigate the effect including breaks and whether including them causes significant transients thereby reducing output.

4.3.2 HOW WERE THE BREAKS INCLUDED IN THE MODEL?

As with the previous graphs there is the predictable warm-up period until the system reaches steady state, Figure 21. At which point the inter arrival times of the trucks at the excavator is uniform. At ten o'clock or thereabouts each driver discharges his load and proceeds to the rest area. One driver is allowed the same amount of time for his break as his colleague. Since the start of everyone's break is staggered then so must the end. Staggering the breaks ensures that the system remains at steady state. Hence, over the course of a working day there is no difference between estimating output with or without breaks, providing that the same number of productive hours is used to calculate output. Therefore, rest and meal breaks shall not be included in the modules. If a driver lingers at the end of his break then congestion along the haul road will occur lowering output until the system reaches steady state.

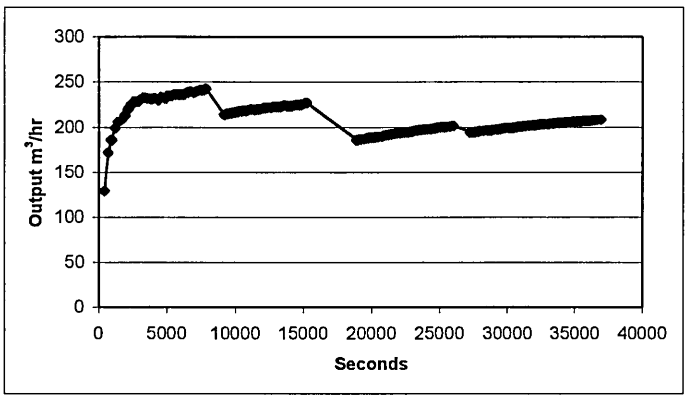

Figure 21 Average Output m^3 per hr.

4.3.3 CONCLUSIONS TO THE EXPERIMENTS: MODELING EARTHWORKS AS A TERMINATING OR NONTERMINATING SYSTEM.

Under steady state conditions, trucks would normally discharge material at approximately the same rate that material is excavated. However, at the beginning of the shift although material is excavated it is not discharged for the first say ten minutes. Equivalent to the length of time required for filling the first truck and transporting the excavated material to the discharge site. The longer it takes to load the truck, and haul material the lower the output for a given period of time.

The warm-up period is so influential that the average output per hour is also largely dependent upon the proportion of the time that the system operates at steady state and is therefore dependant upon the length of the shift. The shorter the day the lower the average output per hour.

The results from a simulation experiment are often not implemented, not because the results are inaccurate but they are perceived to be inaccurate. One way of developing user confidence is to include logic that is technically unnecessary, but the user knows that an operation occurs in real life and therefore expects to see it in the model. Increasing the correlation between the simulation model and reality may increase the user's perception of a valid model. Including breaks may increase the user's perception of a valid model. However, personnel questioned on the A1-M1 link road considered the simulation model sufficiently valid without incorporating the additional logic required to model breaks. Hence, breaks shall not be included within the modules.

The results also indicate that there is little difference between the output achieved either with or without breaks, providing that the amount of productive time is the same. Thus providing that the person for whom the model is built has sufficient confidence in the results, then it is not necessary to include breaks in the model.

Obviously if the drivers wait for each other at the end for each break this would further reduce the amount of productive time and therefore lower output.

4.4 SINGLE VERSUS MULTIPLE CHAINAGES

4.4.1 INTRODUCTION

Section 4.1 identified that the length of the haul road is the most significant factor in determining the length of time required to excavate, haul and discharge a quantity of material.

The length of the haul road is traditionally considered static, with neither the location of the excavation or discharge sites changing. Although this might be appropriate for modelling say mining, since the location of the excavation site barely moves, it does not resemble what occurs in road construction. Roads are usually built over undulating ground with the vertical position of the road chosen so that the minimum quantity of material has to be excavated, hauled and discharged.

When calculating the area under a curve it is normal to discretise it into a number of small rectangles of width dx. The smaller dx the better the estimation of the area. It is therefore reasonable to suppose the completion time can be estimated with greater accuracy through discretising earthworks into small sections. With the distance travelling by the dumper truck changing dependant upon the location of the cut and fill.

Experiments are performed establishing whether there is any significant difference between results obtained through modelling the haul road as single or multiple chainages. Through altering the ratio of the haul to excavation length, the relationship between these factors is established.

4.4.2 PROBLEM DEFINITION

For each experiment, material is excavated from a number of chainages; on a shortest haul first basis. Each chainage is uniform in depth requiring some 165m^3 of material to be excavated. It is assumed that the capacity and layout of the discharge area is such that it can be considered as a single chainage.

For the first experiment the mean length of the haul and excavation site are similar. Experiments are performed with output recorded. The distance material is hauled is increased, the number of available D400 articulated trucks adjusted and the model re-run. The layout of the excavation and discharge areas is represented in Figure 22.

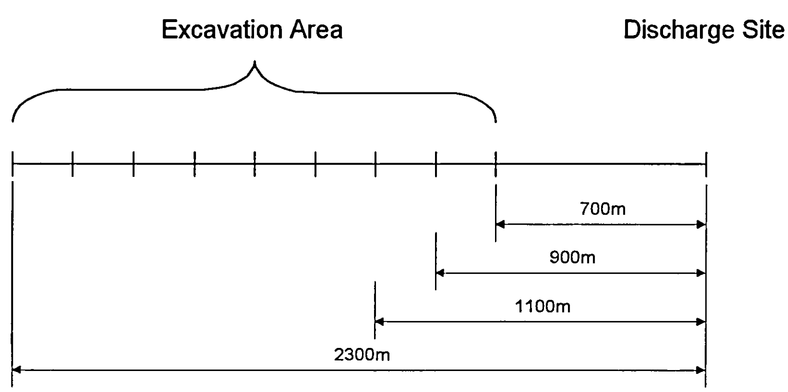

Figure 22 Picture length of the haul road

The first chainage to be excavated is located 700m from the discharge site, the second is 900m, with the third 1100m, culminating with a haul of 2300m.

4.4.3 RESULTS

To establish the most desirable number of trucks a single chainage model is developed where the haul distance is equivalent to the mean (1500m) in the above diagram. The number of trucks available is entered, model run and results recorded. By examining the utilisation of the excavator, the most desirable number of trucks is derived.

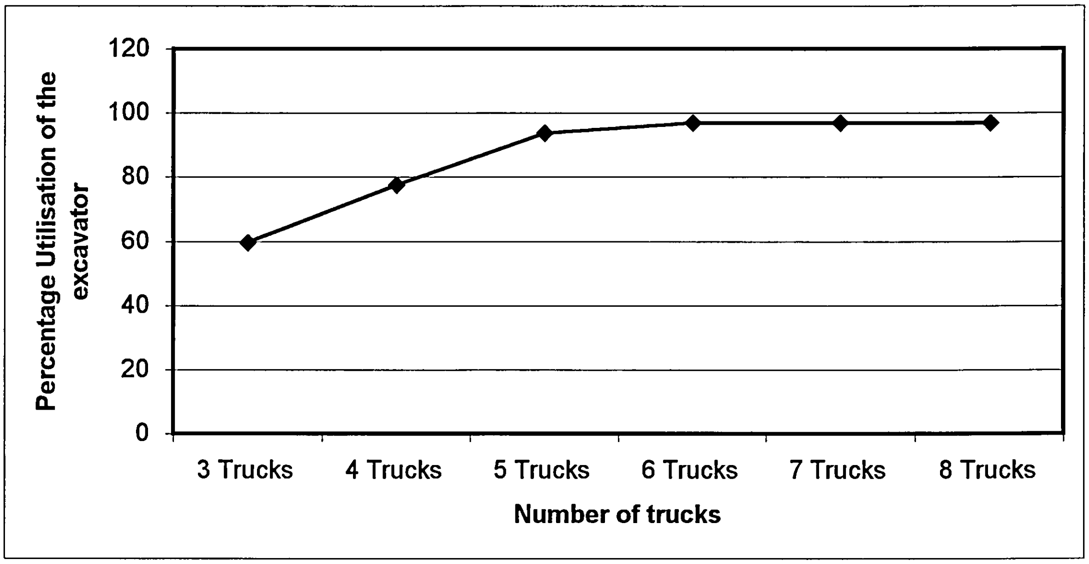

Figure 23 Utilisation of excavator.

Figure 23, increasing the number of trucks from 3 to 4 substantially increases the utilisation of the excavator. As does increasing the number of trucks from 4 to 5. Increasing the number of trucks beyond five does not substantially increase the utilisation of the excavator. Therefore, it is considered that the system is most efficient when five trucks are used.

Using a multiple chainage model, the time required to excavate all material over several chainages is determined. Comparing the results from the single and multiple chainage experiments reveals, Figure 24, that when the system is under resourced i.e. with three trucks there is minimal difference between the results obtained from the multiple and single chainage models.

Using four trucks increases the difference to almost 4% while when five trucks are used the difference peaks at just over 8%. As the system becomes over resourced with trucks, the percentage difference between the models diminishes.

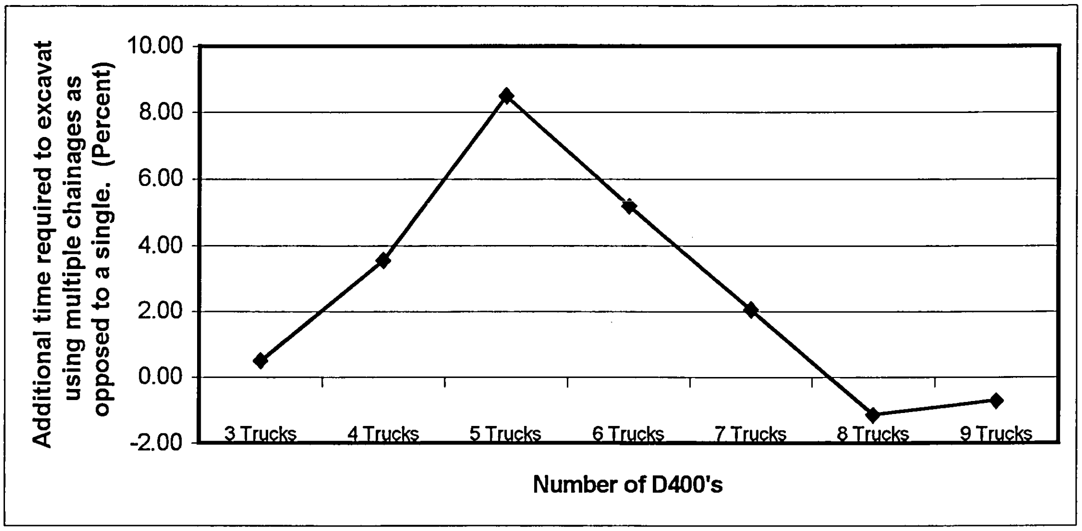

Figure 24 Percentage difference between single and multiple chainages.

Examining the utilisation of the excavator at different haul distances reveals that its utilisation remains roughly constant until the mean haul distance is reached,

Figure 25. If the number of trucks required is calculated using the mean haul distance, then when the haul distance is less than the mean the system is over resourced with trucks. As the haul distance increases the system becomes balanced with sufficient resources available to provide a constant supply of trucks by the excavator without the trucks needlessly queuing waiting to be serviced. Consequentially the excavators' and trucks' cycle time match. When the haul distance is greater than the mean, the excavator becomes under resourced, its utilisation and output diminishes. Site

foremen often adjust the number of dumper trucks servicing an excavator once work has started, this may explain why.

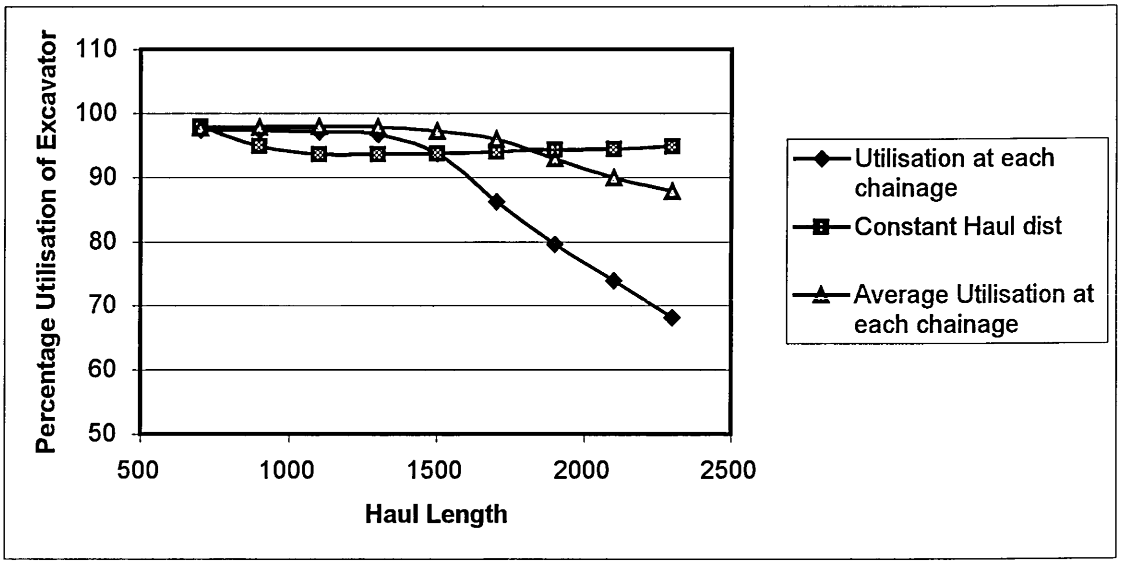

Figure 25 Utilisation of the excavator against haul distance using five D400's.

The experimental results presented in Figure 24 demonstrate that there is substantial difference between modelling the haul road as multiple or as a single chainage. However, the results from a single experiment do not imply that there is always a significant difference between modelling the excavation site as a single or multiple chainage. Thus further experiments were undertaken with the average haul distance increasing to 3500m and the length of cut remaining constant. Again the number of trucks available is entered, model run and results recorded. Figure 26.

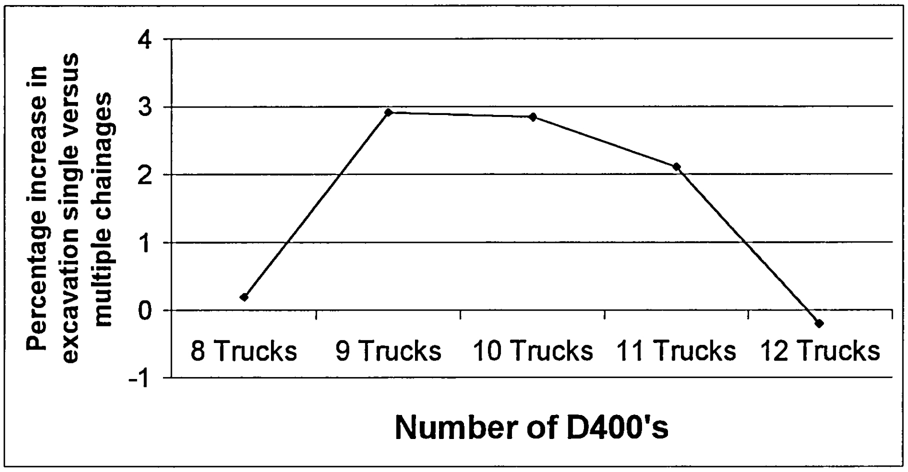

Figure 26 Difference between single and multiple chainages

The trend line depicted in Figure 26 echoes that of the previous experiments. However, this time the difference between modelling the problem as a single as opposed to multiple chainage is less significant than for the previous experiment. In the first set of experiments the ratio of cut length to average haul length was almost one to one, while this time the ratio is changed to 8:25. This infers that the greater the difference between the average length of the haul road and the excavation site the greater the difference between modelling the problem as a single as opposed to multiple chainages.

To confirm this theory four further sets of experiments are performed with the average length of the haul road increasing each time by 500m, so that the ratio of cut to average haul varied within the range of 1:1 and 8:25. In each case, the optimum number of trucks is calculated using a static model with the difference between the results plotted in Figure 27.

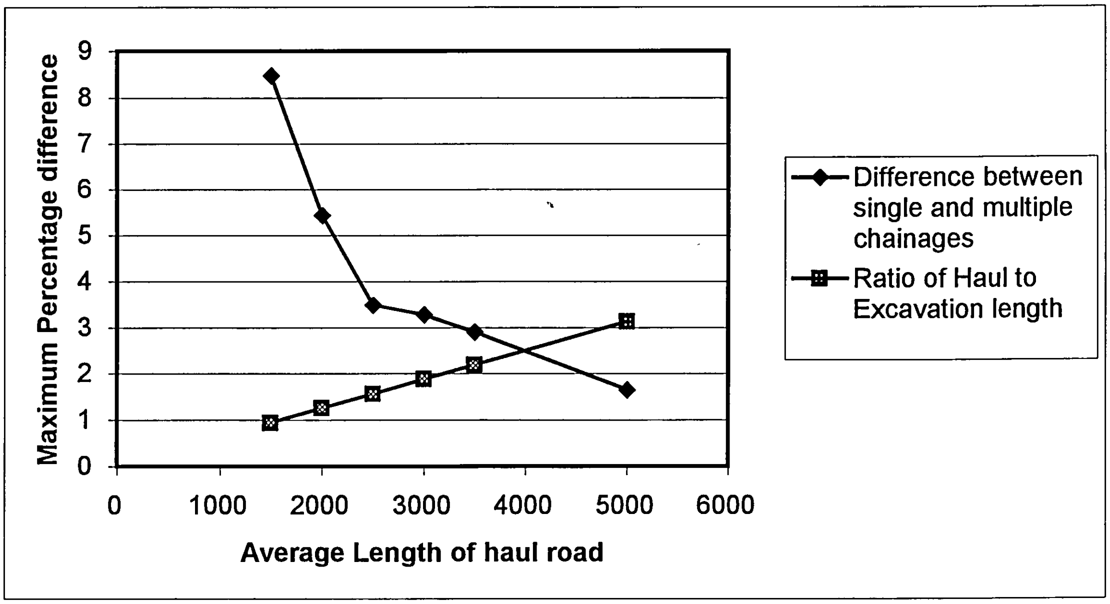

Figure 27 shows how the difference between single and multiple chainages as the ratio of cut to average haul length alters.

4.4.4 CONCLUSION TO SINGLE VERSUS MULTIPLE CHAINAGES.

The results obtained from these experiments confirm that there is a difference between modelling earthworks over multiple as opposed to a single chainage. The extent that output is over estimated is dependant upon the ratio of cut to haul length. In Figure 24 output was overestimated by 8%. The difference between the results emanates from the system being initially over resourced with trucks when the haul distance is less than the mean. As excavation progresses the haul distance increases and the workcycle of the excavator and the trucks becomes balanced.
The haul distance further increases and the system becomes under resourced. The extent to which altering the trucks work cycle disrupts and consequential reduces output is proportional to the ratio of length of cut to length of haul road. Thus the longer the excavation area is in comparison to the length of the haul road the greater the difference between modelling the system as a single as opposed to multiple chainages.

A module enabling multiple chainages to be simulated with ease is developed in chapter 5. However, whether it is beneficial to use this module is dependant upon the accuracy of the data available, the ratio of the excavation area to the length and the accuracy of the results required.

4.5 CONCLUSION TO THE CHAPTER

The significance of each factor has been established together with the appropriate level of detail to be included within the modules. Two of the most significant factors affecting model runtime and production rates were examined.

The necessity of simulating earth moving for roadworks as a terminating system has been determined. Thus when estimating the number of hours required to complete a job it is important to know the duration of each shift. Further experiments established that it is not necessary to include; morning, dinner and afternoon breaks when calculating completion time. Providing that the time allocated for breaks is not included in the number of working hours.

The final series of experiments within this chapter investigated the importance of modelling earthmoving as a single chainage or as a number of chainages. Is it preferable to model the excavation using single or multiple chainages bearing in mind the increased time required for model development, data collection, and execution of the model. Where the optimum number of trucks is calculated based upon the mean haul distance there will always be a difference between results obtained from the two models. However, the significance of the difference is proportional to the ratio of cut to haul length. Where the haul length is far greater than the length of the cut, the difference between the models diminishes.

Performing experiments and analysing the results has improved the understanding of earthworks and the role of each factor is better understood. This enables relevant data to be collected and modules developed.

5 Development of generic modules

5.1 INTRODUCTION

The literature survey established that simulation has not been widely used within the construction industry. A methodology was selected for the development of future simulation models within this industry. Simulation models were developed in chapter four and experiments performed upon them. The most significant factors and the level of detail appropriate to those factors were established, enabling efficient collection of data and a suitable level of complexity for each module to be determined. This chapter, 'Development of Generic Modules', is the culmination of the work undertaken in previous chapters.

The literature survey revealed that the difficulties encountered in model building are; the length of time required to build a model is too long and the models are often perceived as too abstract. To counteract the arguments within this chapter, a series of generic modules are developed that can be connected together to create new simulation models. With these models, an individual is able to experiment with the available resources to estimate the length of time required to excavate a quantity of material. Other outputs, such as resource utilisation are also made available to the user facilitating efficient use of available resources. To increase the credibility and acceptability for using simulation each module shall have an animated front-end, with the model logic hidden from view preventing accidental alteration of the control logic.

The construction industry is dynamic, often problems arise that are seldom encountered necessitating the development of new templates or the modification of existing model logic. A methodology is presented to facilitate the creation of new templates, with a suitable framework identified for the development of simulation models within the construction industry. The chapter concludes with a demonstration of how a simulation model is developed using the various modules.

5.2 MODULE OVERVIEW

Within the context of this research a generic module is an element that contains all of the code required to effectively model a sequence of construction operations. It may for example, enable the excavation of, or the transportation material to be rapidly modelled by someone with little or no knowledge of simulation. However, it would be impossible to foresee all eventualities, hence the development of each module is discussed in detail enabling additional modules to be constructed as necessary. The following is a summary of the processes that constitute module development:

- Communicative model.

A paper-based model that enables the developer and the client to discuss the problem

- Programming

Translation of the communicative model into a computer based simulation model using language specific modelling constructs.

- Animation

Assists in validating the model through facilitating communication between the model developer and the client.

- Examples

To translate a generic module into a site specific modelling construct data must be entered into each module. This section illustrates the type of data that could be entered.

- Prompts.

Each of the cells within the data entry form can accept a range of data the sections entitled 'prompts' is used to illustrate the function of the each cell and the range of data that may be entered.

The modules shall solely concern the excavation, transportation and discharge of material. They shall be documented to enable effective use of the modules and facilitate where necessary the development of future templates.

5.3 MODEL FORMULATION

Through discussions with construction personnel, a mental picture of what typically occurs on construction sites developed. Several conflicting opinions of what happens on site were presented; each interviewee had their own perception of what occurred on site. Some discussed the ideal while others the worst case. A model of what takes place on site could have been created from a list of assertions. However, it is easy for a list to be incomplete with the omission going unnoticed until after the model has been built. A diagram on the other hand provides us with the opportunity to take an overview of a system with detail added later. An overview of earthworks is given Figure 28.

5.4 COMMUNICATIVE MODEL.

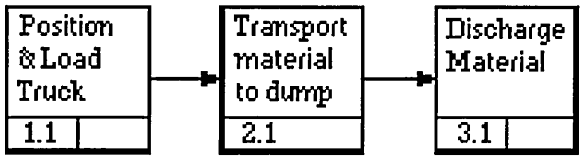

Figure 28 Process overview

To create the modules each of the process boxes, 1.1, 2.1, 3.1, are taken in turn with detail added through the addition of layers.

Taking the excavation site as our first black box (process 1.1), lower level models are created. The excavation modules naturally encompass all activities relating to the excavation of material, be it the speed that material can be excavated or the capacity of the trucks.

Factor analysis established the need to model an excavation site as either a single or several chainages. Thus two excavation modules are developed.

- Excavation of material from a single chainage using one or more excavators.
- Excavation using a single excavator where the haul distance increases as material is removed from one chainage to another.

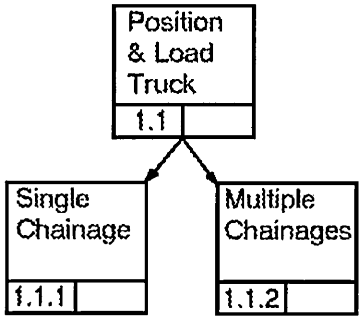

Figure 29 Different types of excavation site

5.5 MAIN TOPIC SINGLE CHAINAGE

This module is the first of the two excavation modules. As the name suggests it is here that material is excavated and loaded into trucks. It contains all of the logic required for creating the desired combination of resources and governs the arrival, allocation of trucks too and the departure of trucks from the first available excavator. The module enables a planner to use between one and five excavators, servicing up to thirty trucks. The number of trucks available can be any combination of D400 or D300 articulated trucks.

5.5.1 COMMUNICATIVE MODEL

A communicative model is developed on paper enabling rapid development of the model using a medium with which people are comfortable. It is a compilation of different people's perceptions of how a system might function and should therefore be considered invalid until proven otherwise. The simplest scenario is the single excavator operating from a single chainage. Trucks arrive and wait adjacent to the excavation area. When an excavator becomes available the truck manoeuvres into position with its back open to the excavator, material is loaded until full and the truck departs for the discharge site. There are occasions where more than one excavator is available, where this is the case the trucks proceed to the first available excavator.

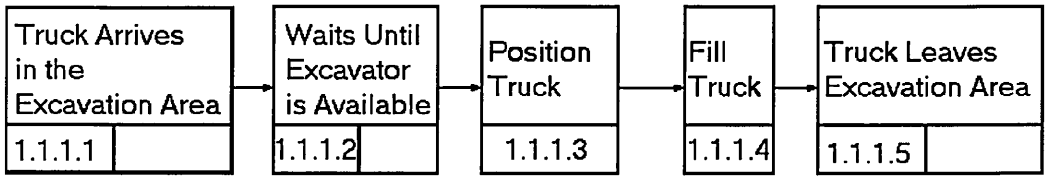

Figure 30 Single chainage communicative model

5.5.2 PROGRAMMING

The translation of the communicative model constitutes the process of programming. The modules read top to bottom, left to right. The logic controlling the function of the module is presented Figure 31. It was assumed that all of the trucks begin each day by the excavators, thus the characteristics of the trucks are defined in the excavation modules. Where time is limited and there is sufficient quantity of material and space available, two or more excavators may be used. Rather than develop a module for a specific number of excavators it was considered desirable to develop a single module and enable the number of excavators can be increased from say one to five.

Entities are used to control the movement of the trucks these are created in the 'arrive block', one entity per truck. The first entity is assigned an identifier, ident 2. Thus, the first entity assigns the variables "number of D400's" and "number of D300's" with the values entered in the data entry form. All other entities immediately proceed to the 'choose block'. Once there, each entity is assigned the characteristics of either a D400 truck or D300 truck.

With the characteristics of the trucks defined the number of available excavators are specified. If there are two excavators available then excavators, 3, 4 and 5 are assigned a capacity of zero; thus entities cannot seize those excavators. The entities and hence the trucks proceed to the waiting area. As soon as an excavator becomes available, a truck seizes it. The truck proceeds to the excavator and is delayed equivalent to the length of time required for it to be loaded. The quantity of material held by the truck is deducted from the quantity available. Once full, the excavator is released and the truck (entity) proceeds to the transport block.

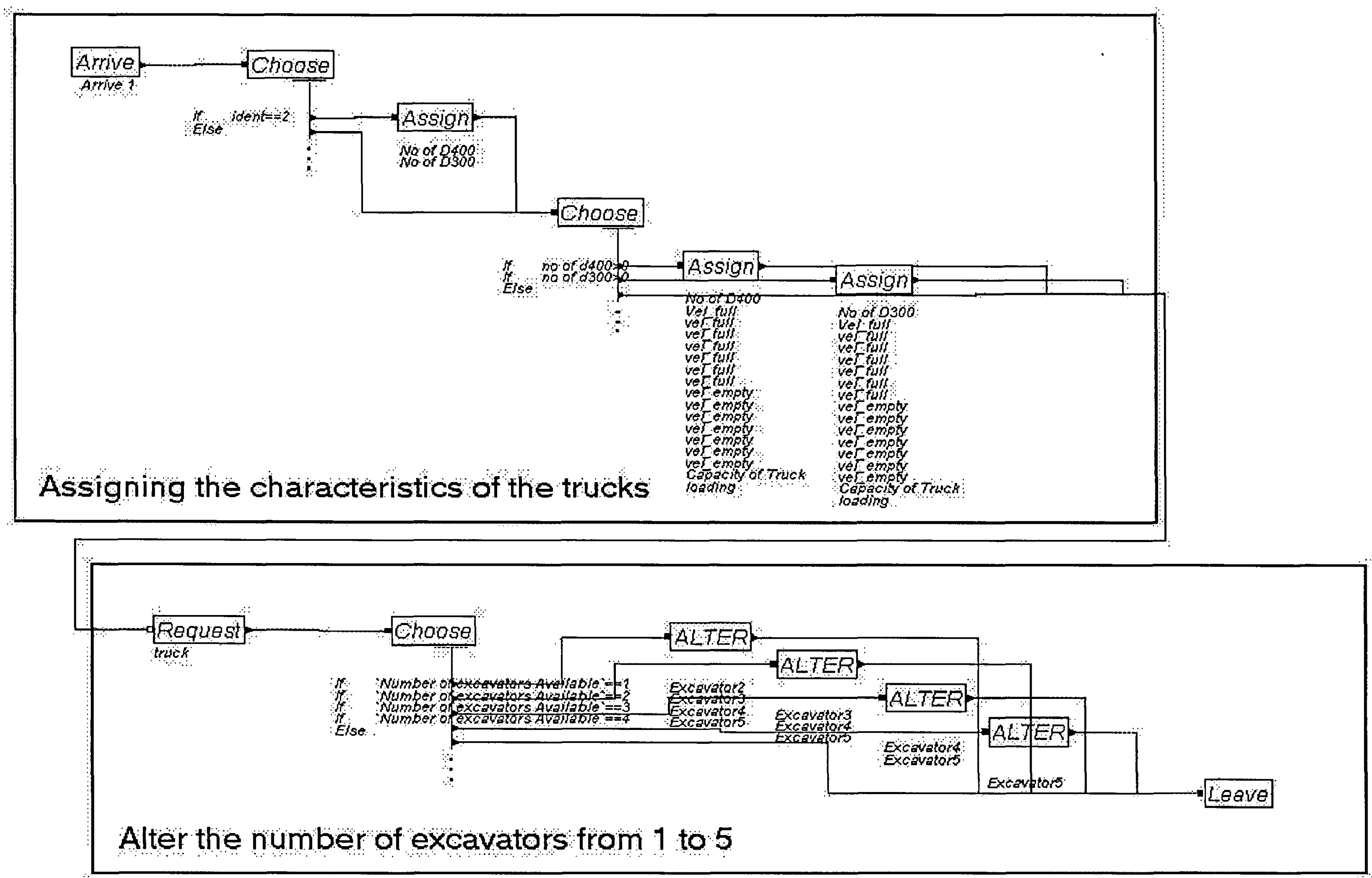

Figure 31 Single Chainage Logic, a.

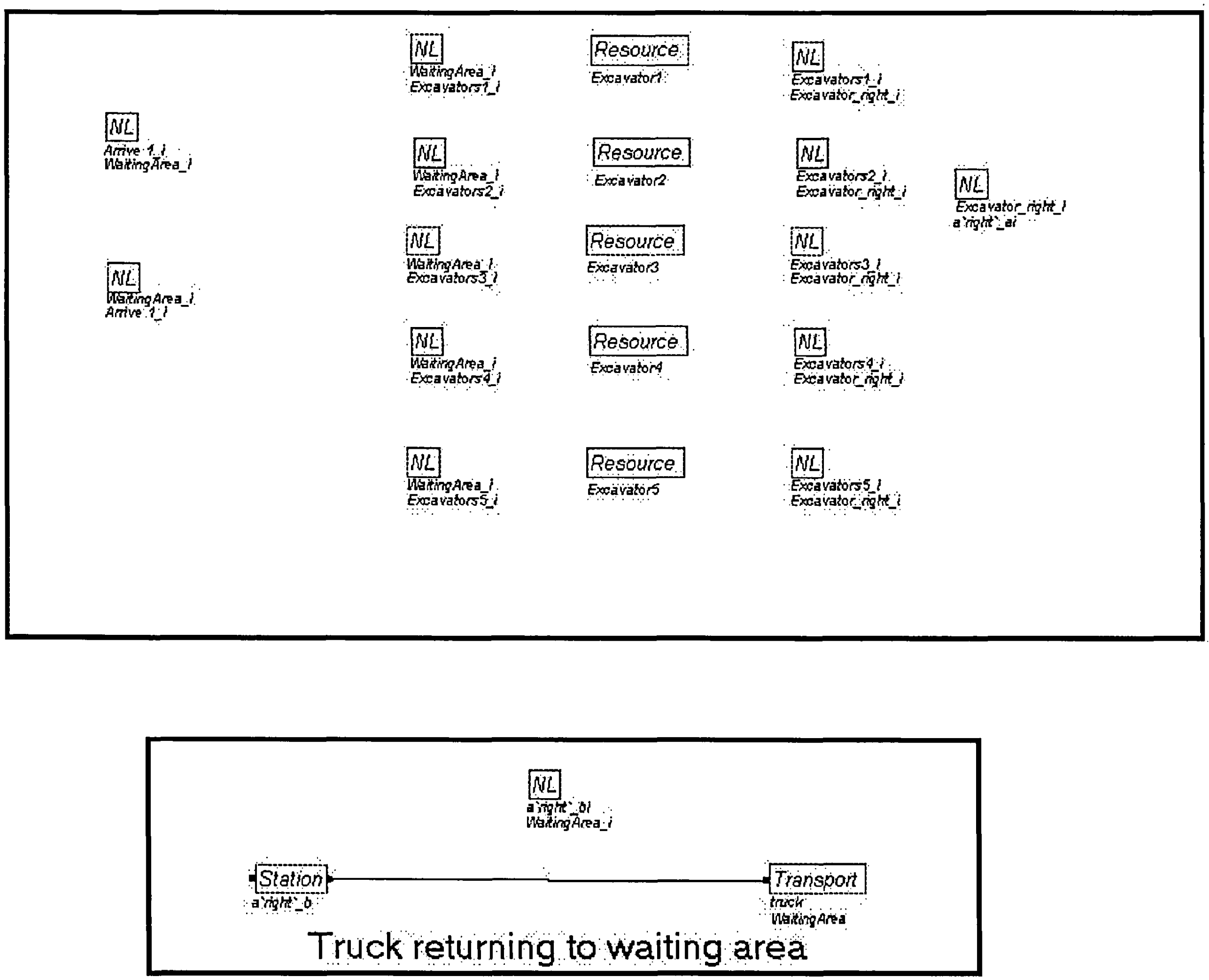

Figure 32 Single Chainage Logic, b.

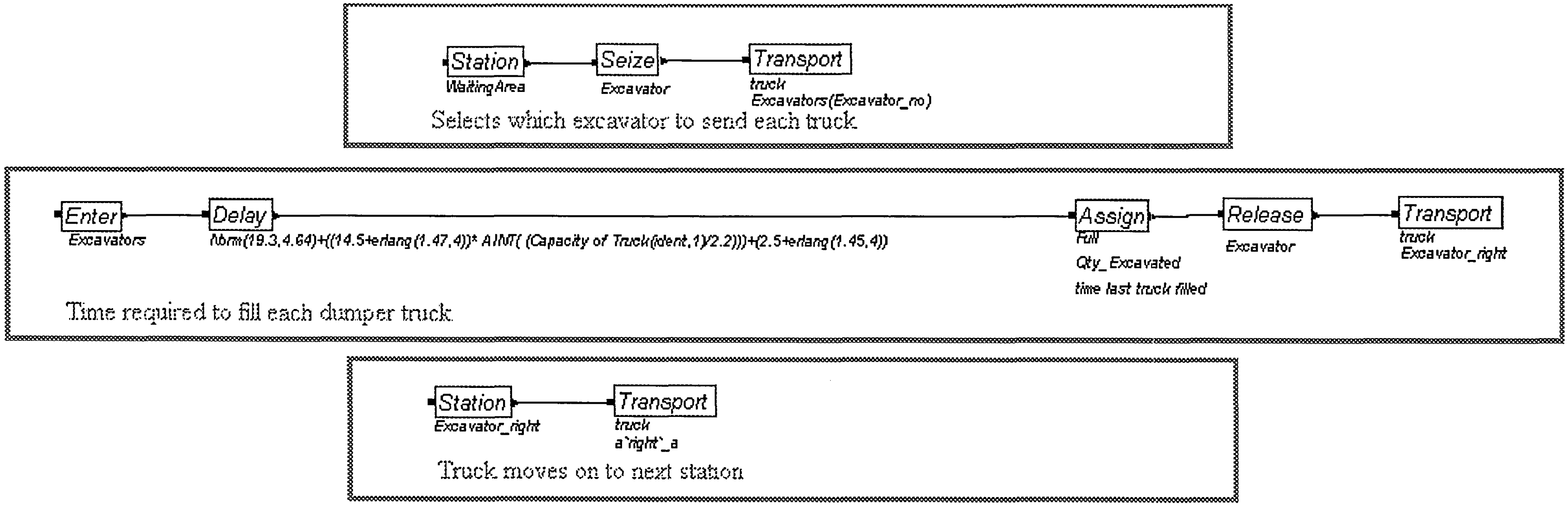

Figure 33 Single Chainage Logic, c.

The entity leaves the module re-entering only after the material has been discharged. The truck enters the module from the right and travels to the waiting area. This cycle is repeated until either all of the material has been excavated or the end of the shift is reached.

5.5.3 ANIMATION

Presenting the construction industry with a simulation model in the form of a logic diagram would do little to increase the utilisation of simulation. A logical model although conceptually valid is very abstract. The construction personnel interviewed wanted to see pictures of trucks and excavators. Thus for each module an animated front-end was developed so that if for example the user wanted to use two excavators and ten trucks that is what he would see, with the trucks moving along the haul road. Figure 34.

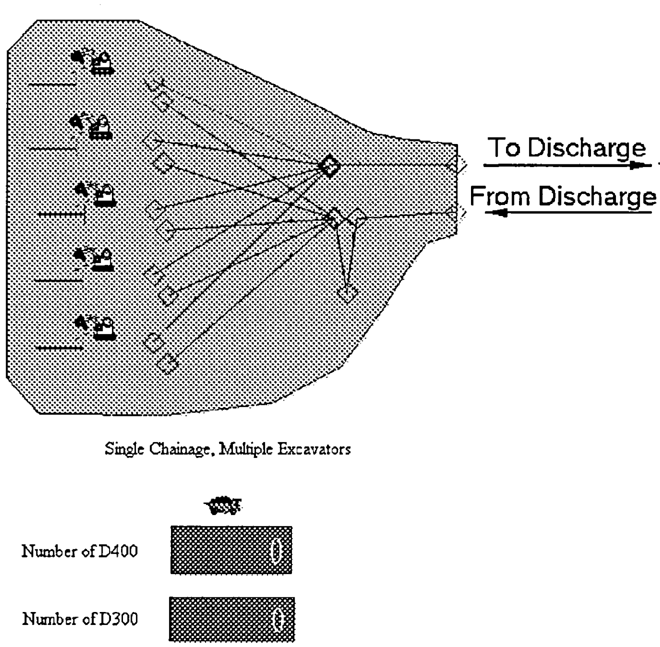

Figure 34 Single chainage with multiple excavators

5.5.4 EXAMPLES

The single chainage module is configured for a particular application by entering site specific data into the data entry form, Figure 35. This is achieved by double clicking in the module to reveal the data entry form.

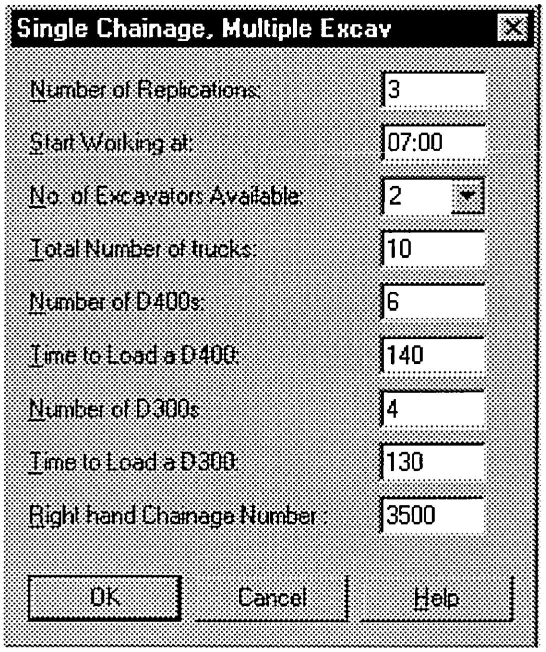

Figure 35 Single chainage data entry form

- Number of replications

The results from a simulation model are generated by running the model for a specific duration. Since the random numbers used within ARENA are actually pseudo-random in that they follow a set pattern a simulation experiment should be replicated several times to ensure that the results that are generated are not due to the pseudo-random number sequence. In this example the experiment was be replicated 3 times.

- Start work at

This is the time that the shift and hence the model shall start running, here 7:00 o'clock is used.

- Number of excavators.

As stated overleaf the number of excavators within this module can be varied between one and five. In this example work is performed by two identical excavators.

- Total number of trucks.

This is the summation of the number D400 and D300 articulated trucks.

- Number of D400s and D300s

Excavated material must be discharged into a suitable resource. Within this module a fleet of single type or a mixed fleet of trucks can be assigned. Here there are six D400s and four D300s.

- Time to load a D400 and time to load a D300

The mean time to load an articulated truck is a function of the type of excavator used, the material to be excavated and the size of the truck's payload. Since the D300 is smaller than the D400 it takes less time to fill. In this illustration the D400 takes 140 seconds and the D300 takes 130 seconds.

- Right hand chainage number

This is used to enable one module to communicate with another, for example the haul road may be placed adjacent to the excavation module with the right-hand chaniage number of the excavator matching the left hand chainage of its adjacent module.

5.5.5 PROMPTS

To enable each module to be used with ease, tables of; 'prompts', 'valid entries' and 'defaults' are presented. The prompts describe the function of the data entered. The valid entry specifies the types of data that are allowed. While the defaults, specify the initial value of each prompt.

Prompts	Valid Entry	Default
Number if replications – This field defines the integer number of simulation replications to be executed. Each replication will run until either the end of the shift is reached or all of the material has been excavated.	Positive integer	1
Start work – in this field the time that the shift should start is specified. If the field is left blank when the model is run it starts from time zero.	Time	00:00
Number of excavators – from this popup box the number of excavators is specified.	1 – 5	1
Number of trucks – in this field the total number of trucks must be specified.	1 – 30	Required
Number of D400's – in this field the number of D400 articulated trucks is specified.	0 – 30	0
Loading time for D400's – in this field the time required to load a D400 articulated dumper truck is specified.	Positive integer	
Number of D300's – in this field the number of D300 articulated trucks is specified.	0 – 30	0
Loading time for D300's – in this field the time required to load a D300 articulated dumper truck is specified.	Positive integer	
Varance1 – Specifies the variance on the loading time.	Positive integer	10
Leave – Defines the next module to which the trucks will travel. It will typically be the road module, but may also be the traffic light, Bridge or Discharge site.	Integer	Required

Table 10 Single Chainage Prompts

5.5.6 REMARKS

The number of excavators and trucks available remain constant for the duration of the experiment. With loading time variability a function of material type and the location of the truck in relation to the excavator. The sum of the number of D300's and D400's must equal the variable 'number of trucks'. The excavation module can be connected or used in conjunction with any other module except 'multiple chainage'.

One of the aims of this thesis was to increase the accessibility of simulation within the construction industry through simplifying the model development process. To establish whether this has been achieved comparisons are drawn between constructing the excavation module using the standard constructs supplied within ARENA or using the generic module that has just been developed.

Since the underlying model logic of both the excavation model and modules are similar then the results from simulating the same system should be identical. However there are several factors associated with developing models using the traditional approach, which reduce the probability of successfully developing and experimenting with a simulation model.

To develop a model using the standard elements within a simulation package necessitates familiarity with language specific modelling constructs and how they interact with each other. Hence, developing a model in this manner is far more time consuming and fraught with many difficulties.

Time consuming: e.g. to model the single chainage excavation site using standard modelling constructs necessitates selecting, connecting and entering data into approximately 40 elements. It is obviously less time consuming to construct a model by selecting the excavation site as a single entity, position it on the screen and enter site specific data via a single popup menu.

Once the model is constructed the time required to perform an experiment is far greater using the traditional approach, since each time the excavation module is used it must be validated. To do this for each scenario is extremely repetitious, time consuming and unnecessary. Especially so since the generic module once validated is there to be used, as and when required, without necessarily re-validating the logic. Using the standard modelling constructs is fraught with many difficulties. When modelling a system it is common for the same or related data to be stored in several different elements. Thus it is very easy to alter the data in one element and perhaps unintentionally, forget to alter it in another. The problem with this kind of error is that the model may compile, run and present answers that appear at first glance to be correct, when obviously if the input data is invalid then so will the output data. Below, Figure 36, is an example of the various locations where the same data is often stored.

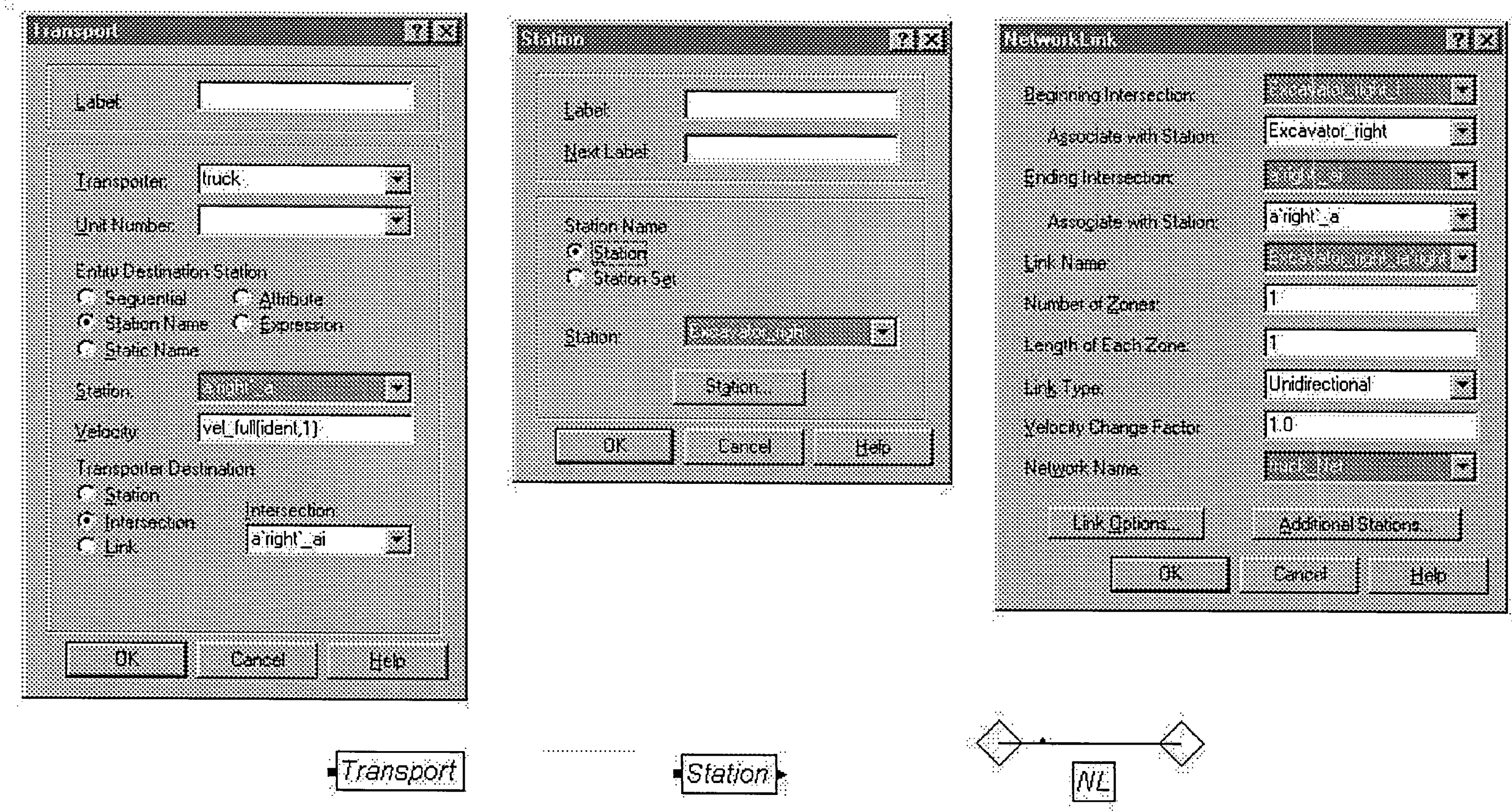

Figure 36 Triplicate Data Entry

If the location of the excavation site was to change, it would have to be altered in the Transport element, Network link and Station elements. Whereas with the generic excavation module, the three elements are related to each other by a single variable which can be altered using one data entry form, Figure 35.

Generic modules also have the additional benefit of shielding the experimenter from the intricacies of the model. Thereby reducing the possibility that the integrity of the model will be lost through unintentional modification to model logic.
These points are summarised in Table 11.

	Traditional Simulation Language Specific Modelling Constructs	Domain Specific Modelling Constructs
The familiarity of modelling constructs required for model development.	Vast knowledge	Limited understanding
Number of programming commands necessary	Hundreds	Tens
Length of time required to develop model	High	Low
Data collection	Required each time model is developed	Collect once and use many times
Probability of duplicating data entry	High	Low
Proportion of time spent validating model	Significant	Insignificant
Probability of model logic being corrupted	High	Low
Reusability of commands	Seldom, if at all	Frequent

Table 11 Summary of model development. Traditional vs. domain specific modelling constructs

Of course a single module in itself does not facilitate the creation of a simulation model. Hence, additional modules, multiple chainage excavation, haul road, traffic light, bridge and a discharge site, are developed.

5.6 MULTIPLE CHAINAGE

When excavating material prior to the construction of a road the location of the cut and fill often change. Factor analysis identified that where the distance the material is hauled changes significantly, then it is desirable to model earthmoving using multiple as opposed to a single chainage. Alkoc (1993) investigated the effect of increasing haul distance for a concreting operation, however the model required that the haul distance be manually increased. This not only means that the experimenter must be present when the model is run but also, each time the haul distance changes the model has to be stopped. When a model is stopped and restarted, there is an associated warm-up period, which in the physical world does not occur. This leads to output being underestimated. With the generic module the distance material is hauled automatically increases without having to stop the model. This enables the excavation rate to be estimated with greater accuracy.

5.6.1 COMMUNICATIVE MODEL

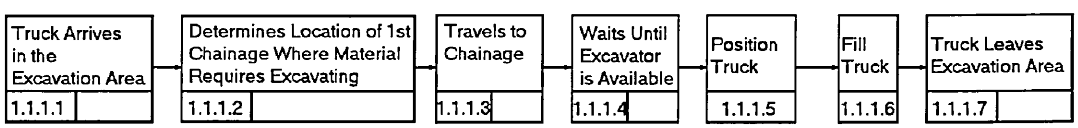

Figure 37 Multiple chainage communicative model

The first truck travels to the first chainage. Using a simple calculation the second truck assesses whether there is sufficient material at the first chainage to fill both trucks. If there is, then the second truck proceeds to that chainage. The remaining trucks travel to the appropriate chainage depending upon the quantity of material at that chainage. Upon arriving at the excavator material is excavated and discharged into each truck. When full the truck leaves the excavation area, re-entering the module after it has discharged its load. Each truck then proceeds to the first available chainage where there is material waiting to be excavated. The cycle of selecting an appropriate chainage, travelling to it, being filled, travelling to the discharge site and returning, is repeated until either the shift ends or there is no more material remaining to be transported.

5.6.2 PROGRAMMING

Figure 38, 44 and 45. Similarly to the single chainage module, one entity is created to control the movement of each truck. The characteristics of each truck are also assigned in a similar manner. The first entity proceeds to the choose block using the in sequence or IS number, the available soil at the first chainage is checked. If there is sufficient material, the entity proceeds to that chainage. If not, the variable 'Job step' is incremented and the availability of material at the next chainage is checked. The entity leaves the first chainage and proceeds to the excavation area. Once there a truck is requested. The truck waits in a queue until the variable 'number' equals the IS number. When the two match the truck is able to proceed to and seize the excavator. The truck is filled, the excavator is released and the truck leaves the module. Control logic at the discharge site determines to which excavation chainage the trucks return. Controlling the movement of the trucks from the discharge site prevents the trucks making unnecessary journeys to the excavator at the end of the shift.

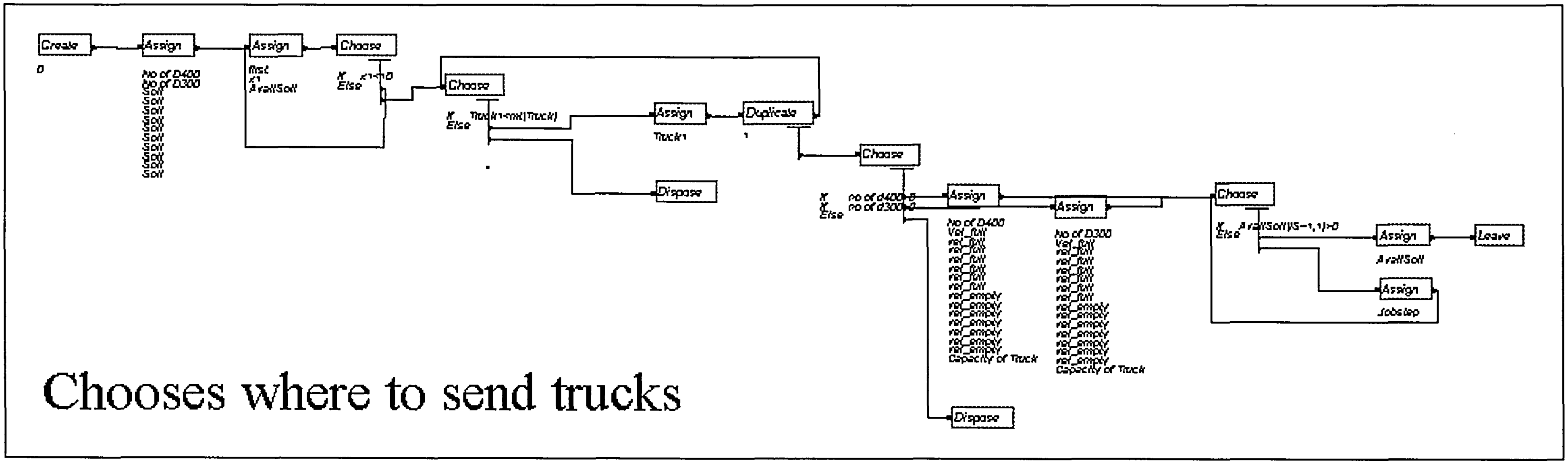

Figure 38 Multiple Chainage Logic, a.

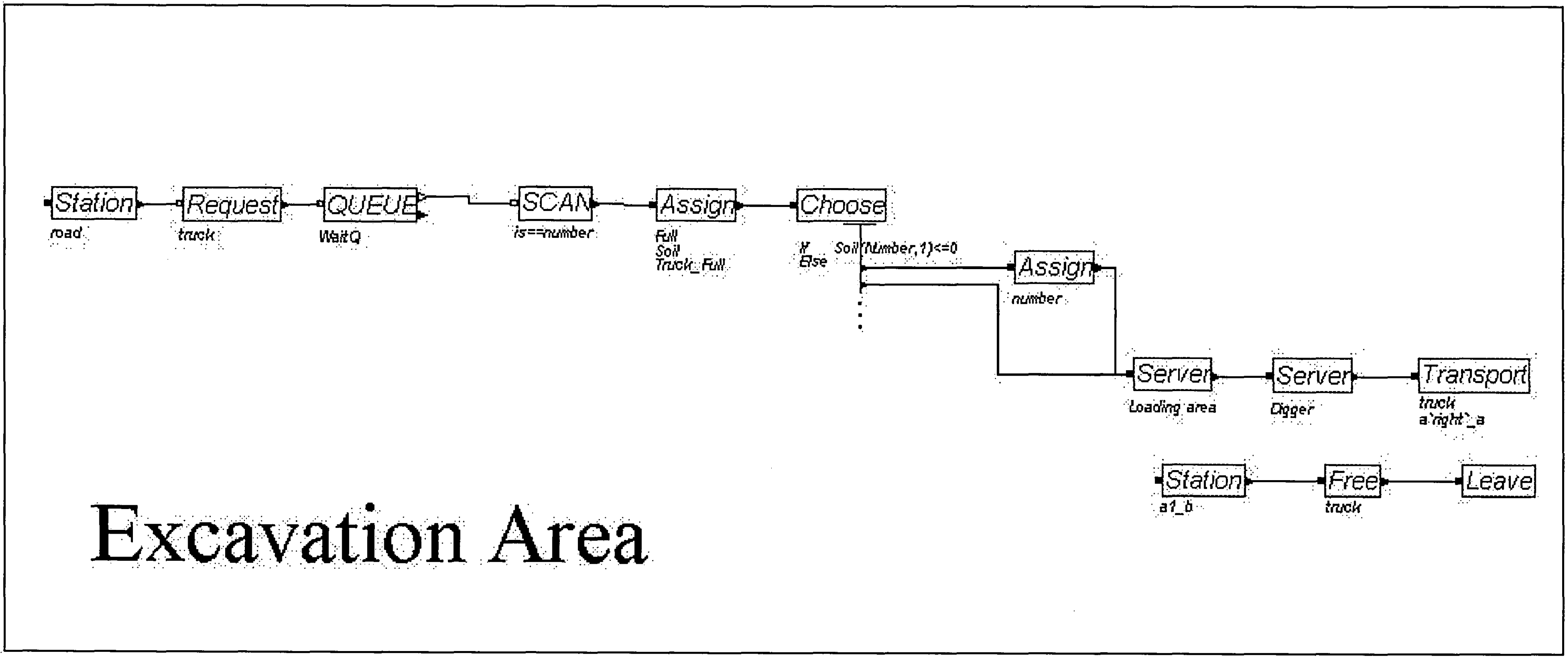

Figure 39 Multiple Chainage Logic, b.

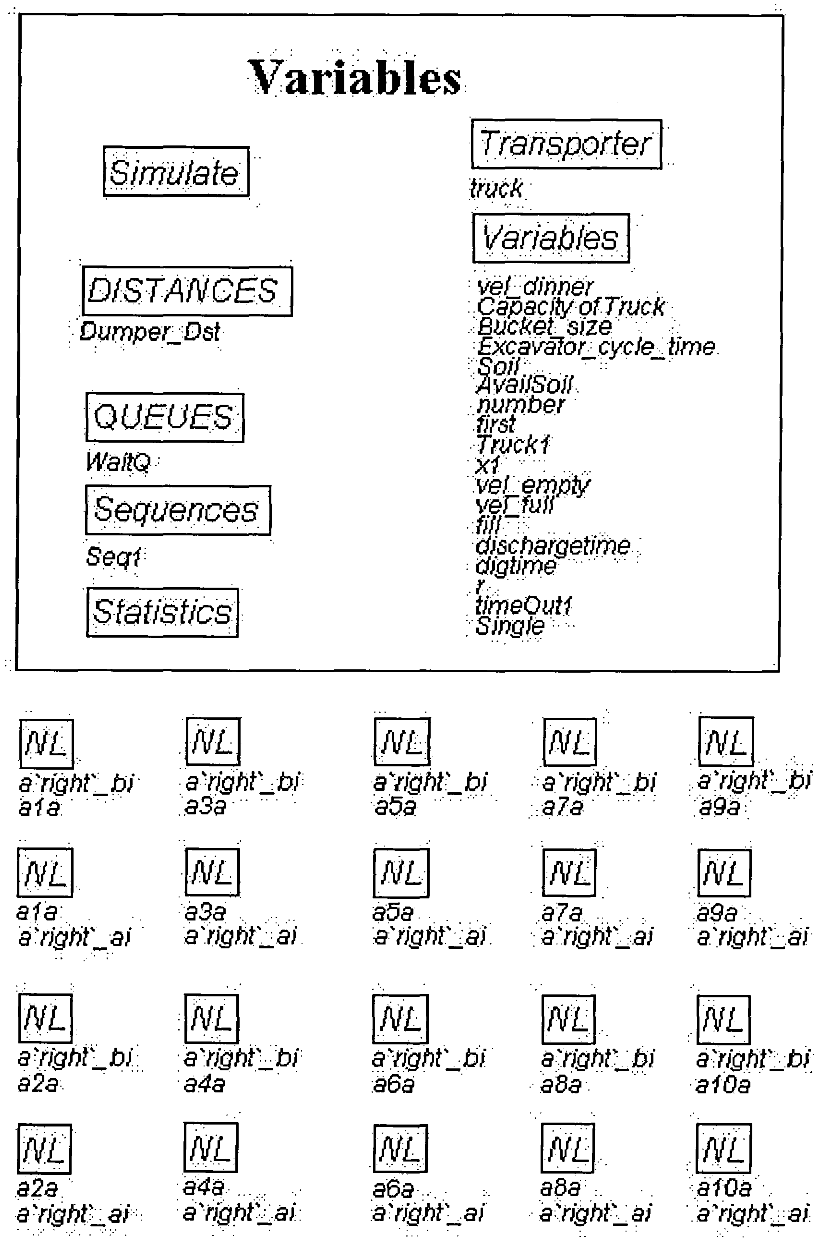

Figure 40 Multiple chainage Logic, c.

5.6.3 ANIMATION

For the purpose of animation material is excavated from right to left. However, in the data entry form, Figure 42, the distance to each chainage is entered independently of other chainages. This enables alternative configurations to be modelled. As material is excavated from each chainage the distance the trucks must travel to the discharge site alters. A diamond represents the location of each chainage. Above each, there is a variable, which displays the quantity of material at that chainage, Figure 41.

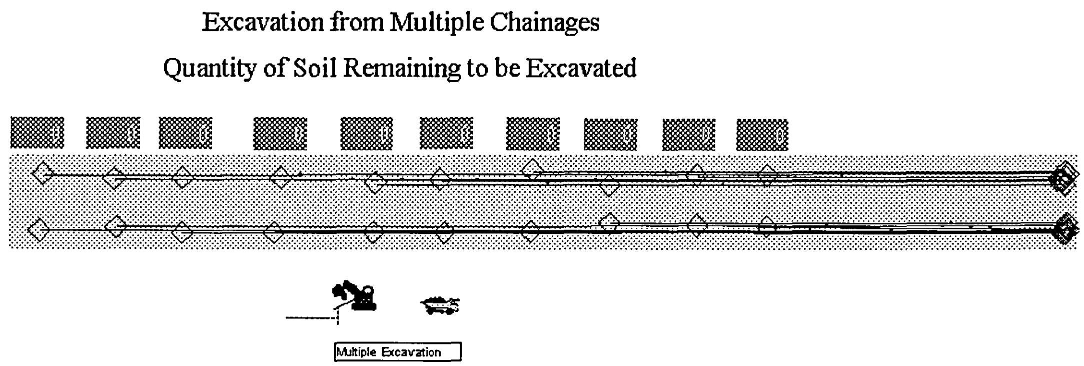

Figure 41 Multiple chainages

5.6.4 EXAMPLES

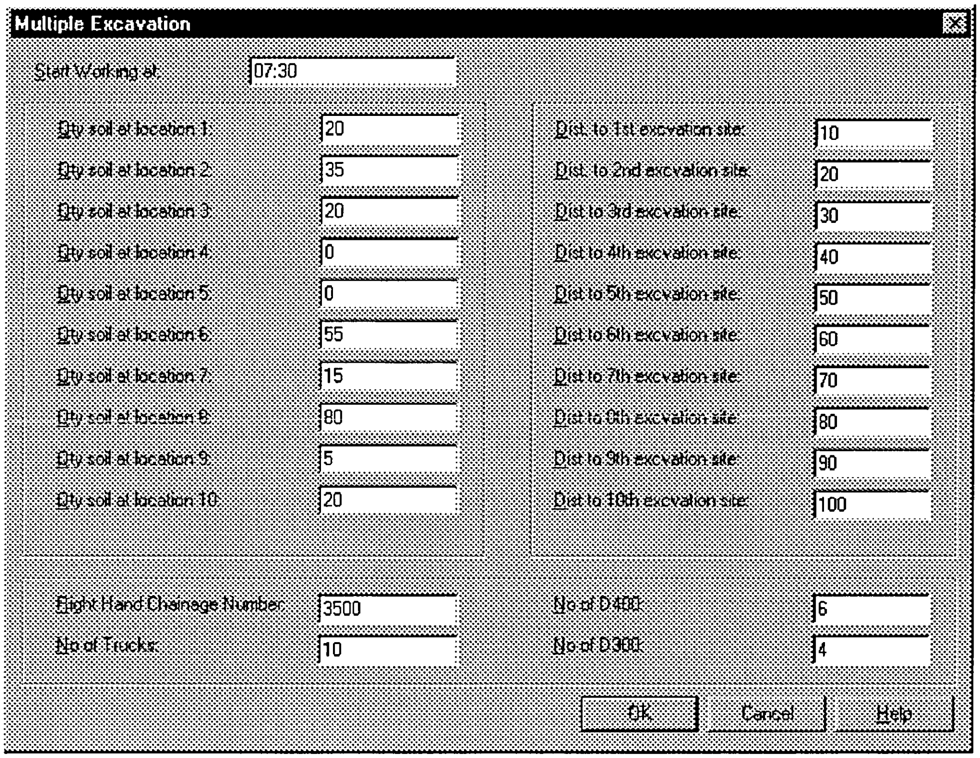

Figure 42 Multiple chainage data entry form

As with the single chainage module site specific are entered via a popup. In this example, Figure 42 work commences at 7:30. At chainage 1, 200m from the entrance to the module (10 sectors, each 20m in length), 200m^3 of material requires excavating. When all of the material has been excavated the excavator moves onto the second chainage where there is 350m^3 of material. Chainage 2 is 400m (20 sectors each being 20m in length) from the entrance. At locations 4 and 5 there is no material thus the trucks move from chainage 3 to 6 missing out the intermediate chainages. As with the single chainage module this module is connected to adjacent modules using the 'right-hand chainage number' e.g. 3500. In the last two cells the number of trucks available are specified, in this example ten trucks are used, six D400s and four D300s.

5.6.5 PROMPTS

Prompts	Valid Entry	Default
Number of replications – This field defines the number of simulation replications to be executed. Each replication will run until either the end of the shift is reached or all of the material has been excavated.	Positive integer	1
Start work – in this field the time that the shift should start is specified. If the field is left blank the when the model is run it starts from time zero.	Time	00:00
Quantity of soil at location 1 – this field is repeated so that a quantity of material for chainages 1 to 10 can be entered.	Positive integer	0
Distance to 1st excavation site – this field is also repeated. The distance material has to be hauled from entering the excavation area to the excavation site has to be entered	Positive integer	Required
Number of trucks – in this field the total number of trucks must be specified	0 – 30	
Number of D400's – in this field the number of D300 articulated trucks is specified.	0 – 30	
Loading time for D400's – in this field the time required to load a D400 articulated dumper truck is specified.	Positive integer	
Number of D300's – in this field the number of D300 articulated trucks is specified.	0 – 30	
Loading time for D300's – in this field the time required to load a D300 articulated dumper truck is specified.	Positive integer	
Variance1 – Specifies the variance on the loading time.	Positive integer	10
Leave – Defines the next module to which the trucks will travel. It will typically be the road module but may also be the traffic light, Bridge or Discharge site.	Integer	Required

Table 12 Multiple Chainage Prompts

5.6.6 REMARKS

For the distance between the excavation and discharge site to increase significantly over the course of a day it is likely that the depth of cut would be shallow or the quantity of material at each chainage be fairly small. For this reason, the number of excavators was limited to one.

To complete both the single and multiple chainage modules requires the collection of accurate excavation data.

5.6.7 DATA COLLECTION

Factor analysis identified that in order to determine production rate, accurate loading times must be used within the excavation templates. Thus the precise sequence of operations and process distributions were obtained from observing the excavation of material prior to the construction of the A1-M1 link road near Leeds.

The time required to excavate different classes of material is given in the Caterpillar Performance Handbook (1985). To ensure that the theoretical excavation rates corresponded with actual, an excavation site was selected where the material to be excavated was considered to be homogenous, with no voids, nor was the transportation of material considered to be restricted by space, or the presence of other vehicles. The excavation process was captured onto videotape enabling subsequent detailed analysis.

If the observed mean excavation rate corresponds to the values given in the handbook then the values given in the book shall be used to establish the loading time for different classes of material to those observed. Factor analysis indicated the precise shape of the distribution appears less significant than the mean, thus the observed loading times shall be used to form a standard distribution which shall be applied to all classes of material.

The excavation cycle was divided into three components, position, load and compact. This enables the loading time to be applicable to trucks differing in capacity from the observed D400.

Trucks arriving at the excavation site form a queue and wait to be served by the excavator. Figure 43, location A.

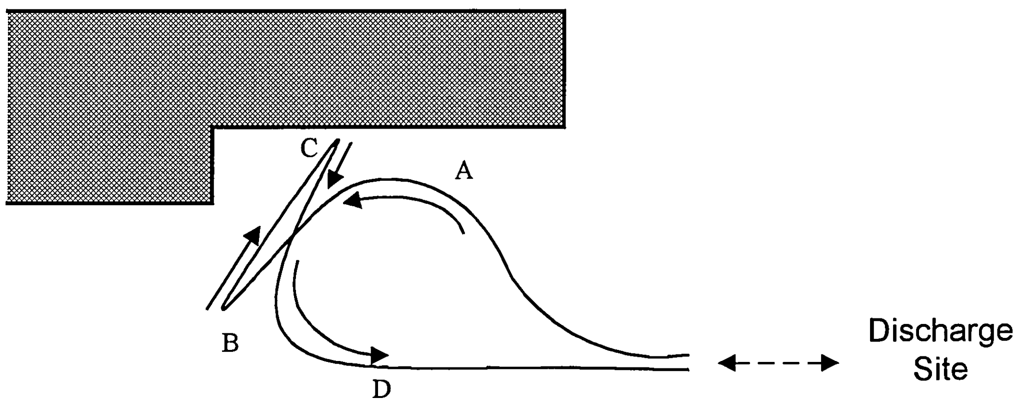

Figure 43 Physical excavation site

When the excavator becomes available the dumper truck at the head of the queue proceeds to (B) before reversing to (C). While the dumper truck is positioning, a single bucket full of material is excavated which is deposited in the back of the truck as soon as the truck stops moving. The excavator continues to load material into the back of the truck until the truck is filled to capacity. Once full, the excavator compacts the material on the back of the dumper truck. To reduce the amount of material spilt along the haul road the excavator compacts the excavate onto the back of the dumper truck.

Once full, the trucks proceed to the discharge site. Where providing that all subsequent material has been compacted, the dumper truck discharges the material before returning to (A), where the material handling cycle is repeated until all material has been excavated and transported.

On the day this data was recorded, the contractor had at his disposal a D350 excavator and two identical D400's dumper trucks each with a carrying capacity of 16.5 m^3. Although the excavator was under-utilised the combination of equipment was considered to be representative of what typically occurs on site.

5.6.8 POSITION TRUCK

The time required to position the D400 with its back open to the excavator was recorded as the time required to drive from (A), to (B) and reverse to (C), Figure 43.

Thirty separate observations were recorded, Figure 44.

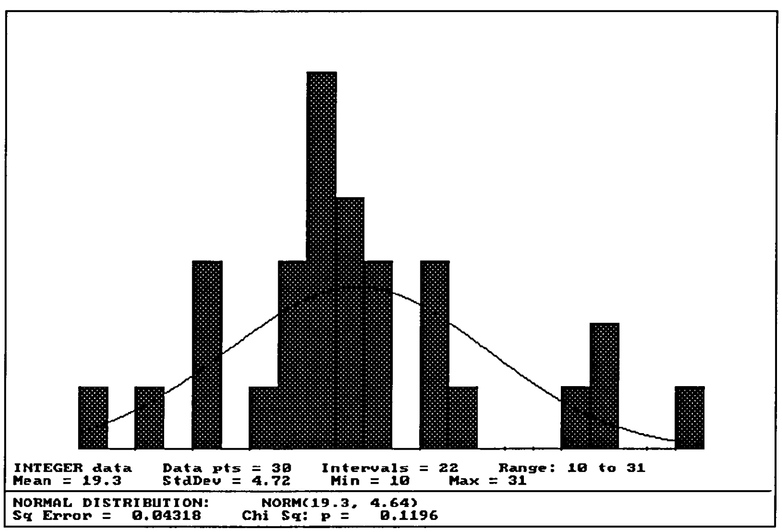

Figure 44 Time required to position

Simulation models can, typically utilise either discrete input data or a mathematical distribution. To reduce the quantity of data required to be input into future simulation models an appropriate distribution was applied to the sample data. Using the statistical package within ARENA a best-fit was found.

5.6.9 LOAD TRUCK

Once in position each excavation cycle comprises of;

- Excavate material,
- Swing the excavators arm to the dumper truck,
- Discharge the excavated material,
- Swinging the arm from the dumper truck. This cycle is repeated until the truck is fully loaded.

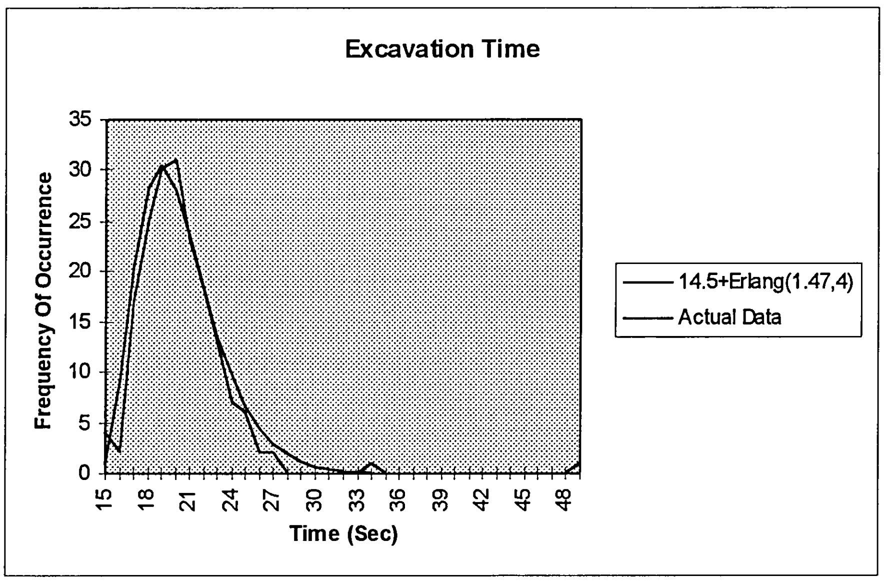

Figure 45 Loading time for dumper truck

Mean 20.4 sec = 0.34 min

Over the observation period 182 separate excavation cycles were recorded, enabling the excavation cycle to be plotted. Again to simplify data input the excavation times were converted into a probabilistic distribution. With the Erlang distribution proving the best fit.

5.6.10 COMPACTION

With the truck full, the excavator compacts material on the truck allowing the maximum possible load to be carried with minimum spillage of material. The length of time required to compact the material was recorded as the time it takes from the excavator discharging the last bucket of material to the moment the truck starts to leave the excavation area, Figure 46.

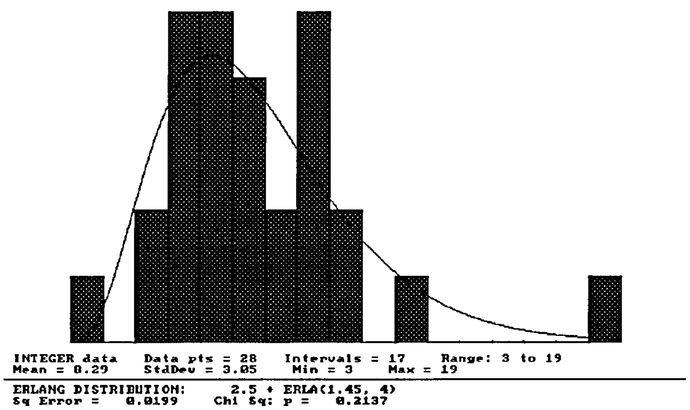

Figure 46 Compact material on the back of the dumper truck.

The observed mean excavation rate coincides closely with that given in the 'Caterpillar Performance Handbook'. It also enabled an appropriate shape of the distribution for each excavation cycle. 30 manoeuvre times, 174 excavation cycles (consisting of load bucket, swing loaded, dump bucket, swing empty), with the material on the back of the truck compacted on 27 occasions.

For each category of excavator, the Caterpillar handbook provides us with an appropriate excavator cycle time for different site conditions. It was considered easier to excavate material from the observed site than could typically be expected. Thus, the mean cycle time for the collected data and handbook are comparable, Figure 47.

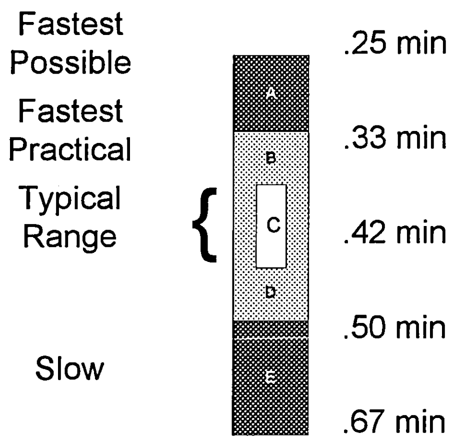

Figure 47 Typical excavation rate for Cat 350, Caterpillar Performance Handbook

Since the observed excavation rate coincides closely with that given in the caterpillar handbook then future models of different sites shall use the rates given in the handbook. A distribution of appropriate shape shall be applied based to the observed data.

Gaarslev (1969) in Technical Report no.26 studied service time distribution and found it to be either log-normal or normal distribution. Gaarslev did however use the Erlang distribution as it can be either a normal or log-normal depending upon the value of the variable K. Values of K=1 gives an exponential distribution, K=5 a log normal and K=20 a normal distribution.

He found that under simple earth excavation conditions the value of K did not significantly affect production rate.

With the dumper trucks filled using either of the excavation modules they proceed to the discharge site along the haul route.

5.7 THE HAUL ROUTE

As the name suggests the haul route is the path that a truck will take when transporting material to the discharge site. The truck leaves the excavation area, accelerates and travels along the haul route at constant velocity to the discharge site. The proportion of time spent accelerating is considered negligible in comparison to the duration of the journey and is therefore excluded from the simulation modules.

The time required to traverse the haul route is typically represented by using a delay block, Halpin (1990), of appropriate duration. This was identified as inappropriate in chapter 3. Construction personnel perceive the delay block as too abstract, not physical, since they can not see a delay. They want to see animated trucks travelling from excavation to discharge site at an appropriate speed. The delay block does not enable output in congested environments to be estimated. Nor is the duration of a delay directly reusable, since variables such as length of the haul road and velocity that the trucks may travel could be easily lost. The length of time required to reach the discharge site is a function of the haul route and obstructions along it.

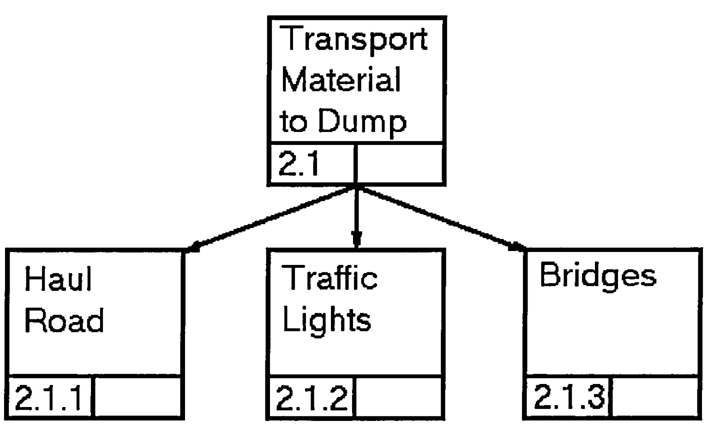

Figure 48 Transportation modules.

5.7.1 COMMUNICATIVE MODEL

The haul road is perhaps the simplest of the modules requiring little logic or data input. A truck enters the haul road, Module 2.1.1, travelling at a particular speed depending upon the type of truck and the total rolling resistance of the road. It continues at that speed unless it meets an obstruction such as a bridge or the gradient of the road changes. The haul road must therefore be able to connect to anyother module including itself, Figure 49.

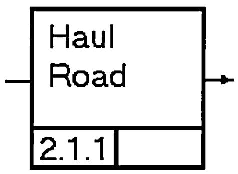

Figure 49 Haul road

5.7.2 PROGRAMMING

Trucks enter the haul road module from the left, station 1 and transports material at a given velocity to the discharge site. The velocity that a truck can travel is dependent upon the characteristics of both itself and the total rolling resistance of the haul road.

In section 4.2.6, Factor analysis was used to established that the time to haul the material and hence velocity each truck can travel is important. Yet the precise shape of the variability distribution is relatively unimportant. Velocity is affected by many factors, including total rolling resistance, obstructions and speed limits; to isolate velocity from these factors would be difficult and impractical to record on actual sites. Thus, the mean velocity that a truck can travel under different site conditions was taken from the Caterpillar Performance Handbook. Smith (1995a) and Gaarslev (1969) examined earthmoving and independently concluded from their data that it was appropriate to use the Erlang distribution for estimating haul duration. However, to enable different haul routes to be modelled the factors, velocity and distance are used to generate haul duration. A normal distribution is used within the modules to determine velocity since obstructions along the haul route create congestion and hence increase the haul duration. Hence, if velocity is entered into the model using a normal distribution the haul duration because of obstructions/congestion tends to become Erlang.

5.7.3 ANIMATION

Using guided paths provides not only animation of the trucks travelling along the haul road, but also enables production rates in congested environments to be estimated, chapter 4. The animation and logic for the haul road is shown below, Figure 50.

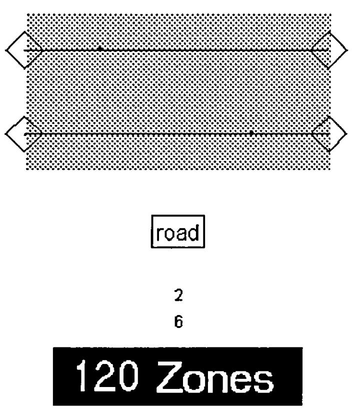

Figure 50 Haul-road animation

Trucks may enter the module from either direction. They may pass in opposite directions without interference but may not overtake each other.

5.7.4 EXAMPLES

In this example, Figure 51, the left-hand and right-hand chainage numbers are 3400 and 1000 respectively. Each zone is 20m in length. There are 120 zones, and thus the truck must travel the equivalent of 2400m. The total rolling resistance is 2 when to the discharge site and 6 when travelling from. Thus the articulated truck can travel at different speeds from one section of road to another. Here a variance of 20% is applied to velocity.

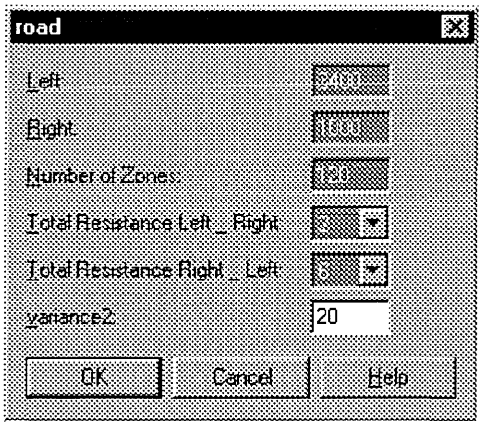

Figure 51 Haul-road data entry form

5.7.5 PROMPTS

Prompts	Valid Entry	Default
Left – This field contains the chainage number on the left-hand side of the module. It must be the same as right-hand chainage of the module immediately to its left.	Positive integer	Required
Right – This field contains the chainage number on the right-hand side of the module. It must be the same as left-hand chainage number of the module immediately to its right.	Positive integer	Required
Number of zones – This field defines the length of the haul-road. However since each zone is 20m in length the length of the haul must be divided by 20 to determine the number of zones.	Positive integer	Required
Total Rolling Resistance Left-Right –this pop-up determines the velocity that a truck can travel. The lower the 'Total Rolling Resistance' the faster the truck. The gradient and condition of the haul road determines Total Rolling Resistance.	2, 4, 6, 8	Required
Total Rolling Resistance Right-Left – similar to left-right however, when calculating total rolling resistance it should be born in mind that a positive gradient in one direction is negative in the other.	2, 4, 6, 8	Required
Variance – Specifies the variance in the velocity when travelling along the road.	Positive integer	Required

Table 13 Haul Road Prompts

5.7.6 REMARKS

The haul road module can be connected to any other module, including itself. This will be necessary if the total rolling resistance of the haul road varies significantly between the excavation and discharge site.

Unfortunately, the haul road is usually more complex than a simple change in gradient. Obstructions such as bridges or traffic lights often impede the movement of trucks.

5.8 BRIDGES

Geographical features; rivers, soft ground or even obstructions such as a railway line may necessitate the construction of a bridge. The type used depends upon the urgency of the project and cost of the alternatives.

A bridge can be used in three main ways:

- One that allows the movement of trucks in either direction without impeded their movement.
- Many trucks can cross the bridge but only in any one direction at a time.
- Only one truck can cross in either direction at a time.

The first bridge does not require a specific module to be developed since it does not affect the movement of the trucks; a haul road module could be used to represent the bridge. The other two bridges do affect the movement of the trucks and it is for these that modules are developed.

5.9 BAILEY BRIDGE

Since both bridge modules are used in a very similar manner they shall be described as if they are one, with the differences between them highlighted.

5.9.1 COMMUNICATIVE MODEL

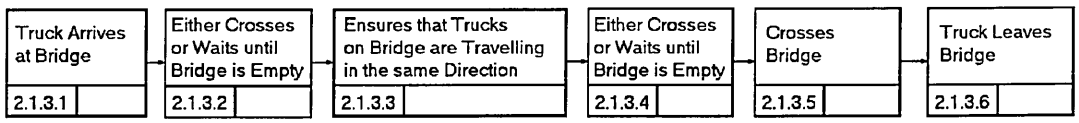

Figure 52 Bridges

If the bridge is sufficiently strong to withstand more than one truck crossing in the same direction then this is allowed. N.B. For safety there should be no less than 10m between the trucks.

5.9.2 PROGRAMMING

Since the type of bridge dictates that the trucks operate differently, separate logical models are required.

The logical model of the one-at-a-time Bailey bridge, Figure 53, is simpler than the other bridge. This bridge can be considered as a resource with a capacity of one. In the model a truck entering the bridge seizes it. This prevents another truck crossing until the truck leaves and the bridge becomes available. Thus once a truck enters the bridge; all other traffic must wait until the truck has crossed.

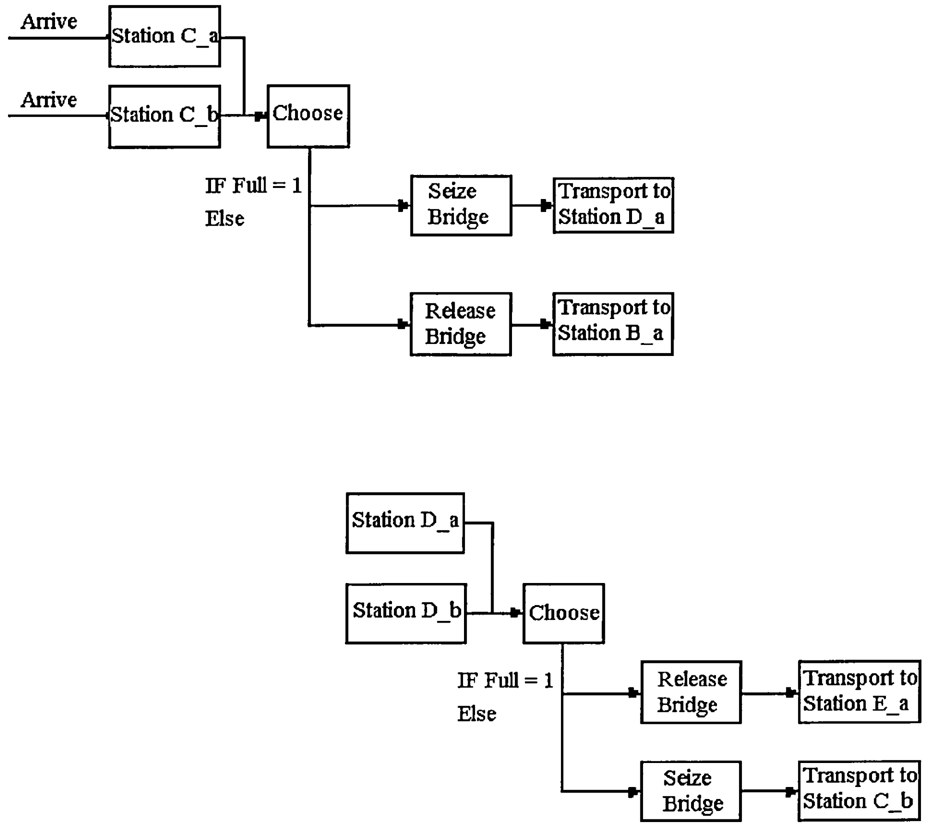

Figure 53 Bridge, one truck at a time

More control logic is required for this bridge, as it cannot be considered a resource. If it were to have a capacity it would be assigned indiscriminately by the resource, allowing trucks travelling in either direction to occupy it. To overcome this problem, wait and signal blocks are used, Figure 54. When entering the bridge module the signal module indicates the presence of a truck. If empty, the truck is assumed to have crossed the bridge and therefore proceeds to the excavation site. If full, the truck proceeds to the choose block where depending upon whether the variable bridge busy is greater a zero either waits or crosses the bridge. At the far side of the bridge, another signal is given indicating when the truck has crossed. The truck leaves the module. If the truck arrives from the excavation site its presence is signalled before proceeding to the wait module where it is delayed until the bridge is empty. The truck crosses and leaves the module.

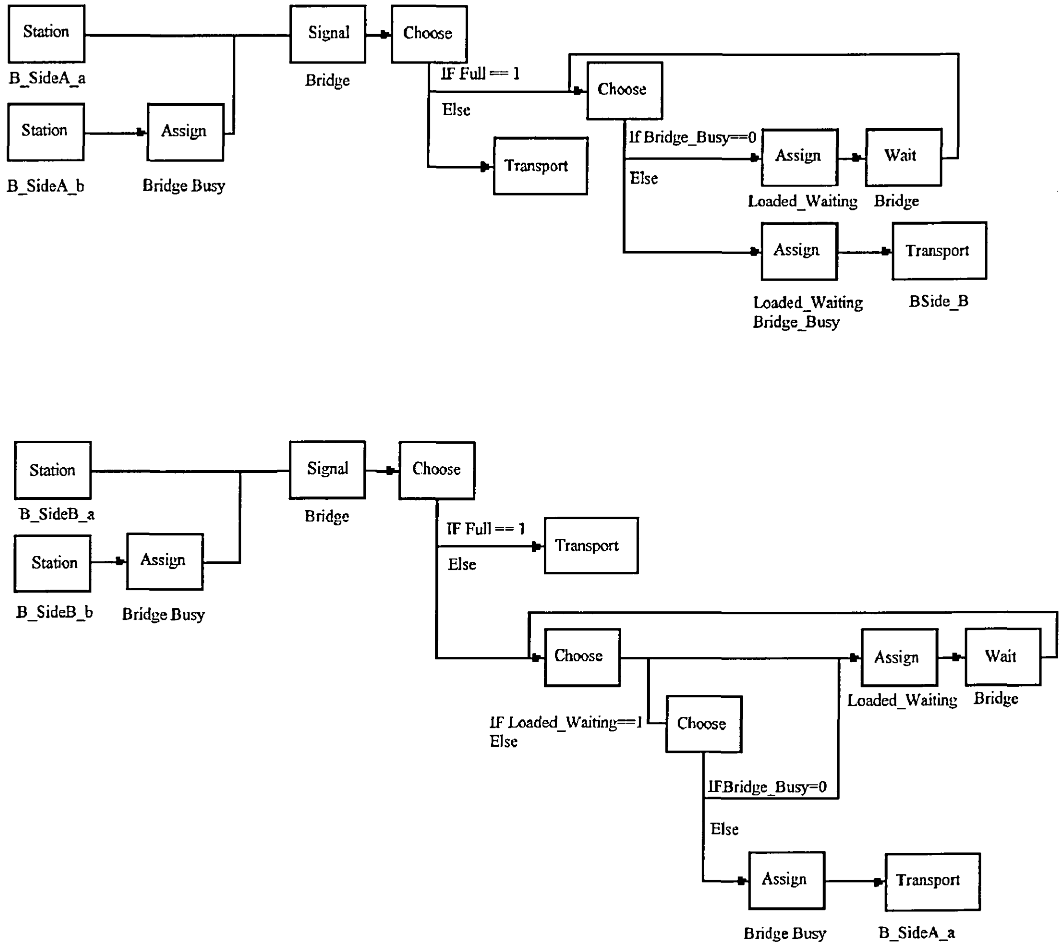

Figure 54 Bridge, one direction at a time

5.9.3 ANIMATION

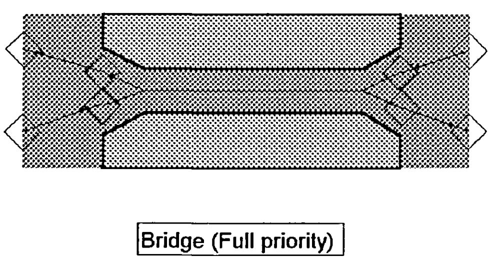

Figure 55 Bridge animation

The animation is the same for either bridge. Trucks can cross either bridge in one direction at a time. Trucks arrive fully laden at the left-hand side of the bridge, wait until the bridge is empty and cross. Trucks arriving at the right of the bridge have to wait until there are no loaded trucks waiting to cross. Loaded trucks have priority over empty, since an empty truck can accelerate to its top speed quicker than a full truck. Either bridge can be used in conjunction with any other module.

5.9.4 EXAMPLES

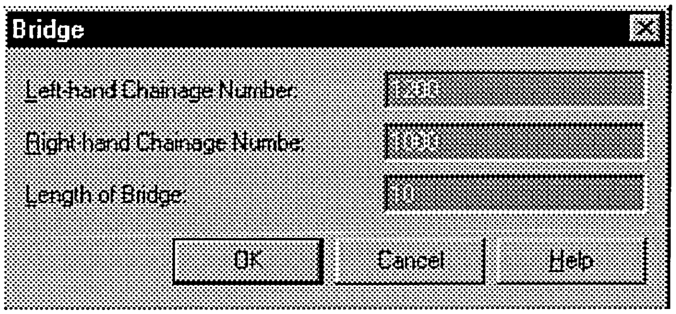

Figure 56 Bridge data entry form

As with the other modules, both bridges are connected to adjacent modules using the left and right-hand chainage numbers, in this example 1200 and 1000 respectively. The bridge is 10m long.

5.9.5 PROMPTS

Prompts	Valid Entry	Default
Left – This field contains the chainage number on the left-hand side of the module. It must be the same as right-hand chainage of the module immediately to its left.	Positive integer	Required
Right – This field contains the chainage number on the right-hand side of the module. It must be the same as left-hand chainage number of the module immediately to its right.	Positive integer	Required
Length of the bridge – This field defines the length of the bridge.	Positive integer	Required

Table 14 Bridge Prompts

5.9.6 REMARKS

The bridge modules are used in the same way as the haul road module. They can be connected to each other, a haul road module, excavation, discharge site or traffic lights.

5.10 TRAFFIC LIGHTS

Traffic lights are perhaps the most common obstruction encountered on haul routes. They exist as either as a temporary fixture where the haul road crosses the main road or as a permanent fixture where two or more roads meet. Here we investigate the former since the vehicles used for hauling material on the observed sites were too large to use main roads. Traffic lights are relatively difficult to model since any truck travelling in either direction can activate their timing sequence. It is here that the modules come into their own.

5.10.1 COMMUNICATIVE MODEL

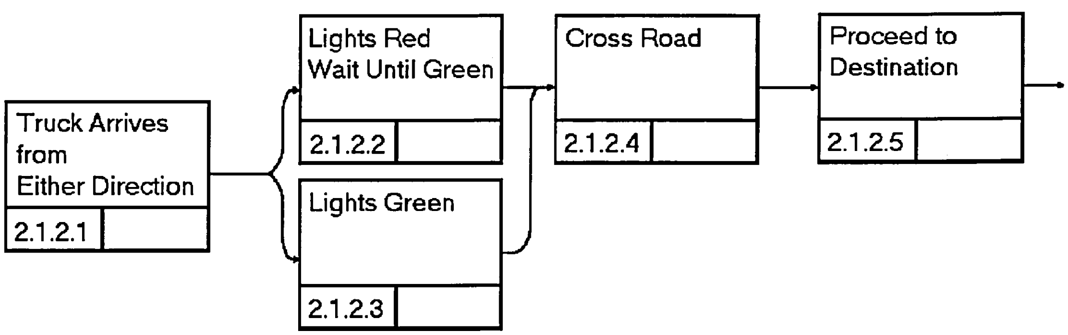

Figure 57 Traffic light

The timing and control logic for the temporary traffic lights (Haul route controllers) was determined from the 'Highways Agency' equipment specification MCE0137. When a truck driver nears the haul route controller he looks ahead to check the signal indicated by the lights, if green the driver slows the truck to an appropriate speed for crossing the road. Since the traffic on the public highway has priority over the haul-route, the traffic lights are usually red for the haul route; hence the trucks must stop. Haul-route controllers sense the presence of a truck and all of the lights change to red for a period of at least 10 seconds, to ensure that there is sufficient time for the crossing to clear of traffic. With a green signal the truck accelerates, crosses the road and proceeds to its destination. The lights remain green for approximately 30 seconds. If during this period another truck arrives then the lights remain green for a further 16 seconds before returning to their natural state.

5.10.2 PROGRAMMING

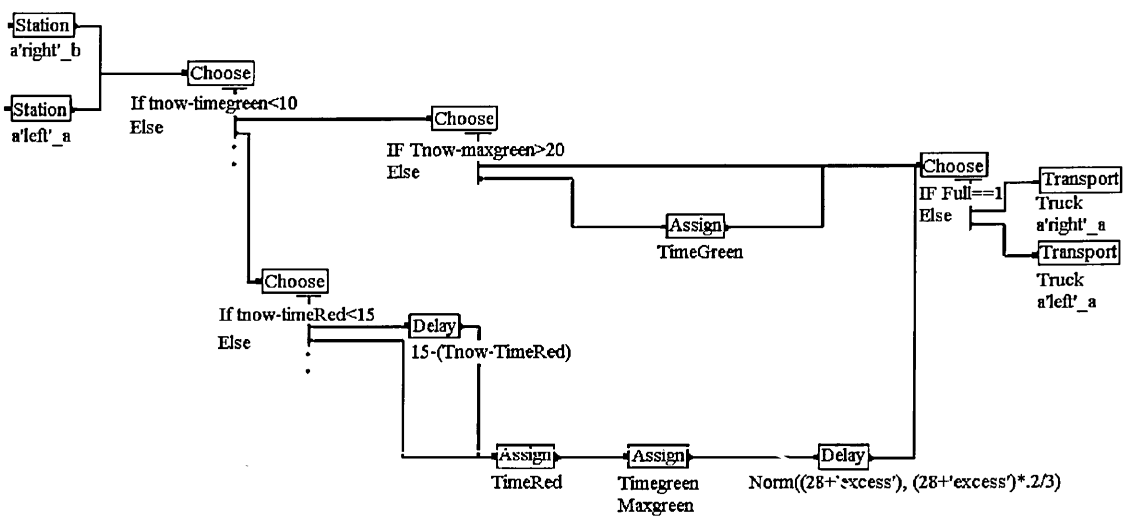

Figure 58 Traffic light logic

A truck enters the module either from the excavation or discharge site, station "a`right`_b" or station "a`left`_a". assuming that the lights are at red for the haul road and the minimum all red period has been exceeded then the lights automatically turn all red for 15 seconds. This allows the traffic travelling along the main road to clear the crossing before the green signal is given to the articulated trucks. The variable 'TimeRed' is assigned the current simulation time so that any trucks in the vacinity of the traffic lights can cross the road without being delayed. The trucks are delayed equivalent to the length of time required to accellerate and cross the main road. When the current time exceeds the 'TimeRed' + 'MaxGreen' then the trucks are prevented from crossing the road.

5.10.3 ANIMATION

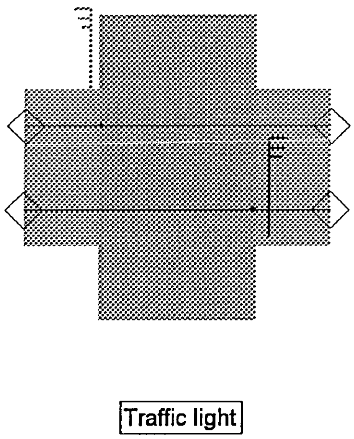

Figure 59 Traffic-light animation

5.10.4 EXAMPLES

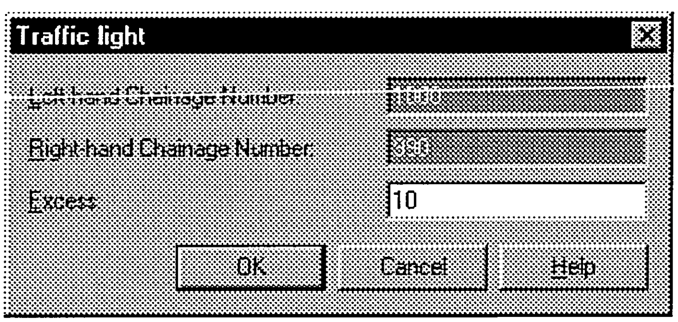

Figure 60 Traffic-light data entry form

Left and Right hand chainage numbers are 1000 and 990 respectively. An excess of ten seconds is applied to enable any trucks on the main road to clear the junction.

5.10.5 PROMPTS

Prompts	Valid Entry	Default
Left-hand Chainage Number – This field contains the chainage number on the left-hand side of the module. It must be the same as right-hand chainage of the module immediately to its left.	Positive integer	Required
Right-hand Chainage Number – This field contains the chainage number on the right-hand side of the module. It must be the same as left-hand chainage number of the module immediately to its right.	Positive integer	Required
Excess – depending upon the type of main road that the trucks must cross an excess all red period may be required.	Positive integer	Required

Table 15 Traffic light Prompts

5.10.6 REMARKS

This module can also be connected to any other module including itself if desired. The variable 'excess' enables an additional delay to be entered to take account of an increase in say the width of the road being crossed or the additional delay required for the all red period when the haul road crosses a high speed main road.

5.11 DISCHARGE SITE

At the opposite end of the haul road to the excavation site is the discharge site. This is where excavated material is discharged from the dumper trucks, spread and compacted. It was considered that there would always be sufficient machinery available in the discharge area to spread and compact the discharged material without impeding the movement of the dumper trucks, hence the spreading and compaction machinery is not included in this module.

For the same reason that the excavation site was considered to span several chainages so does the discharge site. If the user wants to consider modelling the discharge site as if it were a single chainage then the experimenter merely has to ensure that the capacity of the first chainage is sufficient to accommodate all of the excavated material.

5.11.1 COMMUNICATIVE MODEL

The necessity of modelling road construction as a terminating system was the established using factor analysis. The beginning of each shift was entered in the excavation module with the end incorporated into this, the discharge module.

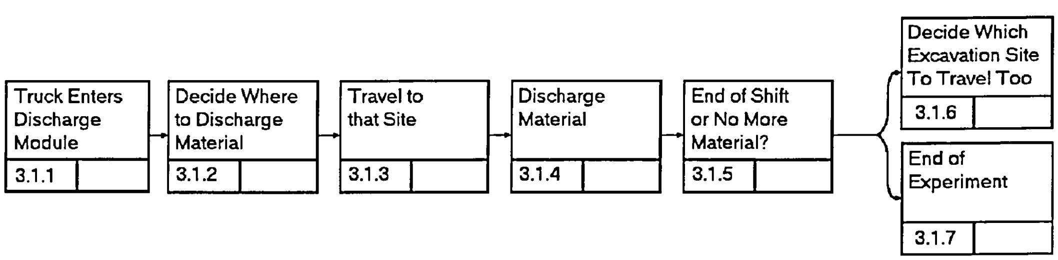

Figure 61 Communicative model Discharge site

5.11.2 PROGRAMMING

A truck arrives in the discharge area. The trucks travel to the nearest discharge area where there is space to dump there load. Material is discharged. The volume of material discharged is subtracted from the capacity of the fill. The remaining sequence of choose blocks enable the trucks to return to the correct excavation chainage irrespective of which excavation module is used. Towards the end of a shift the trucks drivers check to ensure that they can complete one more excavation and discharge cycle before the end of the shift. Where this is not possible the trucks are held within the excavation module and the experiment ends.

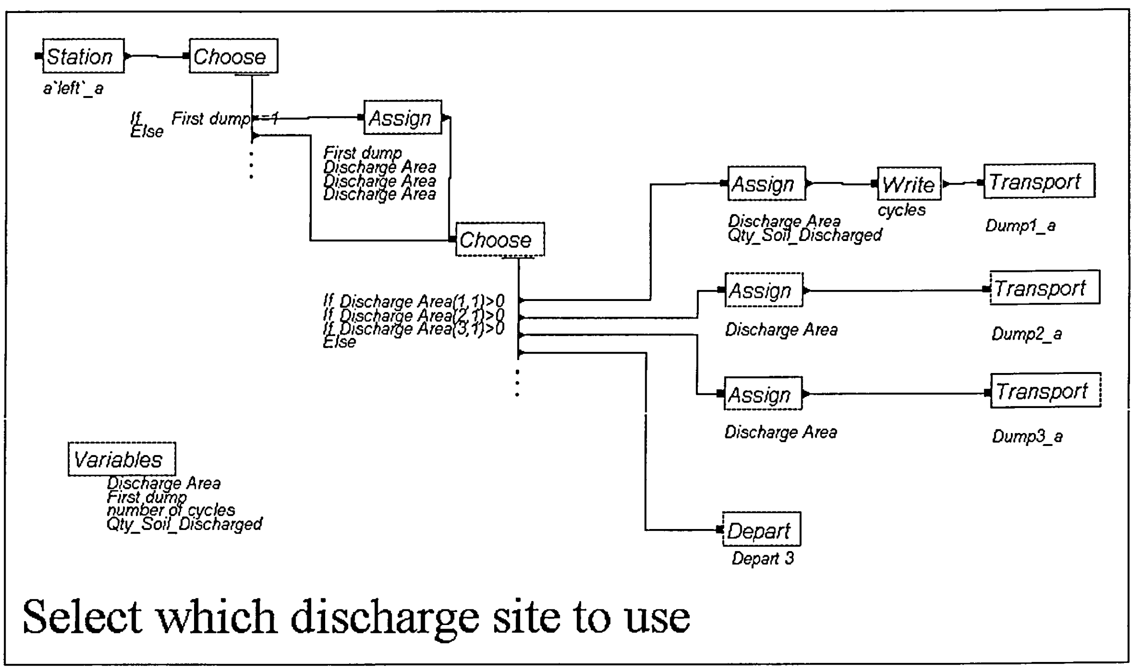

Figure 62 Discharge Site, a.

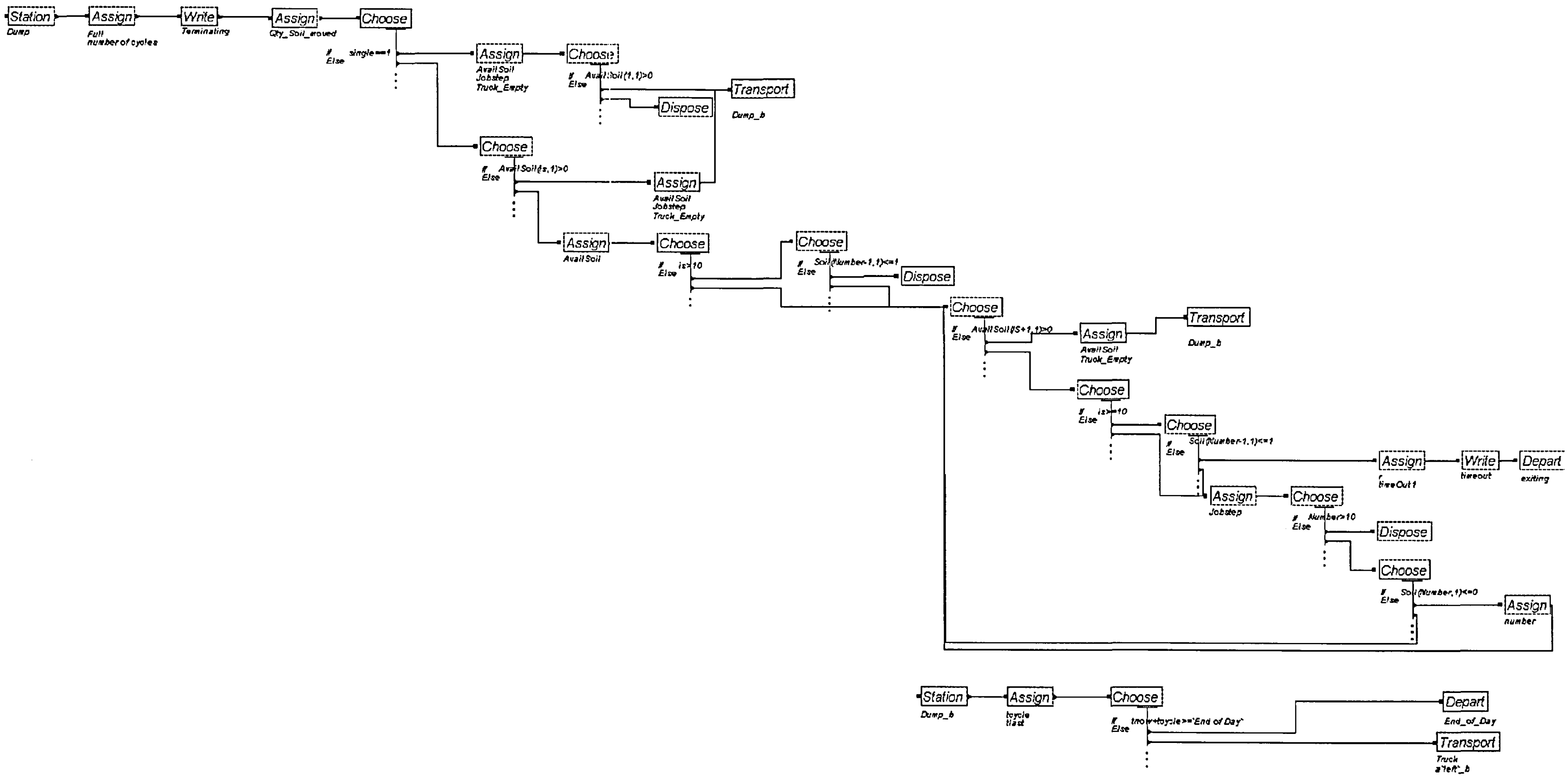

Figure 63 Discharge Site, b.

5.11.3 ANIMATION

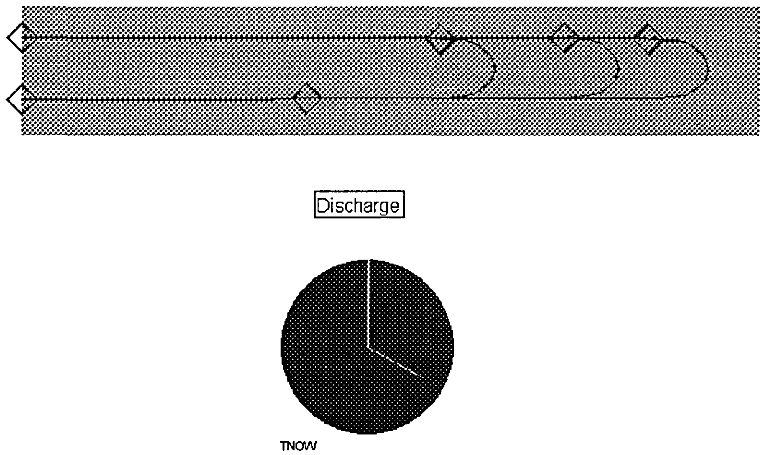

Figure 64 Discharge site animation

Trucks enter the module full at the top left-hand side. Travel to an appropriate chainage and discharge material. The iconic representation of a truck change from loaded to empty. The truck proceeds around the module and departs for the excavation site. An analogue clock provides the simulation analyst with an estimation of the current time, making it easier to compare the progress of the trucks with what can be observed on site.

5.11.4 EXAMPLES

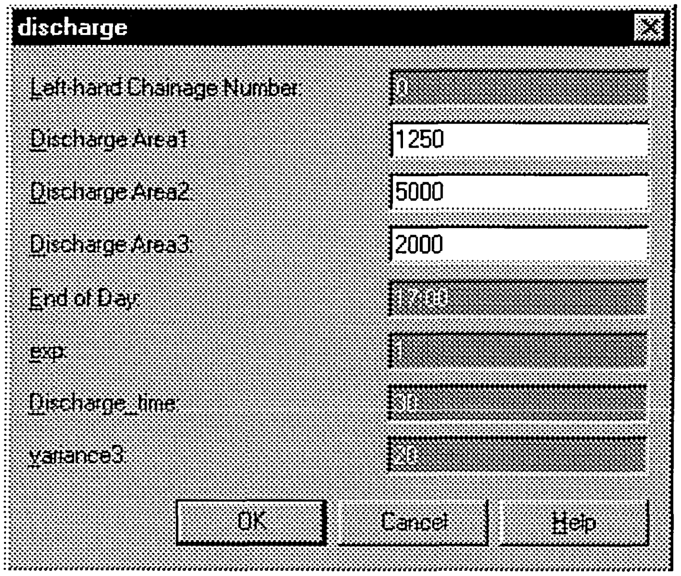

Figure 65 Discharge site data entry form

The left-hand chainage number, 0, is entered to connect this module to any other module. However, it will typically be connected to the haul road. The capacity of the first discharge area is 1250m^3 with the second and third 5000m^3 and 2000m^3 respectively. At 17:00 the shift and hence the experiment ends. To enable different results to be stored for different experiments a number or letter must be entered for the variable 'exp'. In this example the 1 is entered hence, the results will be found in experiment file 'exp1.txt'. The material discharge time is 30 seconds with a variance of 20% is applied.

5.11.5 PROMPTS

Prompts	Valid Entry	Default
Left-hand Chainage Number – This field contains the chainage number on the left-hand side of the module. It must be the same as right-hand chainage of the module immediately to its left.	Positive integer	Required
Discharge Area 1,2 & 3 – This field contains the volume of material that can be stored at any chainage.	Positive integer	Required
End of Shift – This field defines the end of the shift.	Positive integer	Required
Experiment Number – This field contains the number or letter that is used to form the name that the experiments are saved as.	Alpha numeric	Required
Discharge time – This field contains the length of time required to discharge the material.	Positive integer	Required
Variance – This field defines the variation in discharge time.	Positive integer	Required

Table 16 Discharge Prompts

5.11.6 REMARKS

Originally, morning, dinner and afternoon breaks were included within this module. However, the experiments performed in the previous chapter established that it was not necessary to include these breaks in output. Therefore, the completed modules do not include these factors.

The discharge module can be connected to any other module except itself. Only one discharge module can be included in the simulation model. When entering the start and end of the shift an allowance should be made for each break.

5.12 LIMITATIONS

The templates are limited to the excavation, transportation and disposal of material using single or multiple excavators with up to thirty articulated trucks.

When creating modules within ARENA arrays must be defined before compiling the programming code. The size of an array affects the amount of memory required and run speed of the final simulation model. Therefore, it was decided to limit the maximum number of trucks available to thirty. Similarly, because of the additional logic required for modelling each excavator, an upper limit of five excavators for the single chainage and one for the multiple chainage was imposed.

5.13 VALIDATION

Before the modules can be used to develop simulation models upon which experiments can be performed each module must be validated, verified and tested. Otherwise, there is a danger that the results may be acted upon when in fact they are invalid. The goal when validating a model is to ensure that the model is good enough to enable decisions about a system similar to those that would have been made were it feasible and cost effective to experiment with the physical system, Law (1981).

Balci (1994) stated that informal techniques are among the most commonly used simulation techniques for validation, verification and testing of simulation models, and it is these informal techniques that are primarily used to validate each simulation module.

Each of the modules and models developed within this thesis were validated using the three-step approach proposed by Law (1981).

1 Develop a model with high face validity.

Experienced construction personnel at Henry Boot, a national construction organisation, examined the paper-based modules checking that the operational logic and assumptions were valid. Once validated the paper based communicative models were transposed into computer code. Developing computer-based modules is by necessity an iterative process. Code is added, checked, modified and re-checked to ensure that the simulation modules are representative of the paper based systems.

When a model is compiled an in-built debugger within ARENA checks the model syntax for errors. When an error is found the statement containing the error is highlighted enabling the model builder to amend the model syntax. Once successfully compiled the semantics of the model must be checked, this is an altogether more difficult and time consuming process. The model builder must design a series of tests to establish the credibility of each model.

Testing

Within this research unitary process data was initially entered enabling the operation of the model logic to be compared against the sequence in which operations actually occurred. When validating, deterministic data provides several benefits over stochastic data namely the output is easier to calculate with the results repeatable. When errors were found, the cause was sought and the logic amended. To establish validity a structured walk through was performed. This is where another model builder examines each model statement, to assess its necessity and validity. When superfluous code was found it was removed, thereby minimising the risk of two pieces of code conflicting and reducing the validity of the model.

Once convinced that as many errors as possible were trapped, the unitary data was replaced with actual distributions. The model was initially run with one truck until a specified quantity of material had been excavated, hauled and discharged. Comparisons between simulation and mathematical results were drawn. When one truck is used, neither congestion nor queuing can be present, hence the output estimated from a mathematical model and the simulation model must be virtually identical. Initially there were the inevitable differences between the results from the two models. The models were amended until the differences were eliminated or accounted for by rounding errors.

A further series of experiments were performed where the level of different input parameters were changed to ensure that the model behaved and produced outputs that were considered reasonable, e.g. it is generally believed that if the length of the haul road or excavation rate is increased, with all other factors remaining constant, output should decrease. This phenomenon was found to occur.

Each module was developed in several stages, the validity of each module was established at each stage before the complexity of the model was increased. E.g. during the early stages of module development only the characteristics of a single type of truck was included, the model was validated and additional types of truck added.

Animation was used extensively to aid validation providing an invaluable overview of the system; e.g. it was immediately apparent if the logic controlling the movement of the trucks was valid, since one could observe the route that a vehicle took. Using a single entity and hence a single truck, the model was stepped through so that the movement and associated journey times could be recorded. Following the entity through the modules ensured that the operating logic performed as desired.

2 Test the Assumptions of the model Empirically

With the model syntax and semantics checked for errors, the sensitivity of each factor was established using factor analysis. This ensured that the system was modelled at an appropriate level of detail. Those factors that were particularly sensitive were analysed to a greater extent. Both the method and result of this analysis can be found in section chapter 4.2.

3 Determine the representativeness of the output data.

Askin (1993) stated that "it is often too costly and time consuming to determine that a model is *absolutely* valid". Balci (1995) affirmed this view. "How much to test or when to stop testing depends on the study objectives. The testing should continue until we achieve sufficient confidence in the credibility and acceptability of the results. The sufficiency of the confidence is dictated by the study objectives."

The models presented within this thesis were developed to establish whether it is possible to model construction activities, demonstrate a methodology for rapidly developing simulation models and to determine which of several equipment configurations would provide the most effective use of resources. The objective was not to determine the precise level of output attainable, and hence the level of detail and amount of validation required is significantly less. The following example is used to enhance the validity of the simulation modules can be illustrate their use.

5.13.1 MATHEMATICAL MODEL

It could be argued that a simulation model should be validated against the output-achieved on a physical site. However, the purpose of developing a simulation model is to enable output to be predicted. Hence, if a model builder waited until excavation had finished before establishing the validity of the model, then the model would be of little value, hence an alternative method of validating the model was sought.

It is proposed that the validity of the simulation model be determined using a mathematical model. Paulson (1995) concurs with this view stating that, "for systems that are planned for the future – as is typical when estimating new work – the model results can still be compared with conventional deterministic calculations, and be modified with efficiency or contingency factors as appropriate. Significant differences in model behaviour should be accounted for, and modifications and resetting may be necessary." Hence mathematical and simulation models of an actual construction site shall be developed, experiments performed, with the results evaluated to determine the validity of the modules.

The main contractor for the construction of the A1-M1 link-road wished to establish the extent that output would be affected under the following operating conditions.

- Using either manned or automatic haul-route crossings.
- Using either a restrictive one-at-a-time bridge or a non-restrictive bridge.

- Also, it is not always feasible to obtain the desired number of identical trucks. Therefore, additional experiments are performed to determine how output is affected if a smaller, D300, truck is used to supplement the fleet.

The haul route consists of four crossings and a single bridge as illustrated in Figure 66.

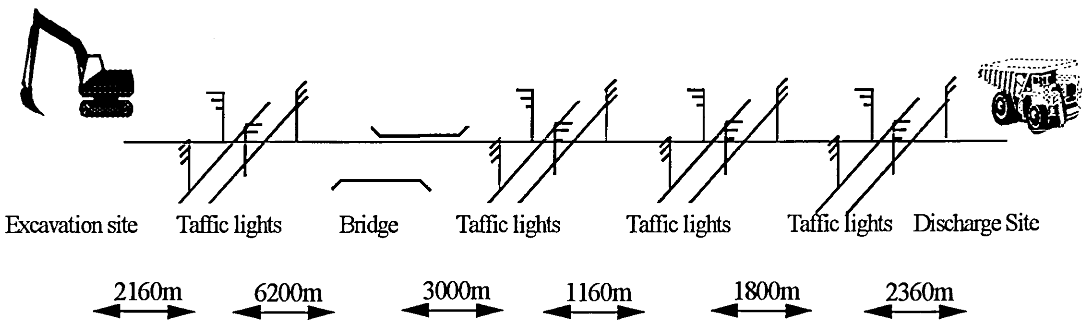

Figure 66 Illustration of haul route

Although the complexity of a mathematical model could be almost infinite, this is not what tends to happen. As the planner tends to revert "to simple calculations…and applying efficiency factors to make the answers come out closer to reality", Paulson (1995). Hence the mathematical model shall be constructed using equations 1 and 2 presented earlier within this thesis.

The number of trucks required is determined from dividing the trucks' work cycle by the length of time required to fill the truck with material. Thus the length of time required for a D400 to complete a single work cycle equals the time required to excavate and fill the truck, plus the time required to haul the material to the excavation site, discharge it and return empty to the excavators.

N.B. When calculating the time required for travelling to and from the excavation site the effect of both bridges and traffic lights should be taken into consideration.

Thus, the number of trucks required = duration of trucks work cycle / loading time.

Duration of trucks work-cycle = 4045.96 seconds

Loading time = 194.79 seconds

Number of trucks required = 20.77

Excavator utilisation is calculated by dividing the number of available trucks by the ideal number of trucks.

E.g.

Utilisation of Excavator with 20 trucks = 20 / 20.77 = 96%

And with 21 or more trucks the Excavators' Utilisation = 100%

Thus the utilisation of the excavator for any number of trucks can be estimated. A graph comparing the mathematically estimated utilisation against a simulation model is plotted in Figure 68. However, a mathematical model assumes that resources are always in the correct location at the correct time, with neither congestion nor trucks queuing waiting to be filled by the excavator. This is an idealistic and hence unrealistic assumption; thus efficiency factors are often used to amend the results. When there is just one truck available there can be neither, congestion along the haul-road nor queuing at the excavator. Hence, the quantity of material excavated and hauled should be identical for both the mathematical and simulation model, providing that the results from the simulation model are taken during steady state. (The explanation of steady and transient behaviour can be found in section 4.3.1.)

5.14 SIMULATION MODEL DEVELOPMENT AND VALIDATION

Using the generic modules developed within this chapter, a simulation model of the physical haul route is constructed. Modules are taken from the tab bar and placed on the model building screen. The excavation site is placed first, followed by a length of haul road. The traffic light, bridge and haul road modules are placed one after another until the haul route is complete. Finally, a discharge module is placed, Figure 67. Each module is opened in tern. Data is entered, transforming the generic modules into a site-specific simulation model.

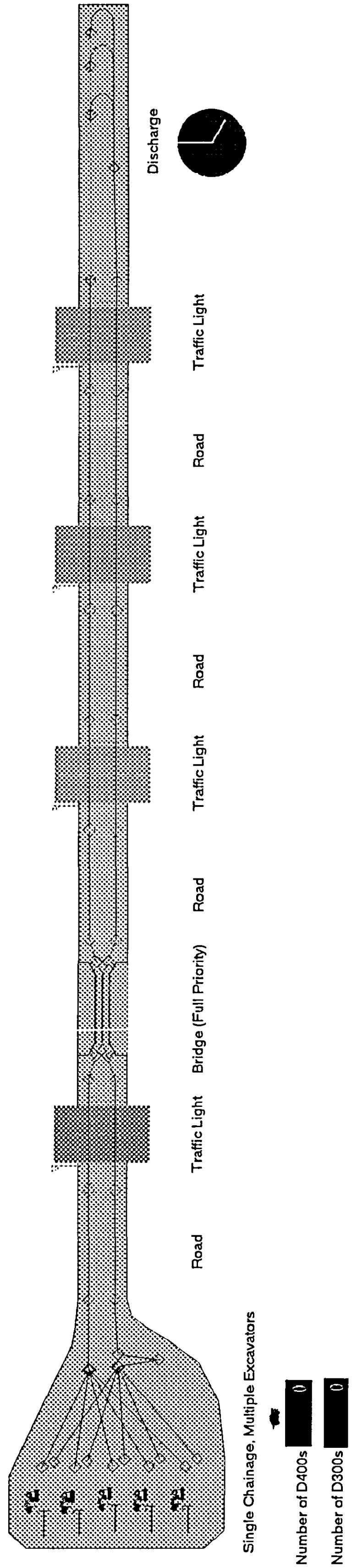

Figure 67 Complete model

With data entered the simulation model development is complete. Upon running the model ARENA checks that the logic and data entered is valid. If there is an error, it may well result from adjacent chainage numbers not matching. The data should be amended and model re-compiled. Using an excavator and a single truck the simulation model is run and results recorded during steady state. As a rule of thumb, a simulation experiment should be replicated three or more times. If there is a significant difference between the results, the model should be replicated until an average can be calculated.

When a single truck is used, the utilisation of the excavator is 4.227%, 4.214% and 4.225%, for the first, second and third replication, with the mathematical model estimating 4.814%. As the number of trucks available increases so does the amount of queuing within the system, hence the results from the two models diverge. The more trucks that are added the less the impact congestion has on the excavator's utilisation, hence the results converge.

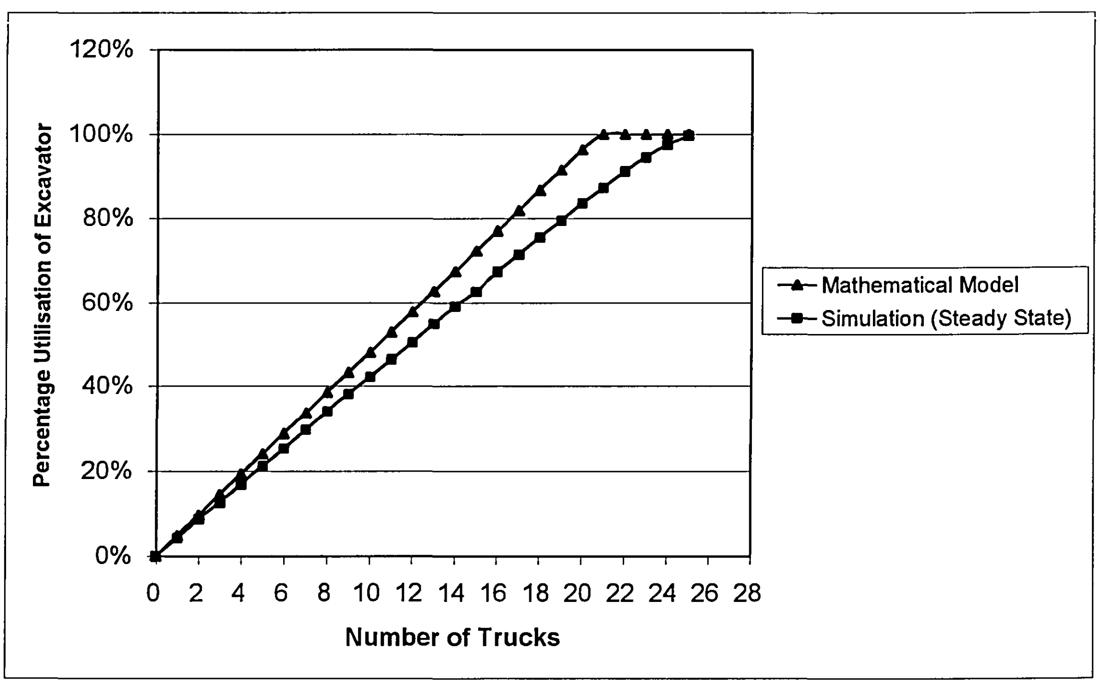

Figure 68 Comparison between mathematical and steady state simulation model

Even though the simulation results were recorded during steady state the mathematical model consistently over estimates the output attainable because the mathematical model cannot accurately determine the congestion induced by the traffic lights, Bailey bridge or process variability. When a single truck is used the output estimated using the simulation model and mathematical model are the very similar. Also, as the number of trucks available increase the results both diverge and converge as anticipated. Hence, the simulation model is considered to be sufficiently valid to enable comparative studies to be performed. However, construction sites tend to operate solely during day light hours and as such the results should actually take into account the transient period.

5.14.1 EXPERIMENTATION

It is assumed throughout these experiments that a single excavator services the articulated trucks; and that the duration of the shift is ten hours with two hours output lost to breaks, hence the actual productive time is eight hours.

Four scenarios are modelled. For each scenario the configuration of the haul road was modified. The experiments were performed as per Table 17 with the traffic lights alternated between automatic and manual, and the bridge from unidirectional to bi-directional. For the first scenario, trucks are allowed to cross the bridge one at a time, with priority given to full trucks. In addition, the haul route crossings are operated automatically by sensing the presence of a truck. For the second, the bi-directional replaces the unidirectional bridge, with the lights remaining automatic. With the manual crossing replacing the automatic crossing for the third and fourth scenarios.

Scenario	Bridge type	Type of Haul route crossing	Number of trucks
1	Unidirectional, one truck at a time	Automatic	18 - 26
2	Bi-directional, unlimited	Automatic	18 – 26
3	Unidirectional, one truck at a time	Manned	18 - 26
4	Bi-directional, unlimited	Manned	18 – 26

Table 17 Table of experiments

5.14.2 COMPARISON OF RESULTS BETWEEN MATHEMATICAL AND SIMULATION MODELS.

Earlier within this chapter, the simulation model was validated using a mathematical model with output determined during steady state. However, a construction site may have a long transient period, which reduces the output attainable. Plotting the excavators' utilisation determined mathematically against that predicted using simulation, Figure 69, clearly shows that the mathematical model consistently over estimates the output attainable in some cases by as much as 20%.

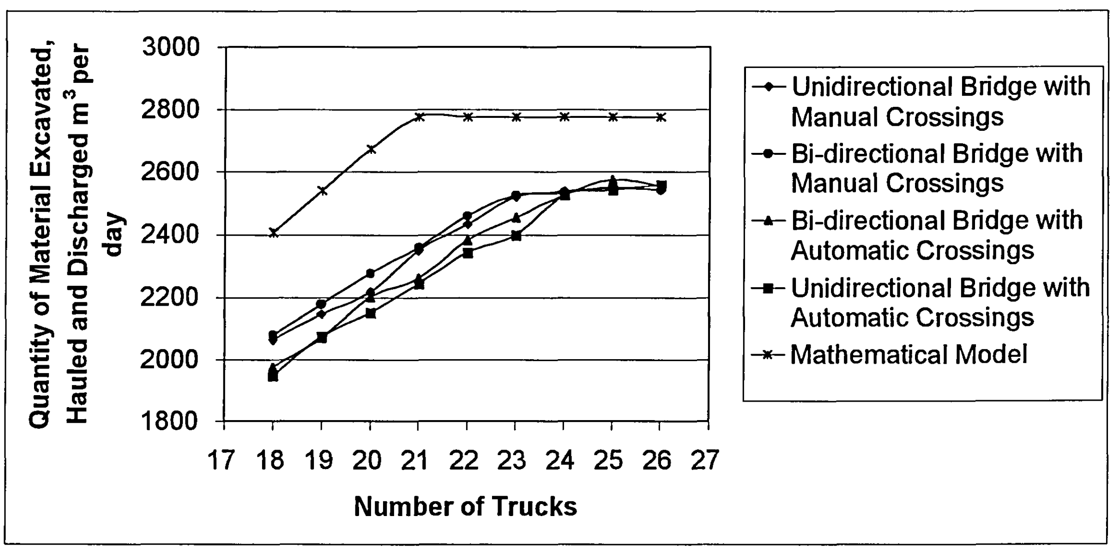

Figure 69 Utilisation of the excavator against operating policies

For the majority of experiments, results illustrate that there is little difference between using either a unidirectional or a bi-directional bridge. With the greatest, 3% difference in output occurring when 20 articulated trucks are used in conjunction with manual crossings.

Using manned as opposed to automatic crossings improves system output especially when there is less than the optimum number of trucks available. Since automatic crossings tend not to sense the presence of trucks far enough in advance, the trucks have to slow or stop at the crossing. Hence, the trucks work-cycle is longer when automatic rather than manned crossings are used. Thus, more trucks are required to achieve output using automatic as opposed to manned crossings.

In an ideal world equipment would not breakdown and there would always be sufficient identical resources to undertake any task. However, the construction industry does not operate in such an environment. Site-foreman are often faced with, either operating with fewer trucks than desired or using trucks with different characteristics. Simulation enables the effect of mixing fleet characteristics to be evaluated.

As an example, assume that only 20 D400's are available and one D300. The site-foreman wished to establish whether it is preferable to use every available truck or will mixing the fleet creates excessive congestion, eradicating the benefit of utilising the additional truck.

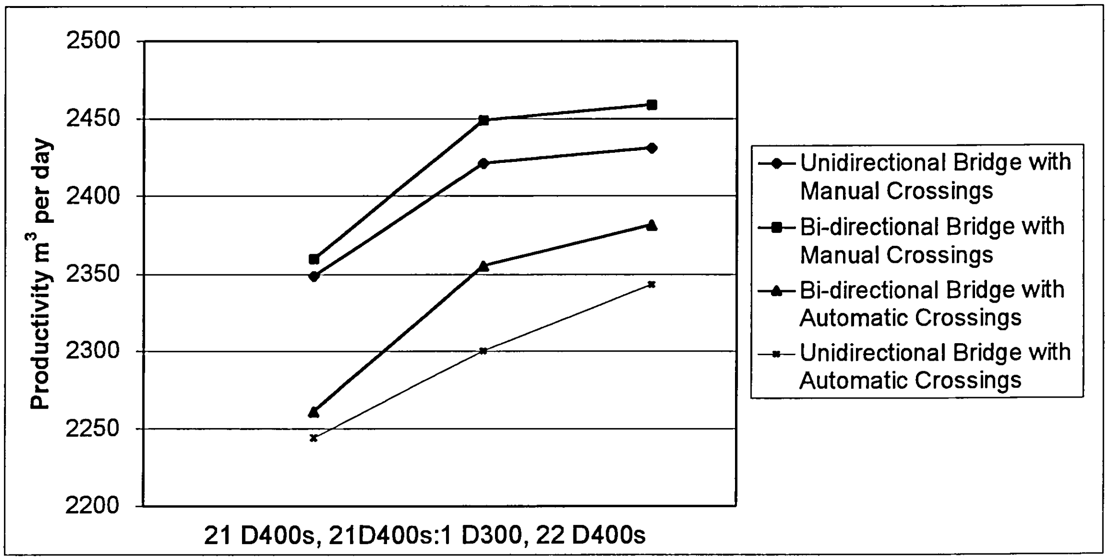

Figure 70 Output

When 22 identical trucks are used the output is greater than would have been attained through using a mixed fleet totalling the same number of trucks. When non-identical trucks are employed, congestion increases with a consequential reduction in output. However, the system is still more productive than had the smaller D300 not been used. Hence, in these scenarios it is preferable to utilise all the available resources.

5.14.3 EXPERIMENTAL CONCLUSIONS

The comparative ease with which a simulation model can be developed using the set of predefined modules as opposed to using individual modeling elements has been demonstrated. The conceptual validity of the modules has been further enhanced through demonstrating that both the mathematical and simulation models produce comparable results during steady state when a single truck is used. In addition, congestion increases proportional to the number of trucks the system. Again, this concurs with the modelers expectations. Hence, the modules were considered sufficiently valid to perform comparative studies.

A number of additional experiments have been performed with the results presented and interpreted. For the scenario modelled, the experiments established that there is little difference between using a unidirectional or bi-directional bridge. However, the results of these experiments should not be taken to imply that a unidirectional bridge is always preferable to the more expensive bi-directional bridge. Since the choice of bridge is influenced by the availability of other resources and the nature of the haul road. Typically it is more expensive to man, than automate haul route crossings. Thus unless it is imperative that the trucks are not delayed at each crossing than it is preferable to use automatic crossings.

Using non-identical trucks causes congestion, with a consequential loss of output. However, the reduction in output is less than had the smaller truck not been used. The results further demonstrate the necessity of using simulation to determine and evaluate the output attainable under different resource configurations.

5.15 SUMMARY AND CONCLUSIONS TO CHAPTER

To simplify the model building process it was proposed that generic models were developed. The previous chapter identified the factors that are significant in earthmoving. In this chapter, data were collected on the significant factors with those factors included in the modules.

Simulation module and model building is an iterative process. The better our understanding of the system the more refined our objectives become. As new production methods are explored, the modules evolve until the most commonly encountered problems can be successfully modelled with minimal modification of model logic. The modules presented are the result of this iterative process. The stages involved in the module building process are documented.

The communicative model develops until all parties agree that the model is representative of the system. Once completed the communicative model is translated into computer code. Animation provides an invaluable tool to aid communication of the modules. The programmer benefits by enabling the movement of entities to be traced through the model with programming errors more easily identified. Animation also assists in communicating the model to site personnel by reducing the level of abstraction. Through allowing them to see the excavation area, haul route, discharge site with resources moving from one location to another.
Each module is validated, verified and tested throughout its development using a selection of techniques suggested by Balci (1994). Often validation consisted of tracing the movement of the entities, using static unitary process durations and comparing output against mathematical calculations. For each of the modules a communicative model was presented, programming logic documented, animation provided, with prompts and remarks given. The chapter concluded with an illustrative example of how a complex scenario can be modelled using the modules. The results were compared with those from a mathematical model further enhancing the conceptual validity of the modules and illustrating the limitations of modelling construction sites using mathematics.

Conclusions drawn from the work undertaken within this chapter.

- It is feasible to discretise road construction operations for earthworks, enabling the development of generic building blocks for modelling specific construction scenarios.

- Some of the criticisms levelled at simulation have been eroded through;
    - ♦ Modularising road construction operations. This significantly reduces the length of time and degree of computer literacy required for developing a working simulation model.
    - ♦ Process data are transferable from one site to another. Excavation cycle times and truck velocities are predictable providing influential factors can be determined. Thus a database of resources and their characteristics should be developed.
    - ♦ Use of animation reduces the level of abstraction. With the appearance of the simulation model representative of what occurs on site. A graphical front-end and animation of resources assists in communicating the model to other members of staff.

- Site specific models can be rapidly developed using modules. This enables a greater proportion of the time available to be spent experimenting with the model and interpreting the results.

6 Conclusions and Recommendations

6.1 INTRODUCTION

This chapter contains a summary of the main conclusions drawn from the work described within this thesis. The purpose of this research was to:

- Assess the benefits of using dynamic as opposed to static planning tools within the construction industry.
- Establish an appropriate methodology for modelling earthworks for road construction.
- Identify which factors influence the output of road construction sites via simulation.
- Develop a means of accelerating the model building process.

The literature survey highlighted the inadequacy of the planning techniques currently utilised within the construction industry. Simulation was identified as a means of achieving greater efficiency through incorporating the dynamics present in construction activities. Areas previously explored using simulation were documented, with reasons cited for industry's reluctance to adopt the technology.

It was demonstrated in chapter 3 that simulation can be used, in earthworks for road construction, to estimate the resources required and the improved output achievable under different operating conditions. Three methodologies for modelling road construction operations were investigated; activity cycle, process and event based simulation. The most appropriate, process based simulation, was selected for the development of future models based upon the comparative ease that complex model can be developed, coupled with functionality ARENA which is based on this methodology.

A greater understanding of the factors affecting earthworks was obtained through performing factor analysis. The main and higher order interactions between factors were identified, with a more detailed study of important influential factors undertaken. Studying these factors enabled efficient allocation of resources for the collection of significant data.

The stages involved in developing the modules are documented providing a simulation model builder with an in-depth methodology for the development of further modules. Data were collected on significant factors, with those factors previously disregarded incorporated into these modules. An example of how the modules can be used to rapidly develop an innovative working simulation model of earthworks is presented.

6.2 CONTRIBUTION TO KNOWLEDGE

This section provides a précis of the major contributions to knowledge documented within this thesis.

- *The factors affecting the efficiency of haulage in earthworks were identified. The main effects and interaction between factors were determined, with an appropriate level of detail established for two of the most significant factors.*

- *The necessity of developing industry-specific modelling constructs for rapid model development has been substantiated.*

Both of the above statements are elaborated below:

6.2.1 CRITICAL FACTORS

- *The factors affecting the efficiency of haulage in earthworks were identified. The main effects and interaction between factors were determined, with an appropriate level of detail established for two of the most significant factors.*

Factor analysis was used to ascertain the individual and combined effect of each factor, as demonstrated in chapter 4. It was established that not all factors are independent. For example:

- Increasing the number of available trucks increases output by different amounts depending on the length of the haul road.
- The length and condition of the haul road, the number of trucks, and the type of material to be excavated are typically the most important factors. It is these factors that the site supervisor and model builder should observe to ensure that the desired output is achieved.
- It was found that the 'length of the haul road' was the most important factor to affect output and modelling the system as 'nonterminating or terminating' had the greatest influence on model run time.

Significant factors can be modelled in varying degrees of detail. Thus, further experiments were devised and performed investigating how output is affected by increasing the validity of the model with reality.

A simulation model can be classified as either terminating or nonterminating. This is investigated in section 4.3.1. Since earthworks typically start at dawn and end at dusk they are considered to be terminating. If work progresses 24 hours per day it would be considered to be nonterminating. The difference between the two is due to the length of the warm-up period as examined in chapter 4. Its effect on output is proportional to the duration of the trucks' work-cycle and inversely proportional to the length of the day.

Further analysis of the factor 'length of the haul road', section 4.4, established that modelling the haul road as though its length remains constant produces less accurate results than modelling it as though it consists of multiple chainages. The difference is most pronounced when the ratio of excavation length to haul length is large; when this is the case it is preferable to model the excavation area as a series of chainages. The number of trucks required is calculated using the ratio of trucks to excavator's work-cycle time. When the haul length is small, a minor increase in haul length significantly increases the duration of a truck's work-cycle and therefore the optimum number of trucks.

6.2.2 ROAD CONSTRUCTION SPECIFIC MODEL

- *The necessity of developing industry-specific modelling constructs for rapid model development has been substantiated.*

The literature survey established that simulation is not widely utilised within the construction industry. One of the reasons sited was that simulation models are time consuming to develop and the data collected are not reusable. To increase the utilisation of simulation it was proposed that, where possible, construction processes be discretised into reusable modules. Chapter 5 documents the methodology employed in capturing operational logic, recording process duration's for the significant factors and constructing innovative simulation modules.

Each module is self-contained, comprising of operational logic, a data entry form and an animated front-end. They may be placed in any order so that a realistic representation of the complexities involved in hauling material can be obtained. The stages involved in the model building cycle are documented with the method for creating new modules illustrated. For each module the significant logic was defined, data collected, and module validated. The method for constructing a simulation model from the generic modules and determining an appropriate resource allocation is presented.

Within section 5.13 simulation and mathematical models are constructed for a physical construction site. The validity of each module is determined, with comparisons drawn between the results from the two models. At worse the mathematical model, because of its inability to incorporate complex interactions between resources, over estimated output by 20%, section 5.14.2, compared to that predicted using the simulation model constructed from the generic modules.

6.3 RECOMMENDATIONS FOR FUTURE WORK

The programme of research documented within this thesis has focused upon a specific sector of the construction industry, namely earthworks for road construction. However, earthworks form but one part of a construction project. Hence, further research should be undertaken to identify where simulation could be applied within the lifecycle of a construction project. This in turn would increase the scope of simulation to encompass other repetitive processes such as house construction.

A logical progression from this research project would be to increase the boundary of simulation within road construction. This section highlights the form that such research would take. To date, models have been developed where material is transported using articulated dumper trucks. This type of truck is typically used for transporting material where the haul distance is between 500 and 3500m. If the quantity of material and the length of the haul road are large then motor scrapers can be used as an alternative. Therefore, to increase the variety of scenarios that may be modelled, different types of equipment could be made available within the modules. To enhance the functionality of the modules, financial data should also be incorporated; enabling decisions to be made based on cost as well as project duration and resource utilisation.

To enable the modules to predict output with greater accuracy over a broader range of operational conditions, additional data should be collected from other construction sites and incorporated into the modules. Thus far, it has been assumed that the performance of the operators and equipment remains constant both over the duration of a working shift and a project. The effect of deteriorating performance should be investigated further, together with the effect of equipment breakdowns on output. To date, modules have been developed for excavation, transportation and discharge of excavated material. There are numerous other road construction processes that are cyclic and repetitive, e.g. kerb, pipe or sub-base laying, which could be successfully modelled using this methodology. Modularising these processes in a similar manner to earthmoving would also improve the allocation of resources. Although this research has highlighted the benefit and a suitable method for the rapid development of simulation models within the construction industry, construction companies are still largely unaware of the potential for using simulation as a decision making tool. To increase the awareness and use of simulation within construction, simulation should be applied to a number of high profile construction projects, and the results widely disseminated.

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Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
Experiment Number										
1	-	-	-	-	-	-	-	-	-	-
2	+	-	-	-	-	-	-	-	-	-
3	-	+	-	-	-	-	-	-	-	-
4	+	+	-	-	-	-	-	-	-	-
5	-	-	+	-	-	-	-	-	-	-
6	+	-	+	-	-	-	-	-	-	-
7	-	+	+	-	-	-	-	-	-	-
8	+	+	+	-	-	-	-	-	-	-
9	-	-	-	+	-	-	-	-	-	-
10	+	-	-	+	-	-	-	-	-	-
11	-	+	-	+	-	-	-	-	-	-
12	+	+	-	+	-	-	-	-	-	-
13	-	-	+	+	-	-	-	-	-	-
14	+	-	+	+	-	-	-	-	-	-
15	-	+	+	+	-	-	-	-	-	-
16	+	+	+	+	-	-	-	-	-	-
17	-	-	-	-	+	-	-	-	-	-
18	+	-	-	-	+	-	-	-	-	-
19	-	+	-	-	+	-	-	-	-	-
20	+	+	-	-	+	-	-	-	-	-
21	-	-	+	-	+	-	-	-	-	-
22	+	-	+	-	+	-	-	-	-	-
23	-	+	+	-	+	-	-	-	-	-
24	+	+	+	-	+	-	-	-	-	-
25	-	-	-	+	+	-	-	-	-	-
26	+	-	-	+	+	-	-	-	-	-
27	-	+	-	+	+	-	-	-	-	-
28	+	+	-	+	+	-	-	-	-	-
29	-	-	+	+	+	-	-	-	-	-
30	+	-	+	+	+	-	-	-	-	-
31	-	+	+	+	+	-	-	-	-	-
32	+	+	+	+	+	-	-	-	-	-
33	-	-	-	-	-	+	-	-	-	-
34	+	-	-	-	-	+	-	-	-	-
35	-	+	-	-	-	+	-	-	-	-
36	+	+	-	-	-	+	-	-	-	-
37	-	-	+	-	-	+	-	-	-	-
38	+	-	+	-	-	+	-	-	-	-
39	-	+	+	-	-	+	-	-	-	-
40	+	+	+	-	-	+	-	-	-	-
41	-	-	-	+	-	+	-	-	-	-
42	+	-	-	+	-	+	-	-	-	-
43	-	+	-	+	-	+	-	-	-	-
44	+	+	-	+	-	+	-	-	-	-
45	-	-	+	+	-	+	-	-	-	-
46	+	-	+	+	-	+	-	-	-	-
47	-	+	+	+	-	+	-	-	-	-
48	+	+	+	+	-	+	-	-	-	-
49	-	-	-	-	+	+	-	-	-	-
50	+	-	-	-	+	+	-	-	-	-
51	-	+	-	-	+	+	-	-	-	-
52	+	+	-	-	+	+	-	-	-	-
53	-	-	+	-	+	+	-	-	-	-

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
54	+	-	+	-	+	+	-	-	-	-
55	-	+	+	-	+	+	-	-	-	-
56	+	+	+	-	+	+	-	-	-	-
57	-	-	-	+	+	+	-	-	-	-
58	+	-	-	+	+	+	-	-	-	-
59	-	+	-	+	+	+	-	-	-	-
60	+	+	-	+	+	+	-	-	-	-
61	-	-	+	+	+	+	-	-	-	-
62	+	-	+	+	+	+	-	-	-	-
63	-	+	+	+	+	+	-	-	-	-
64	+	+	+	+	+	+	-	-	-	-
65	-	-	-	-	-	-	+	-	-	-
66	+	-	-	-	-	-	+	-	-	-
67	-	+	-	-	-	-	+	-	-	-
68	+	+	-	-	-	-	+	-	-	-
69	-	-	+	-	-	-	+	-	-	-
70	+	-	+	-	-	-	+	-	-	-
71	-	+	+	-	-	-	+	-	-	-
72	+	+	+	-	-	-	+	-	-	-
73	-	-	-	+	-	-	+	-	-	-
74	+	-	-	+	-	-	+	-	-	-
75	-	+	-	+	-	-	+	-	-	-
76	+	+	-	+	-	-	+	-	-	-
77	-	-	+	+	-	-	+	-	-	-
78	+	-	+	+	-	-	+	-	-	-
79	-	+	+	+	-	-	+	-	-	-
80	+	+	+	+	-	-	+	-	-	-
81	-	-	-	-	+	-	+	-	-	-
82	+	-	-	-	+	-	+	-	-	-
83	-	+	-	-	+	-	+	-	-	-
84	+	+	-	-	+	-	+	-	-	-
85	-	-	+	-	+	-	+	-	-	-
86	+	-	+	-	+	-	+	-	-	-
87	-	+	+	-	+	-	+	-	-	-
88	+	+	+	-	+	-	+	-	-	-
89	-	-	-	+	+	-	+	-	-	-
90	+	-	-	+	+	-	+	-	-	-
91	-	+	-	+	+	-	+	-	-	-
92	+	+	-	+	+	-	+	-	-	-
93	-	-	+	+	+	-	+	-	-	-
94	+	-	+	+	+	-	+	-	-	-
95	-	+	+	+	+	-	+	-	-	-
96	+	+	+	+	+	-	+	-	-	-
97	-	-	-	-	-	+	+	-	-	-
98	+	-	-	-	-	+	+	-	-	-
99	-	+	-	-	-	+	+	-	-	-
100	+	+	-	-	-	+	+	-	-	-
101	-	-	+	-	-	+	+	-	-	-
102	+	-	+	-	-	+	+	-	-	-
103	-	+	+	-	-	+	+	-	-	-
104	+	+	+	-	-	+	+	-	-	-
105	-	-	-	+	-	+	+	-	-	-
106	+	-	-	+	-	+	+	-	-	-
107	-	+	-	+	-	+	+	-	-	-
108	+	+	-	+	-	+	+	-	-	-

	Experimental Factors									
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
109	-	-	+	+	-	+	+	-	-	-
110	+	-	+	+	-	+	+	-	-	-
111	-	+	+	+	-	+	+	-	-	-
112	+	+	+	+	-	+	+	-	-	-
113	-	-	-	-	+	+	+	-	-	-
114	+	-	-	-	+	+	+	-	-	-
115	-	+	-	-	+	+	+	-	-	-
116	+	+	-	-	+	+	+	-	-	-
117	-	-	+	-	+	+	+	-	-	-
118	+	-	+	-	+	+	+	-	-	-
119	-	+	+	-	+	+	+	-	-	-
120	+	+	+	-	+	+	+	-	-	-
121	-	-	-	+	+	+	+	-	-	-
122	+	-	-	+	+	+	+	-	-	-
123	-	+	-	+	+	+	+	-	-	-
124	+	+	-	+	+	+	+	-	-	-
125	-	-	+	+	+	+	+	-	-	-
126	+	-	+	+	+	+	+	-	-	-
127	-	+	+	+	+	+	+	-	-	-
128	+	+	+	+	+	+	+	-	-	-
129	-	-	-	-	-	-	-	+	-	-
130	+	-	-	-	-	-	-	+	-	-
131	-	+	-	-	-	-	-	+	-	-
132	+	+	-	-	-	-	-	+	-	-
133	-	-	+	-	-	-	-	+	-	-
134	+	-	+	-	-	-	-	+	-	-
135	-	+	+	-	-	-	-	+	-	-
136	+	+	+	-	-	-	-	+	-	-
137	-	-	-	+	-	-	-	+	-	-
138	+	-	-	+	-	-	-	+	-	-
139	-	+	-	+	-	-	-	+	-	-
140	+	+	-	+	-	-	-	+	-	-
141	-	-	+	+	-	-	-	+	-	-
142	+	-	+	+	-	-	-	+	-	-
143	-	+	+	+	-	-	-	+	-	-
144	+	+	+	+	-	-	-	+	-	-
145	-	-	-	-	+	-	-	+	-	-
146	+	-	-	-	+	-	-	+	-	-
147	-	+	-	-	+	-	-	+	-	-
148	+	+	-	-	+	-	-	+	-	-
149	-	-	+	-	+	-	-	+	-	-
150	+	-	+	-	+	-	-	+	-	-
151	-	+	+	-	+	-	-	+	-	-
152	+	+	+	-	+	-	-	+	-	-
153	-	-	-	+	+	-	-	+	-	-
154	+	-	-	+	+	-	-	+	-	-
155	-	+	-	+	+	-	-	+	-	-
156	+	+	-	+	+	-	-	+	-	-
157	-	-	+	+	+	-	-	+	-	-
158	+	-	+	+	+	-	-	+	-	-
159	-	+	+	+	+	-	-	+	-	-
160	+	+	+	+	+	-	-	+	-	-
161	-	-	-	-	-	+	-	+	-	-
162	+	-	-	-	-	+	-	+	-	-
163	-	+	-	-	-	+	-	+	-	-

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
164	+	+	-	-	-	+	-	+	-	-
165	-	-	+	-	-	+	-	+	-	-
166	+	-	+	-	-	+	-	+	-	-
167	-	+	+	-	-	+	-	+	-	-
168	+	+	+	-	-	+	-	+	-	-
169	-	-	-	+	-	+	-	+	-	-
170	+	-	-	+	-	+	-	+	-	-
171	-	+	-	+	-	+	-	+	-	-
172	+	+	-	+	-	+	-	+	-	-
173	-	-	+	+	-	+	-	+	-	-
174	+	-	+	+	-	+	-	+	-	-
175	-	+	+	+	-	+	-	+	-	-
176	+	+	+	+	-	+	-	+	-	-
177	-	-	-	-	+	+	-	+	-	-
178	+	-	-	-	+	+	-	+	-	-
179	-	+	-	-	+	+	-	+	-	-
180	+	+	-	-	+	+	-	+	-	-
181	-	-	+	-	+	+	-	+	-	-
182	+	-	+	-	+	+	-	+	-	-
183	-	+	+	-	+	+	-	+	-	-
184	+	+	+	-	+	+	-	+	-	-
185	-	-	-	+	+	+	-	+	-	-
186	+	-	-	+	+	+	-	+	-	-
187	-	+	-	+	+	+	-	+	-	-
188	+	+	-	+	+	+	-	+	-	-
189	-	-	+	+	+	+	-	+	-	-
190	+	-	+	+	+	+	-	+	-	-
191	-	+	+	+	+	+	-	+	-	-
192	+	+	+	+	+	+	-	+	-	-
193	-	-	-	-	-	-	+	+	-	-
194	+	-	-	-	-	-	+	+	-	-
195	-	+	-	-	-	-	+	+	-	-
196	+	+	-	-	-	-	+	+	-	-
197	-	-	+	-	-	-	+	+	-	-
198	+	-	+	-	-	-	+	+	-	-
199	-	+	+	-	-	-	+	+	-	-
200	+	+	+	-	-	-	+	+	-	-
201	-	-	-	+	-	-	+	+	-	-
202	+	-	-	+	-	-	+	+	-	-
203	-	+	-	+	-	-	+	+	-	-
204	+	+	-	+	-	-	+	+	-	-
205	-	-	+	+	-	-	+	+	-	-
206	+	-	+	+	-	-	+	+	-	-
207	-	+	+	+	-	-	+	+	-	-
208	+	+	+	+	-	-	+	+	-	-
209	-	-	-	-	+	-	+	+	-	-
210	+	-	-	-	+	-	+	+	-	-
211	-	+	-	-	+	-	+	+	-	-
212	+	+	-	-	+	-	+	+	-	-
213	-	-	+	-	+	-	+	+	-	-
214	+	-	+	-	+	-	+	+	-	-
215	-	+	+	-	+	-	+	+	-	-
216	+	+	+	-	+	-	+	+	-	-
217	-	-	-	+	+	-	+	+	-	-
218	+	-	-	+	+	-	+	+	-	-

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
219	-	+	-	+	+	-	+	+	-	-
220	+	+	-	+	+	-	+	+	-	-
221	-	-	+	+	+	-	+	+	-	-
222	+	-	+	+	+	-	+	+	-	-
223	-	+	+	+	+	-	+	+	-	-
224	+	+	+	+	+	-	+	+	-	-
225	-	-	-	-	-	+	+	+	-	-
226	+	-	-	-	-	+	+	+	-	-
227	-	+	-	-	-	+	+	+	-	-
228	+	+	-	-	-	+	+	+	-	-
229	-	-	+	-	-	+	+	+	-	-
230	+	-	+	-	-	+	+	+	-	-
231	-	+	+	-	-	+	+	+	-	-
232	+	+	+	-	-	+	+	+	-	-
233	-	-	-	+	-	+	+	+	-	-
234	+	-	-	+	-	+	+	+	-	-
235	-	+	-	+	-	+	+	+	-	-
236	+	+	-	+	-	+	+	+	-	-
237	-	-	+	+	-	+	+	+	-	-
238	+	-	+	+	-	+	+	+	-	-
239	-	+	+	+	-	+	+	+	-	-
240	+	+	+	+	-	+	+	+	-	-
241	-	-	-	-	+	+	+	+	-	-
242	+	-	-	-	+	+	+	+	-	-
243	-	+	-	-	+	+	+	+	-	-
244	+	+	-	-	+	+	+	+	-	-
245	-	-	+	-	+	+	+	+	-	-
246	+	-	+	-	+	+	+	+	-	-
247	-	+	+	-	+	+	+	+	-	-
248	+	+	+	-	+	+	+	+	-	-
249	-	-	-	+	+	+	+	+	-	-
250	+	-	-	+	+	+	+	+	-	-
251	-	+	-	+	+	+	+	+	-	-
252	+	+	-	+	+	+	+	+	-	-
253	-	-	+	+	+	+	+	+	-	-
254	+	-	+	+	+	+	+	+	-	-
255	-	+	+	+	+	+	+	+	-	-
256	+	+	+	+	+	+	+	+	-	-
257	-	-	-	-	-	-	-	-	+	-
258	+	-	-	-	-	-	-	-	+	-
259	-	+	-	-	-	-	-	-	+	-
260	+	+	-	-	-	-	-	-	+	-
261	-	-	+	-	-	-	-	-	+	-
262	+	-	+	-	-	-	-	-	+	-
263	-	+	+	-	-	-	-	-	+	-
264	+	+	+	-	-	-	-	-	+	-
265	-	-	-	+	-	-	-	-	+	-
266	+	-	-	+	-	-	-	-	+	-
267	-	+	-	+	-	-	-	-	+	-
268	+	+	-	+	-	-	-	-	+	-
269	-	-	+	+	-	-	-	-	+	-
270	+	-	+	+	-	-	-	-	+	-
271	-	+	+	+	-	-	-	-	+	-
272	+	+	+	+	-	-	-	-	+	-
273	-	-	-	-	+	-	-	-	+	-

	Experimental Factors									
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
274	+	-	-	-	+	-	-	-	+	-
275	-	+	-	-	+	-	-	-	+	-
276	+	+	-	-	+	-	-	-	+	-
277	-	-	+	-	+	-	-	-	+	-
278	+	-	+	-	+	-	-	-	+	-
279	-	+	+	-	+	-	-	-	+	-
280	+	+	+	-	+	-	-	-	+	-
281	-	-	-	+	+	-	-	-	+	-
282	+	-	-	+	+	-	-	-	+	-
283	-	+	-	+	+	-	-	-	+	-
284	+	+	-	+	+	-	-	-	+	-
285	-	-	+	+	+	-	-	-	+	-
286	+	-	+	+	+	-	-	-	+	-
287	-	+	+	+	+	-	-	-	+	-
288	+	+	+	+	+	-	-	-	+	-
289	-	-	-	-	-	+	-	-	+	-
290	+	-	-	-	-	+	-	-	+	-
291	-	+	-	-	-	+	-	-	+	-
292	+	+	-	-	-	+	-	-	+	-
293	-	-	+	-	-	+	-	-	+	-
294	+	-	+	-	-	+	-	-	+	-
295	-	+	+	-	-	+	-	-	+	-
296	+	+	+	-	-	+	-	-	+	-
297	-	-	-	+	-	+	-	-	+	-
298	+	-	-	+	-	+	-	-	+	-
299	-	+	-	+	-	+	-	-	+	-
300	+	+	-	+	-	+	-	-	+	-
301	-	-	+	+	-	+	-	-	+	-
302	+	-	+	+	-	+	-	-	+	-
303	-	+	+	+	-	+	-	-	+	-
304	+	+	+	+	-	+	-	-	+	-
305	-	-	-	-	+	+	-	-	+	-
306	+	-	-	-	+	+	-	-	+	-
307	-	+	-	-	+	+	-	-	+	-
308	+	+	-	-	+	+	-	-	+	-
309	-	-	+	-	+	+	-	-	+	-
310	+	-	+	-	+	+	-	-	+	-
311	-	+	+	-	+	+	-	-	+	-
312	+	+	+	-	+	+	-	-	+	-
313	-	-	-	+	+	+	-	-	+	-
314	+	-	-	+	+	+	-	-	+	-
315	-	+	-	+	+	+	-	-	+	-
316	+	+	-	+	+	+	-	-	+	-
317	-	-	+	+	+	+	-	-	+	-
318	+	-	+	+	+	+	-	-	+	-
319	-	+	+	+	+	+	-	-	+	-
320	+	+	+	+	+	+	-	-	+	-
321	-	-	-	-	-	-	+	-	+	-
322	+	-	-	-	-	-	+	-	+	-
323	-	+	-	-	-	-	+	-	+	-
324	+	+	-	-	-	-	+	-	+	-
325	-	-	+	-	-	-	+	-	+	-
326	+	-	+	-	-	-	+	-	+	-
327	-	+	+	-	-	-	+	-	+	-
328	+	+	+	-	-	-	+	-	+	-

	Experimental Factors									
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
329	-	-	-	+	-	-	+	-	+	-
330	+	-	-	+	-	-	+	-	+	-
331	-	+	-	+	-	-	+	-	+	-
332	+	+	-	+	-	-	+	-	+	-
333	-	-	+	+	-	-	+	-	+	-
334	+	-	+	+	-	-	+	-	+	-
335	-	+	+	+	-	-	+	-	+	-
336	+	+	+	+	-	-	+	-	+	-
337	-	-	-	-	+	-	+	-	+	-
338	+	-	-	-	+	-	+	-	+	-
339	-	+	-	-	+	-	+	-	+	-
340	+	+	-	-	+	-	+	-	+	-
341	-	-	+	-	+	-	+	-	+	-
342	+	-	+	-	+	-	+	-	+	-
343	-	+	+	-	+	-	+	-	+	-
344	+	+	+	-	+	-	+	-	+	-
345	-	-	-	+	+	-	+	-	+	-
346	+	-	-	+	+	-	+	-	+	-
347	-	+	-	+	+	-	+	-	+	-
348	+	+	-	+	+	-	+	-	+	-
349	-	-	+	+	+	-	+	-	+	-
350	+	-	+	+	+	-	+	-	+	-
351	-	+	+	+	+	-	+	-	+	-
352	+	+	+	+	+	-	+	-	+	-
353	-	-	-	-	-	+	+	-	+	-
354	+	-	-	-	-	+	+	-	+	-
355	-	+	-	-	-	+	+	-	+	-
356	+	+	-	-	-	+	+	-	+	-
357	-	-	+	-	-	+	+	-	+	-
358	+	-	+	-	-	+	+	-	+	-
359	-	+	+	-	-	+	+	-	+	-
360	+	+	+	-	-	+	+	-	+	-
361	-	-	-	+	-	+	+	-	+	-
362	+	-	-	+	-	+	+	-	+	-
363	-	+	-	+	-	+	+	-	+	-
364	+	+	-	+	-	+	+	-	+	-
365	-	-	+	+	-	+	+	-	+	-
366	+	-	+	+	-	+	+	-	+	-
367	-	+	+	+	-	+	+	-	+	-
368	+	+	+	+	-	+	+	-	+	-
369	-	-	-	-	+	+	+	-	+	-
370	+	-	-	-	+	+	+	-	+	-
371	-	+	-	-	+	+	+	-	+	-
372	+	+	-	-	+	+	+	-	+	-
373	-	-	+	-	+	+	+	-	+	-
374	+	-	+	-	+	+	+	-	+	-
375	-	+	+	-	+	+	+	-	+	-
376	+	+	+	-	+	+	+	-	+	-
377	-	-	-	+	+	+	+	-	+	-
378	+	-	-	+	+	+	+	-	+	-
379	-	+	-	+	+	+	+	-	+	-
380	+	+	-	+	+	+	+	-	+	-
381	-	-	+	+	+	+	+	-	+	-
382	+	-	+	+	+	+	+	-	+	-
383	-	+	+	+	+	+	+	-	+	-

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
384	+	+	+	+	+	+	+	-	+	-
385	-	-	-	-	-	-	-	+	+	-
386	+	-	-	-	-	-	-	+	+	-
387	-	+	-	-	-	-	-	+	+	-
388	+	+	-	-	-	-	-	+	+	-
389	-	-	+	-	-	-	-	+	+	-
390	+	-	+	-	-	-	-	+	+	-
391	-	+	+	-	-	-	-	+	+	-
392	+	+	+	-	-	-	-	+	+	-
393	-	-	-	+	-	-	-	+	+	-
394	+	-	-	+	-	-	-	+	+	-
395	-	+	-	+	-	-	-	+	+	-
396	+	+	-	+	-	-	-	+	+	-
397	-	-	+	+	-	-	-	+	+	-
398	+	-	+	+	-	-	-	+	+	-
399	-	+	+	+	-	-	-	+	+	-
400	+	+	+	+	-	-	-	+	+	-
401	-	-	-	-	+	-	-	+	+	-
402	+	-	-	-	+	-	-	+	+	-
403	-	+	-	-	+	-	-	+	+	-
404	+	+	-	-	+	-	-	+	+	-
405	-	-	+	-	+	-	-	+	+	-
406	+	-	+	-	+	-	-	+	+	-
407	-	+	+	-	+	-	-	+	+	-
408	+	+	+	-	+	-	-	+	+	-
409	-	-	-	+	+	-	-	+	+	-
410	+	-	-	+	+	-	-	+	+	-
411	-	+	-	+	+	-	-	+	+	-
412	+	+	-	+	+	-	-	+	+	-
413	-	-	+	+	+	-	-	+	+	-
414	+	-	+	+	+	-	-	+	+	-
415	-	+	+	+	+	-	-	+	+	-
416	+	+	+	+	+	-	-	+	+	-
417	-	-	-	-	-	+	-	+	+	-
418	+	-	-	-	-	+	-	+	+	-
419	-	+	-	-	-	+	-	+	+	-
420	+	+	-	-	-	+	-	+	+	-
421	-	-	+	-	-	+	-	+	+	-
422	+	-	+	-	-	+	-	+	+	-
423	-	+	+	-	-	+	-	+	+	-
424	+	+	+	-	-	+	-	+	+	-
425	-	-	-	+	-	+	-	+	+	-
426	+	-	-	+	-	+	-	+	+	-
427	-	+	-	+	-	+	-	+	+	-
428	+	+	-	+	-	+	-	+	+	-
429	-	-	+	+	-	+	-	+	+	-
430	+	-	+	+	-	+	-	+	+	-
431	-	+	+	+	-	+	-	+	+	-
432	+	+	+	+	-	+	-	+	+	-
433	-	-	-	-	+	+	-	+	+	-
434	+	-	-	-	+	+	-	+	+	-
435	-	+	-	-	+	+	-	+	+	-
436	+	+	-	-	+	+	-	+	+	-
437	-	-	+	-	+	+	-	+	+	-
438	+	-	+	-	+	+	-	+	+	-

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
439	-	+	+	-	+	+	-	+	+	-
440	+	+	+	-	+	+	-	+	+	-
441	-	-	-	+	+	+	-	+	+	-
442	+	-	-	+	+	+	-	+	+	-
443	-	+	-	+	+	+	-	+	+	-
444	+	+	-	+	+	+	-	+	+	-
445	-	-	+	+	+	+	-	+	+	-
446	+	-	+	+	+	+	-	+	+	-
447	-	+	+	+	+	+	-	+	+	-
448	+	+	+	+	+	+	-	+	+	-
449	-	-	-	-	-	-	+	+	+	-
450	+	-	-	-	-	-	+	+	+	-
451	-	+	-	-	-	-	+	+	+	-
452	+	+	-	-	-	-	+	+	+	-
453	-	-	+	-	-	-	+	+	+	-
454	+	-	+	-	-	-	+	+	+	-
455	-	+	+	-	-	-	+	+	+	-
456	+	+	+	-	-	-	+	+	+	-
457	-	-	-	+	-	-	+	+	+	-
458	+	-	-	+	-	-	+	+	+	-
459	-	+	-	+	-	-	+	+	+	-
460	+	+	-	+	-	-	+	+	+	-
461	-	-	+	+	-	-	+	+	+	-
462	+	-	+	+	-	-	+	+	+	-
463	-	+	+	+	-	-	+	+	+	-
464	+	+	+	+	-	-	+	+	+	-
465	-	-	-	-	+	-	+	+	+	-
466	+	-	-	-	+	-	+	+	+	-
467	-	+	-	-	+	-	+	+	+	-
468	+	+	-	-	+	-	+	+	+	-
469	-	-	+	-	+	-	+	+	+	-
470	+	-	+	-	+	-	+	+	+	-
471	-	+	+	-	+	-	+	+	+	-
472	+	+	+	-	+	-	+	+	+	-
473	-	-	-	+	+	-	+	+	+	-
474	+	-	-	+	+	-	+	+	+	-
475	-	+	-	+	+	-	+	+	+	-
476	+	+	-	+	+	-	+	+	+	-
477	-	-	+	+	+	-	+	+	+	-
478	+	-	+	+	+	-	+	+	+	-
479	-	+	+	+	+	-	+	+	+	-
480	+	+	+	+	+	-	+	+	+	-
481	-	-	-	-	-	+	+	+	+	-
482	+	-	-	-	-	+	+	+	+	-
483	-	+	-	-	-	+	+	+	+	-
484	+	+	-	-	-	+	+	+	+	-
485	-	-	+	-	-	+	+	+	+	-
486	+	-	+	-	-	+	+	+	+	-
487	-	+	+	-	-	+	+	+	+	-
488	+	+	+	-	-	+	+	+	+	-
489	-	-	-	+	-	+	+	+	+	-
490	+	-	-	+	-	+	+	+	+	-
491	-	+	-	+	-	+	+	+	+	-
492	+	+	-	+	-	+	+	+	+	-
493	-	-	+	+	-	+	+	+	+	-

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
494	+	-	+	+	-	+	+	+	+	-
495	-	+	+	+	-	+	+	+	+	-
496	+	+	+	+	-	+	+	+	+	-
497	-	-	-	-	+	+	+	+	+	-
498	+	-	-	-	+	+	+	+	+	-
499	-	+	-	-	+	+	+	+	+	-
500	+	+	-	-	+	+	+	+	+	-
501	-	-	+	-	+	+	+	+	+	-
502	+	-	+	-	+	+	+	+	+	-
503	-	+	+	-	+	+	+	+	+	-
504	+	+	+	-	+	+	+	+	+	-
505	-	-	-	+	+	+	+	+	+	-
506	+	-	-	+	+	+	+	+	+	-
507	-	+	-	+	+	+	+	+	+	-
508	+	+	-	+	+	+	+	+	+	-
509	-	-	+	+	+	+	+	+	+	-
510	+	-	+	+	+	+	+	+	+	-
511	-	+	+	+	+	+	+	+	+	-
512	+	+	+	+	+	+	+	+	+	-
513	-	-	-	-	-	-	-	-	-	+
514	+	-	-	-	-	-	-	-	-	+
515	-	+	-	-	-	-	-	-	-	+
516	+	+	-	-	-	-	-	-	-	+
517	-	-	+	-	-	-	-	-	-	+
518	+	-	+	-	-	-	-	-	-	+
519	-	+	+	-	-	-	-	-	-	+
520	+	+	+	-	-	-	-	-	-	+
521	-	-	-	+	-	-	-	-	-	+
522	+	-	-	+	-	-	-	-	-	+
523	-	+	-	+	-	-	-	-	-	+
524	+	+	-	+	-	-	-	-	-	+
525	-	-	+	+	-	-	-	-	-	+
526	+	-	+	+	-	-	-	-	-	+
527	-	+	+	+	-	-	-	-	-	+
528	+	+	+	+	-	-	-	-	-	+
529	-	-	-	-	+	-	-	-	-	+
530	+	-	-	-	+	-	-	-	-	+
531	-	+	-	-	+	-	-	-	-	+
532	+	+	-	-	+	-	-	-	-	+
533	-	-	+	-	+	-	-	-	-	+
534	+	-	+	-	+	-	-	-	-	+
535	-	+	+	-	+	-	-	-	-	+
536	+	+	+	-	+	-	-	-	-	+
537	-	-	-	+	+	-	-	-	-	+
538	+	-	-	+	+	-	-	-	-	+
539	-	+	-	+	+	-	-	-	-	+
540	+	+	-	+	+	-	-	-	-	+
541	-	-	+	+	+	-	-	-	-	+
542	+	-	+	+	+	-	-	-	-	+
543	-	+	+	+	+	-	-	-	-	+
544	+	+	+	+	+	-	-	-	-	+
545	-	-	-	-	-	+	-	-	-	+
546	+	-	-	-	-	+	-	-	-	+
547	-	+	-	-	-	+	-	-	-	+
548	+	+	-	-	-	+	-	-	-	+

	Experimental Factors									
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
549	-	-	+	-	-	+	-	-	-	+
550	+	-	+	-	-	+	-	-	-	+
551	-	+	+	-	-	+	-	-	-	+
552	+	+	+	-	-	+	-	-	-	+
553	-	-	-	+	-	+	-	-	-	+
554	+	-	-	+	-	+	-	-	-	+
555	-	+	-	+	-	+	-	-	-	+
556	+	+	-	+	-	+	-	-	-	+
557	-	-	+	+	-	+	-	-	-	+
558	+	-	+	+	-	+	-	-	-	+
559	-	+	+	+	-	+	-	-	-	+
560	+	+	+	+	-	+	-	-	-	+
561	-	-	-	-	+	+	-	-	-	+
562	+	-	-	-	+	+	-	-	-	+
563	-	+	-	-	+	+	-	-	-	+
564	+	+	-	-	+	+	-	-	-	+
565	-	-	+	-	+	+	-	-	-	+
566	+	-	+	-	+	+	-	-	-	+
567	-	+	+	-	+	+	-	-	-	+
568	+	+	+	-	+	+	-	-	-	+
569	-	-	-	+	+	+	-	-	-	+
570	+	-	-	+	+	+	-	-	-	+
571	-	+	-	+	+	+	-	-	-	+
572	+	+	-	+	+	+	-	-	-	+
573	-	-	+	+	+	+	-	-	-	+
574	+	-	+	+	+	+	-	-	-	+
575	-	+	+	+	+	+	-	-	-	+
576	+	+	+	+	+	+	-	-	-	+
577	-	-	-	-	-	-	+	-	-	+
578	+	-	-	-	-	-	+	-	-	+
579	-	+	-	-	-	-	+	-	-	+
580	+	+	-	-	-	-	+	-	-	+
581	-	-	+	-	-	-	+	-	-	+
582	+	-	+	-	-	-	+	-	-	+
583	-	+	+	-	-	-	+	-	-	+
584	+	+	+	-	-	-	+	-	-	+
585	-	-	-	+	-	-	+	-	-	+
586	+	-	-	+	-	-	+	-	-	+
587	-	+	-	+	-	-	+	-	-	+
588	+	+	-	+	-	-	+	-	-	+
589	-	-	+	+	-	-	+	-	-	+
590	+	-	+	+	-	-	+	-	-	+
591	-	+	+	+	-	-	+	-	-	+
592	+	+	+	+	-	-	+	-	-	+
593	-	-	-	-	+	-	+	-	-	+
594	+	-	-	-	+	-	+	-	-	+
595	-	+	-	-	+	-	+	-	-	+
596	+	+	-	-	+	-	+	-	-	+
597	-	-	+	-	+	-	+	-	-	+
598	+	-	+	-	+	-	+	-	-	+
599	-	+	+	-	+	-	+	-	-	+
600	+	+	+	-	+	-	+	-	-	+
601	-	-	-	+	+	-	+	-	-	+
602	+	-	-	+	+	-	+	-	-	+
603	-	+	-	+	+	-	+	-	-	+

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
604	+	+	-	+	+	-	+	-	-	+
605	-	-	+	+	+	-	+	-	-	+
606	+	-	+	+	+	-	+	-	-	+
607	-	+	+	+	+	-	+	-	-	+
608	+	+	+	+	+	-	+	-	-	+
609	-	-	-	-	-	+	+	-	-	+
610	+	-	-	-	-	+	+	-	-	+
611	-	+	-	-	-	+	+	-	-	+
612	+	+	-	-	-	+	+	-	-	+
613	-	-	+	-	-	+	+	-	-	+
614	+	-	+	-	-	+	+	-	-	+
615	-	+	+	-	-	+	+	-	-	+
616	+	+	+	-	-	+	+	-	-	+
617	-	-	-	+	-	+	+	-	-	+
618	+	-	-	+	-	+	+	-	-	+
619	-	+	-	+	-	+	+	-	-	+
620	+	+	-	+	-	+	+	-	-	+
621	-	-	+	+	-	+	+	-	-	+
622	+	-	+	+	-	+	+	-	-	+
623	-	+	+	+	-	+	+	-	-	+
624	+	+	+	+	-	+	+	-	-	+
625	-	-	-	-	+	+	+	-	-	+
626	+	-	-	-	+	+	+	-	-	+
627	-	+	-	-	+	+	+	-	-	+
628	+	+	-	-	+	+	+	-	-	+
629	-	-	+	-	+	+	+	-	-	+
630	+	-	+	-	+	+	+	-	-	+
631	-	+	+	-	+	+	+	-	-	+
632	+	+	+	-	+	+	+	-	-	+
633	-	-	-	+	+	+	+	-	-	+
634	+	-	-	+	+	+	+	-	-	+
635	-	+	-	+	+	+	+	-	-	+
636	+	+	-	+	+	+	+	-	-	+
637	-	-	+	+	+	+	+	-	-	+
638	+	-	+	+	+	+	+	-	-	+
639	-	+	+	+	+	+	+	-	-	+
640	+	+	+	+	+	+	+	-	-	+
641	-	-	-	-	-	-	-	+	-	+
642	+	-	-	-	-	-	-	+	-	+
643	-	+	-	-	-	-	-	+	-	+
644	+	+	-	-	-	-	-	+	-	+
645	-	-	+	-	-	-	-	+	-	+
646	+	-	+	-	-	-	-	+	-	+
647	-	+	+	-	-	-	-	+	-	+
648	+	+	+	-	-	-	-	+	-	+
649	-	-	-	+	-	-	-	+	-	+
650	+	-	-	+	-	-	-	+	-	+
651	-	+	-	+	-	-	-	+	-	+
652	+	+	-	+	-	-	-	+	-	+
653	-	-	+	+	-	-	-	+	-	+
654	+	-	+	+	-	-	-	+	-	+
655	-	+	+	+	-	-	-	+	-	+
656	+	+	+	+	-	-	-	+	-	+
657	-	-	-	-	+	-	-	+	-	+
658	+	-	-	-	+	-	-	+	-	+

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
659	-	+	-	-	+	-	-	+	-	+
660	+	+	-	-	+	-	-	+	-	+
661	-	-	+	-	+	-	-	+	-	+
662	+	-	+	-	+	-	-	+	-	+
663	-	+	+	-	+	-	-	+	-	+
664	+	+	+	-	+	-	-	+	-	+
665	-	-	-	+	+	-	-	+	-	+
666	+	-	-	+	+	-	-	+	-	+
667	-	+	-	+	+	-	-	+	-	+
668	+	+	-	+	+	-	-	+	-	+
669	-	-	+	+	+	-	-	+	-	+
670	+	-	+	+	+	-	-	+	-	+
671	-	+	+	+	+	-	-	+	-	+
672	+	+	+	+	+	-	-	+	-	+
673	-	-	-	-	-	+	-	+	-	+
674	+	-	-	-	-	+	-	+	-	+
675	-	+	-	-	-	+	-	+	-	+
676	+	+	-	-	-	+	-	+	-	+
677	-	-	+	-	-	+	-	+	-	+
678	+	-	+	-	-	+	-	+	-	+
679	-	+	+	-	-	+	-	+	-	+
680	+	+	+	-	-	+	-	+	-	+
681	-	-	-	+	-	+	-	+	-	+
682	+	-	-	+	-	+	-	+	-	+
683	-	+	-	+	-	+	-	+	-	+
684	+	+	-	+	-	+	-	+	-	+
685	-	-	+	+	-	+	-	+	-	+
686	+	-	+	+	-	+	-	+	-	+
687	-	+	+	+	-	+	-	+	-	+
688	+	+	+	+	-	+	-	+	-	+
689	-	-	-	-	+	+	-	+	-	+
690	+	-	-	-	+	+	-	+	-	+
691	-	+	-	-	+	+	-	+	-	+
692	+	+	-	-	+	+	-	+	-	+
693	-	-	+	-	+	+	-	+	-	+
694	+	-	+	-	+	+	-	+	-	+
695	-	+	+	-	+	+	-	+	-	+
696	+	+	+	-	+	+	-	+	-	+
697	-	-	-	+	+	+	-	+	-	+
698	+	-	-	+	+	+	-	+	-	+
699	-	+	-	+	+	+	-	+	-	+
700	+	+	-	+	+	+	-	+	-	+
701	-	-	+	+	+	+	-	+	-	+
702	+	-	+	+	+	+	-	+	-	+
703	-	+	+	+	+	+	-	+	-	+
704	+	+	+	+	+	+	-	+	-	+
705	-	-	-	-	-	-	+	+	-	+
706	+	-	-	-	-	-	+	+	-	+
707	-	+	-	-	-	-	+	+	-	+
708	+	+	-	-	-	-	+	+	-	+
709	-	-	+	-	-	-	+	+	-	+
710	+	-	+	-	-	-	+	+	-	+
711	-	+	+	-	-	-	+	+	-	+
712	+	+	+	-	-	-	+	+	-	+
713	-	-	-	+	-	-	+	+	-	+

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
714	+	-	-	+	-	-	+	+	-	+
715	-	+	-	+	-	-	+	+	-	+
716	+	+	-	+	-	-	+	+	-	+
717	-	-	+	+	-	-	+	+	-	+
718	+	-	+	+	-	-	+	+	-	+
719	-	+	+	+	-	-	+	+	-	+
720	+	+	+	+	-	-	+	+	-	+
721	-	-	-	-	+	-	+	+	-	+
722	+	-	-	-	+	-	+	+	-	+
723	-	+	-	-	+	-	+	+	-	+
724	+	+	-	-	+	-	+	+	-	+
725	-	-	+	-	+	-	+	+	-	+
726	+	-	+	-	+	-	+	+	-	+
727	-	+	+	-	+	-	+	+	-	+
728	+	+	+	-	+	-	+	+	-	+
729	-	-	-	+	+	-	+	+	-	+
730	+	-	-	+	+	-	+	+	-	+
731	-	+	-	+	+	-	+	+	-	+
732	+	+	-	+	+	-	+	+	-	+
733	-	-	+	+	+	-	+	+	-	+
734	+	-	+	+	+	-	+	+	-	+
735	-	+	+	+	+	-	+	+	-	+
736	+	+	+	+	+	-	+	+	-	+
737	-	-	-	-	-	+	+	+	-	+
738	+	-	-	-	-	+	+	+	-	+
739	-	+	-	-	-	+	+	+	-	+
740	+	+	-	-	-	+	+	+	-	+
741	-	-	+	-	-	+	+	+	-	+
742	+	-	+	-	-	+	+	+	-	+
743	-	+	+	-	-	+	+	+	-	+
744	+	+	+	-	-	+	+	+	-	+
745	-	-	-	+	-	+	+	+	-	+
746	+	-	-	+	-	+	+	+	-	+
747	-	+	-	+	-	+	+	+	-	+
748	+	+	-	+	-	+	+	+	-	+
749	-	-	+	+	-	+	+	+	-	+
750	+	-	+	+	-	+	+	+	-	+
751	-	+	+	+	-	+	+	+	-	+
752	+	+	+	+	-	+	+	+	-	+
753	-	-	-	-	+	+	+	+	-	+
754	+	-	-	-	+	+	+	+	-	+
755	-	+	-	-	+	+	+	+	-	+
756	+	+	-	-	+	+	+	+	-	+
757	-	-	+	-	+	+	+	+	-	+
758	+	-	+	-	+	+	+	+	-	+
759	-	+	+	-	+	+	+	+	-	+
760	+	+	+	-	+	+	+	+	-	+
761	-	-	-	+	+	+	+	+	-	+
762	+	-	-	+	+	+	+	+	-	+
763	-	+	-	+	+	+	+	+	-	+
764	+	+	-	+	+	+	+	+	-	+
765	-	-	+	+	+	+	+	+	-	+
766	+	-	+	+	+	+	+	+	-	+
767	-	+	+	+	+	+	+	+	-	+
768	+	+	+	+	+	+	+	+	-	+

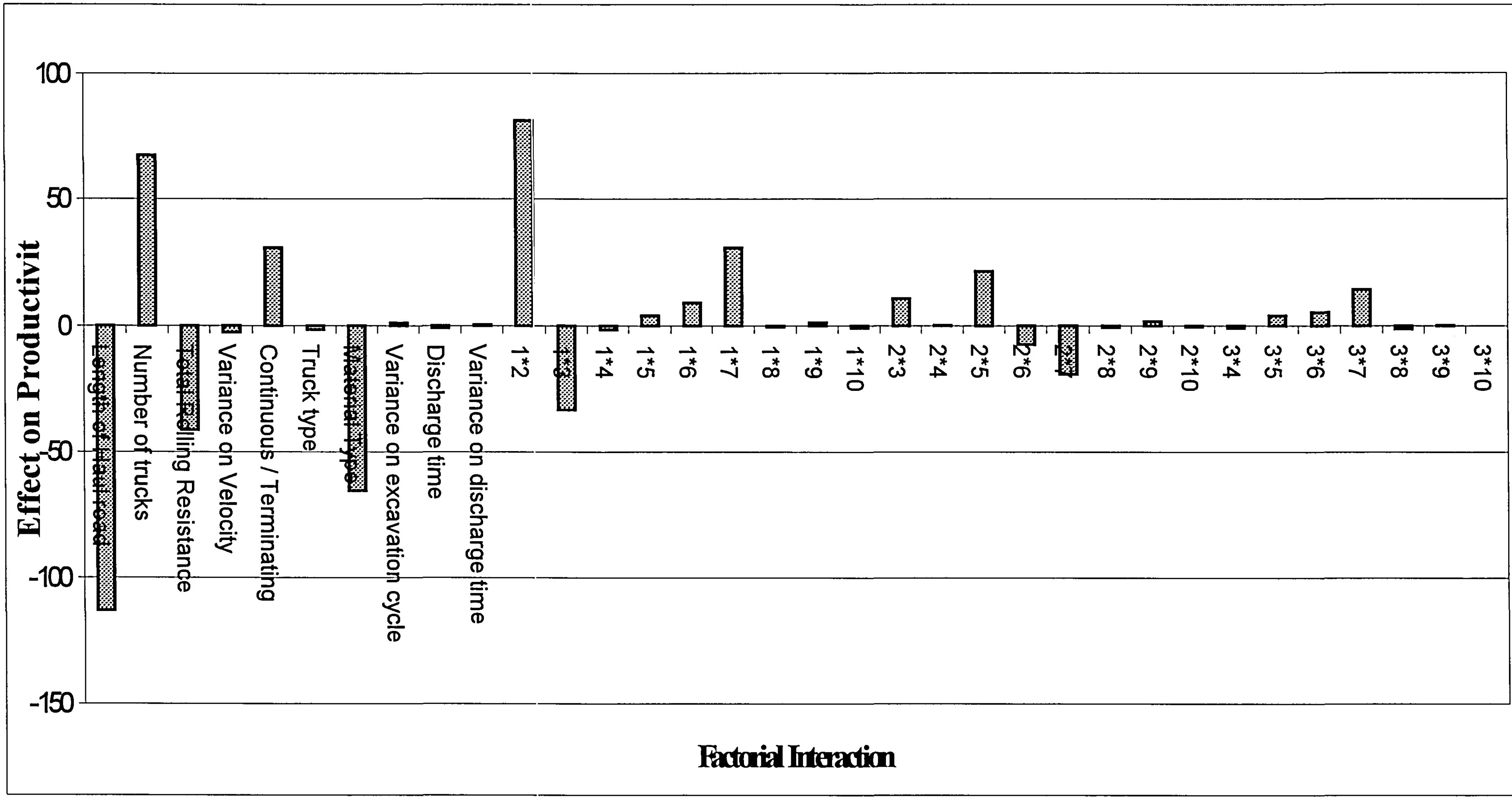
Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
769	-	-	-	-	-	-	-	-	+	+
770	+	-	-	-	-	-	-	-	+	+
771	-	+	-	-	-	-	-	-	+	+
772	+	+	-	-	-	-	-	-	+	+
773	-	-	+	-	-	-	-	-	+	+
774	+	-	+	-	-	-	-	-	+	+
775	-	+	+	-	-	-	-	-	+	+
776	+	+	+	-	-	-	-	-	+	+
777	-	-	-	+	-	-	-	-	+	+
778	+	-	-	+	-	-	-	-	+	+
779	-	+	-	+	-	-	-	-	+	+
780	+	+	-	+	-	-	-	-	+	+
781	-	-	+	+	-	-	-	-	+	+
782	+	-	+	+	-	-	-	-	+	+
783	-	+	+	+	-	-	-	-	+	+
784	+	+	+	+	-	-	-	-	+	+
785	-	-	-	-	+	-	-	-	+	+
786	+	-	-	-	+	-	-	-	+	+
787	-	+	-	-	+	-	-	-	+	+
788	+	+	-	-	+	-	-	-	+	+
789	-	-	+	-	+	-	-	-	+	+
790	+	-	+	-	+	-	-	-	+	+
791	-	+	+	-	+	-	-	-	+	+
792	+	+	+	-	+	-	-	-	+	+
793	-	-	-	+	+	-	-	-	+	+
794	+	-	-	+	+	-	-	-	+	+
795	-	+	-	+	+	-	-	-	+	+
796	+	+	-	+	+	-	-	-	+	+
797	-	-	+	+	+	-	-	-	+	+
798	+	-	+	+	+	-	-	-	+	+
799	-	+	+	+	+	-	-	-	+	+
800	+	+	+	+	+	-	-	-	+	+
801	-	-	-	-	-	+	-	-	+	+
802	+	-	-	-	-	+	-	-	+	+
803	-	+	-	-	-	+	-	-	+	+
804	+	+	-	-	-	+	-	-	+	+
805	-	-	+	-	-	+	-	-	+	+
806	+	-	+	-	-	+	-	-	+	+
807	-	+	+	-	-	+	-	-	+	+
808	+	+	+	-	-	+	-	-	+	+
809	-	-	-	+	-	+	-	-	+	+
810	+	-	-	+	-	+	-	-	+	+
811	-	+	-	+	-	+	-	-	+	+
812	+	+	-	+	-	+	-	-	+	+
813	-	-	+	+	-	+	-	-	+	+
814	+	-	+	+	-	+	-	-	+	+
815	-	+	+	+	-	+	-	-	+	+
816	+	+	+	+	-	+	-	-	+	+
817	-	-	-	-	+	+	-	-	+	+
818	+	-	-	-	+	+	-	-	+	+
819	-	+	-	-	+	+	-	-	+	+
820	+	+	-	-	+	+	-	-	+	+
821	-	-	+	-	+	+	-	-	+	+
822	+	-	+	-	+	+	-	-	+	+
823	-	+	+	-	+	+	-	-	+	+

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
824	+	+	+	-	+	+	-	-	+	+
825	-	-	-	+	+	+	-	-	+	+
826	+	-	-	+	+	+	-	-	+	+
827	-	+	-	+	+	+	-	-	+	+
828	+	+	-	+	+	+	-	-	+	+
829	-	-	+	+	+	+	-	-	+	+
830	+	-	+	+	+	+	-	-	+	+
831	-	+	+	+	+	+	-	-	+	+
832	+	+	+	+	+	+	-	-	+	+
833	-	-	-	-	-	-	+	-	+	+
834	+	-	-	-	-	-	+	-	+	+
835	-	+	-	-	-	-	+	-	+	+
836	+	+	-	-	-	-	+	-	+	+
837	-	-	+	-	-	-	+	-	+	+
838	+	-	+	-	-	-	+	-	+	+
839	-	+	+	-	-	-	+	-	+	+
840	+	+	+	-	-	-	+	-	+	+
841	-	-	-	+	-	-	+	-	+	+
842	+	-	-	+	-	-	+	-	+	+
843	-	+	-	+	-	-	+	-	+	+
844	+	+	-	+	-	-	+	-	+	+
845	-	-	+	+	-	-	+	-	+	+
846	+	-	+	+	-	-	+	-	+	+
847	-	+	+	+	-	-	+	-	+	+
848	+	+	+	+	-	-	+	-	+	+
849	-	-	-	-	+	-	+	-	+	+
850	+	-	-	-	+	-	+	-	+	+
851	-	+	-	-	+	-	+	-	+	+
852	+	+	-	-	+	-	+	-	+	+
853	-	-	+	-	+	-	+	-	+	+
854	+	-	+	-	+	-	+	-	+	+
855	-	+	+	-	+	-	+	-	+	+
856	+	+	+	-	+	-	+	-	+	+
857	-	-	-	+	+	-	+	-	+	+
858	+	-	-	+	+	-	+	-	+	+
859	-	+	-	+	+	-	+	-	+	+
860	+	+	-	+	+	-	+	-	+	+
861	-	-	+	+	+	-	+	-	+	+
862	+	-	+	+	+	-	+	-	+	+
863	-	+	+	+	+	-	+	-	+	+
864	+	+	+	+	+	-	+	-	+	+
865	-	-	-	-	-	+	+	-	+	+
866	+	-	-	-	-	+	+	-	+	+
867	-	+	-	-	-	+	+	-	+	+
868	+	+	-	-	-	+	+	-	+	+
869	-	-	+	-	-	+	+	-	+	+
870	+	-	+	-	-	+	+	-	+	+
871	-	+	+	-	-	+	+	-	+	+
872	+	+	+	-	-	+	+	-	+	+
873	-	-	-	+	-	+	+	-	+	+
874	+	-	-	+	-	+	+	-	+	+
875	-	+	-	+	-	+	+	-	+	+
876	+	+	-	+	-	+	+	-	+	+
877	-	-	+	+	-	+	+	-	+	+
878	+	-	+	+	-	+	+	-	+	+

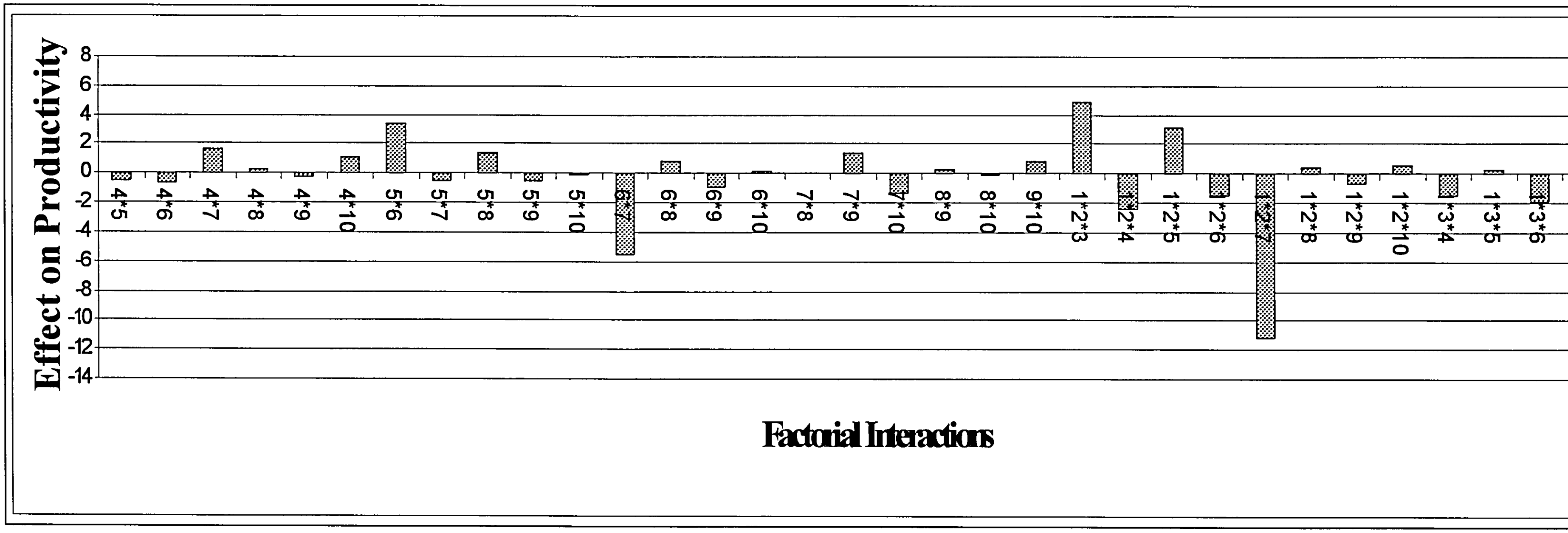
Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
879	-	+	+	+	-	+	+	-	+	+
880	+	+	+	+	-	+	+	-	+	+
881	-	-	-	-	+	+	+	-	+	+
882	+	-	-	-	+	+	+	-	+	+
883	-	+	-	-	+	+	+	-	+	+
884	+	+	-	-	+	+	+	-	+	+
885	-	-	+	-	+	+	+	-	+	+
886	+	-	+	-	+	+	+	-	+	+
887	-	+	+	-	+	+	+	-	+	+
888	+	+	+	-	+	+	+	-	+	+
889	-	-	-	+	+	+	+	-	+	+
890	+	-	-	+	+	+	+	-	+	+
891	-	+	-	+	+	+	+	-	+	+
892	+	+	-	+	+	+	+	-	+	+
893	-	-	+	+	+	+	+	-	+	+
894	+	-	+	+	+	+	+	-	+	+
895	-	+	+	+	+	+	+	-	+	+
896	+	+	+	+	+	+	+	-	+	+
897	-	-	-	-	-	-	-	+	+	+
898	+	-	-	-	-	-	-	+	+	+
899	-	+	-	-	-	-	-	+	+	+
900	+	+	-	-	-	-	-	+	+	+
901	-	-	+	-	-	-	-	+	+	+
902	+	-	+	-	-	-	-	+	+	+
903	-	+	+	-	-	-	-	+	+	+
904	+	+	+	-	-	-	-	+	+	+
905	-	-	-	+	-	-	-	+	+	+
906	+	-	-	+	-	-	-	+	+	+
907	-	+	-	+	-	-	-	+	+	+
908	+	+	-	+	-	-	-	+	+	+
909	-	-	+	+	-	-	-	+	+	+
910	+	-	+	+	-	-	-	+	+	+
911	-	+	+	+	-	-	-	+	+	+
912	+	+	+	+	-	-	-	+	+	+
913	-	-	-	-	+	-	-	+	+	+
914	+	-	-	-	+	-	-	+	+	+
915	-	+	-	-	+	-	-	+	+	+
916	+	+	-	-	+	-	-	+	+	+
917	-	-	+	-	+	-	-	+	+	+
918	+	-	+	-	+	-	-	+	+	+
919	-	+	+	-	+	-	-	+	+	+
920	+	+	+	-	+	-	-	+	+	+
921	-	-	-	+	+	-	-	+	+	+
922	+	-	-	+	+	-	-	+	+	+
923	-	+	-	+	+	-	-	+	+	+
924	+	+	-	+	+	-	-	+	+	+
925	-	-	+	+	+	-	-	+	+	+
926	+	-	+	+	+	-	-	+	+	+
927	-	+	+	+	+	-	-	+	+	+
928	+	+	+	+	+	-	-	+	+	+
929	-	-	-	-	-	+	-	+	+	+
930	+	-	-	-	-	+	-	+	+	+
931	-	+	-	-	-	+	-	+	+	+
932	+	+	-	-	-	+	-	+	+	+
933	-	-	+	-	-	+	-	+	+	+

Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
934	+	-	+	-	-	+	-	+	+	+
935	-	+	+	-	-	+	-	+	+	+
936	+	+	+	-	-	+	-	+	+	+
937	-	-	-	+	-	+	-	+	+	+
938	+	-	-	+	-	+	-	+	+	+
939	-	+	-	+	-	+	-	+	+	+
940	+	+	-	+	-	+	-	+	+	+
941	-	-	+	+	-	+	-	+	+	+
942	+	-	+	+	-	+	-	+	+	+
943	-	+	+	+	-	+	-	+	+	+
944	+	+	+	+	-	+	-	+	+	+
945	-	-	-	-	+	+	-	+	+	+
946	+	-	-	-	+	+	-	+	+	+
947	-	+	-	-	+	+	-	+	+	+
948	+	+	-	-	+	+	-	+	+	+
949	-	-	+	-	+	+	-	+	+	+
950	+	-	+	-	+	+	-	+	+	+
951	-	+	+	-	+	+	-	+	+	+
952	+	+	+	-	+	+	-	+	+	+
953	-	-	-	+	+	+	-	+	+	+
954	+	-	-	+	+	+	-	+	+	+
955	-	+	-	+	+	+	-	+	+	+
956	+	+	-	+	+	+	-	+	+	+
957	-	-	+	+	+	+	-	+	+	+
958	+	-	+	+	+	+	-	+	+	+
959	-	+	+	+	+	+	-	+	+	+
960	+	+	+	+	+	+	-	+	+	+
961	-	-	-	-	-	-	+	+	+	+
962	+	-	-	-	-	-	+	+	+	+
963	-	+	-	-	-	-	+	+	+	+
964	+	+	-	-	-	-	+	+	+	+
965	-	-	+	-	-	-	+	+	+	+
966	+	-	+	-	-	-	+	+	+	+
967	-	+	+	-	-	-	+	+	+	+
968	+	+	+	-	-	-	+	+	+	+
969	-	-	-	+	-	-	+	+	+	+
970	+	-	-	+	-	-	+	+	+	+
971	-	+	-	+	-	-	+	+	+	+
972	+	+	-	+	-	-	+	+	+	+
973	-	-	+	+	-	-	+	+	+	+
974	+	-	+	+	-	-	+	+	+	+
975	-	+	+	+	-	-	+	+	+	+
976	+	+	+	+	-	-	+	+	+	+
977	-	-	-	-	+	-	+	+	+	+
978	+	-	-	-	+	-	+	+	+	+
979	-	+	-	-	+	-	+	+	+	+
980	+	+	-	-	+	-	+	+	+	+
981	-	-	+	-	+	-	+	+	+	+
982	+	-	+	-	+	-	+	+	+	+
983	-	+	+	-	+	-	+	+	+	+
984	+	+	+	-	+	-	+	+	+	+
985	-	-	-	+	+	-	+	+	+	+
986	+	-	-	+	+	-	+	+	+	+
987	-	+	-	+	+	-	+	+	+	+
988	+	+	-	+	+	-	+	+	+	+

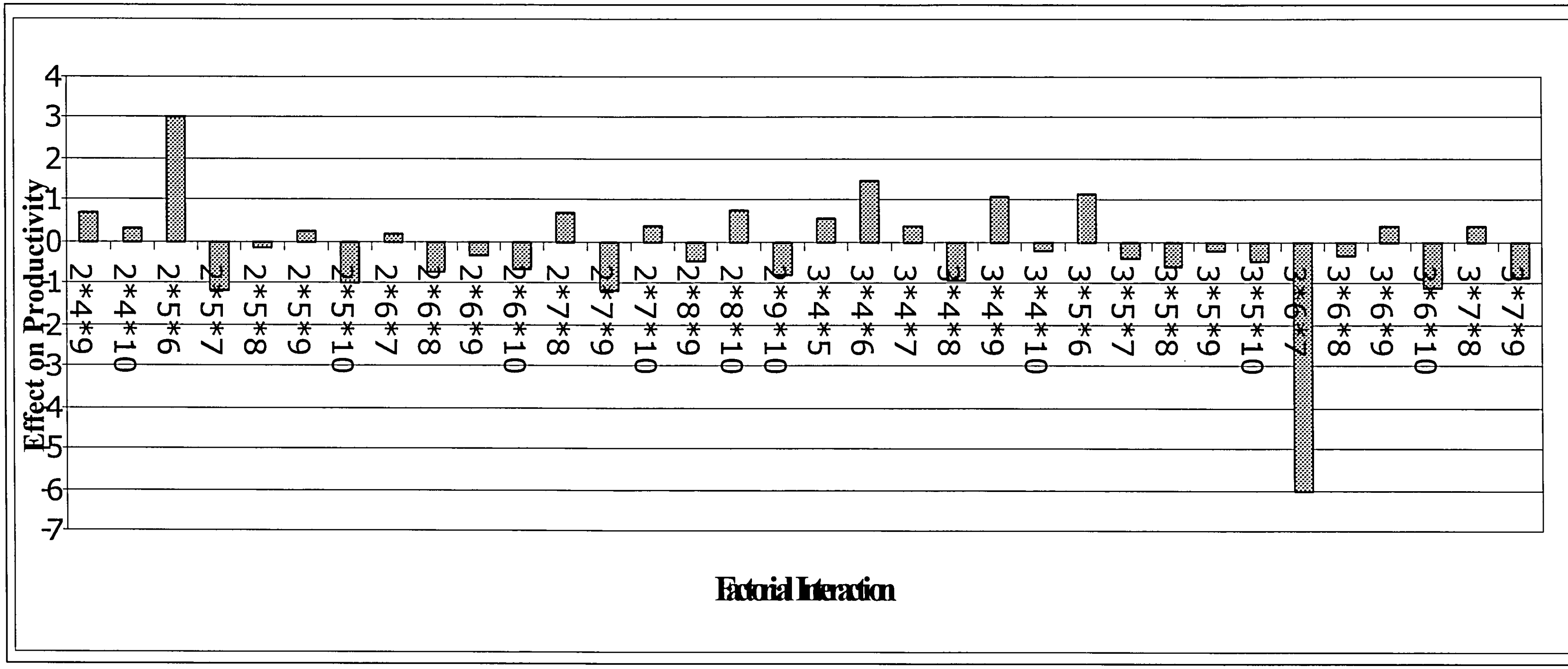
Experimental Factors										
	Length of Haul road	Number of trucks	Total Rolling Resistance	Variance on Velocity	Nonterminating / Terminating	Truck type	Material Type	Variance on excavation cycle	Discharge time	Variance on discharge time
989	-	-	+	+	+	-	+	+	+	+
990	+	-	+	+	+	-	+	+	+	+
991	-	+	+	+	+	-	+	+	+	+
992	+	+	+	+	+	-	+	+	+	+
993	-	-	-	-	-	+	+	+	+	+
994	+	-	-	-	-	+	+	+	+	+
995	-	+	-	-	-	+	+	+	+	+
996	+	+	-	-	-	+	+	+	+	+
997	-	-	+	-	-	+	+	+	+	+
998	+	-	+	-	-	+	+	+	+	+
999	-	+	+	-	-	+	+	+	+	+
1000	+	+	+	-	-	+	+	+	+	+
1001	-	-	-	+	-	+	+	+	+	+
1002	+	-	-	+	-	+	+	+	+	+
1003	-	+	-	+	-	+	+	+	+	+
1004	+	+	-	+	-	+	+	+	+	+
1005	-	-	+	+	-	+	+	+	+	+
1006	+	-	+	+	-	+	+	+	+	+
1007	-	+	+	+	-	+	+	+	+	+
1008	+	+	+	+	-	+	+	+	+	+
1009	-	-	-	-	+	+	+	+	+	+
1010	+	-	-	-	+	+	+	+	+	+
1011	-	+	-	-	+	+	+	+	+	+
1012	+	+	-	-	+	+	+	+	+	+
1013	-	-	+	-	+	+	+	+	+	+
1014	+	-	+	-	+	+	+	+	+	+
1015	-	+	+	-	+	+	+	+	+	+
1016	+	+	+	-	+	+	+	+	+	+
1017	-	-	-	+	+	+	+	+	+	+
1018	+	-	-	+	+	+	+	+	+	+
1019	-	+	-	+	+	+	+	+	+	+
1020	+	+	-	+	+	+	+	+	+	+
1021	-	-	+	+	+	+	+	+	+	+
1022	+	-	+	+	+	+	+	+	+	+
1023	-	+	+	+	+	+	+	+	+	+
1024	+	+	+	+	+	+	+	+	+	+

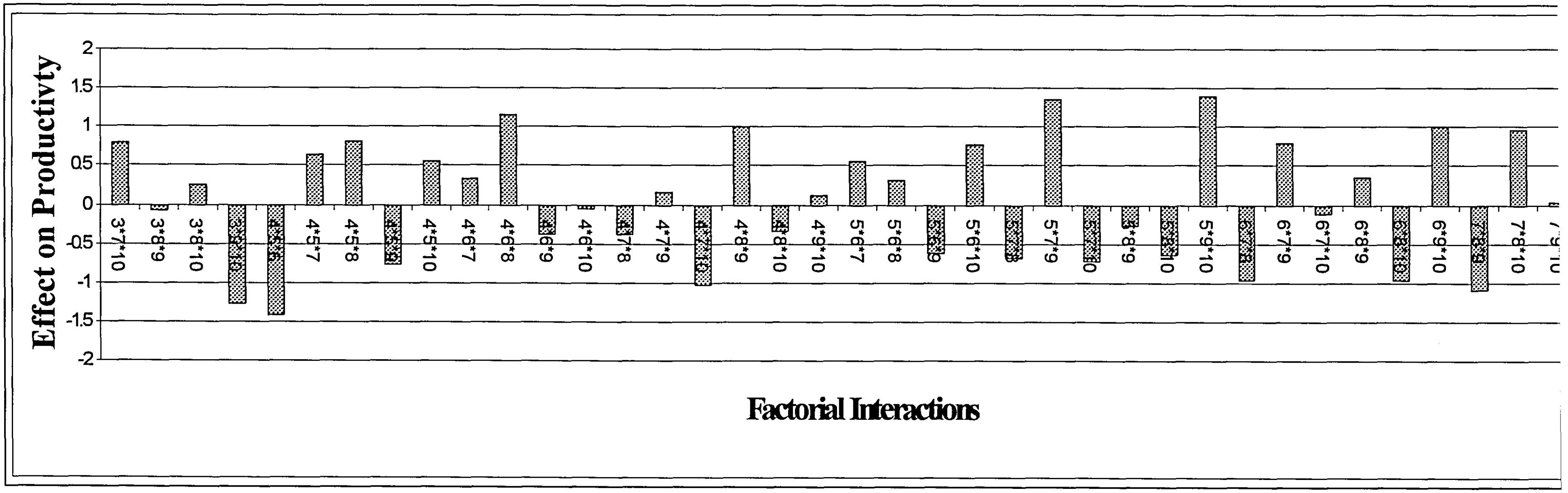


Effect on Productivit
100
50
0
-50
-100
-150
Length of Haul road
Number of trucks
Total Rolling Resistance
Variance on Velocity
Continuous / Terminating
Truck type
Material Type
Variance on excavation cycle
Discharge time
Variance on discharge time
1*2
1*3
1*4
1*5
1*6
1*7
1*8
1*9
1*10
2*3
2*4
2*5
2*6
2*7
2*8
2*9
2*10
3*4
3*5
3*6
3*7
3*8
3*9
3*10
Factorial Interaction



Effect on Productivity
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
4*5
4*6
4*7
4*8
4*9
4*10
5*6
5*7
5*8
5*9
5*10
6*7
6*8
6*9
6*10
7*8
7*9
7*10
8*9
8*10
9*10
1*2*3
1*2*4
1*2*5
1*2*6
1*2*7
1*2*8
1*2*9
1*2*10
1*3*4
1*3*5
1*3*6
Factorial Interactions


Effect on Productivity
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
2*4*9
2*4*10
2*5*6
2*5*7
2*5*8
2*5*9
2*5*10
2*6*7
2*6*8
2*6*9
2*6*10
2*7*8
2*7*9
2*7*10
2*8*9
2*8*10
2*9*10
3*4*5
3*4*6
3*4*7
3*4*8
3*4*9
3*4*10
3*5*6
3*5*7
3*5*8
3*5*9
3*5*10
3*6*7
3*6*8
3*6*9
3*6*10
3*7*8
3*7*9
Factorial Interaction


Effect on Productivty
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
3*7*10
3*8*9
3*8*10
4*5*7
4*5*8
4*5*10
4*6*7
4*6*8
4*6*10
4*7*9
4*8*9
4*9*10
5*6*7
5*6*8
5*6*10
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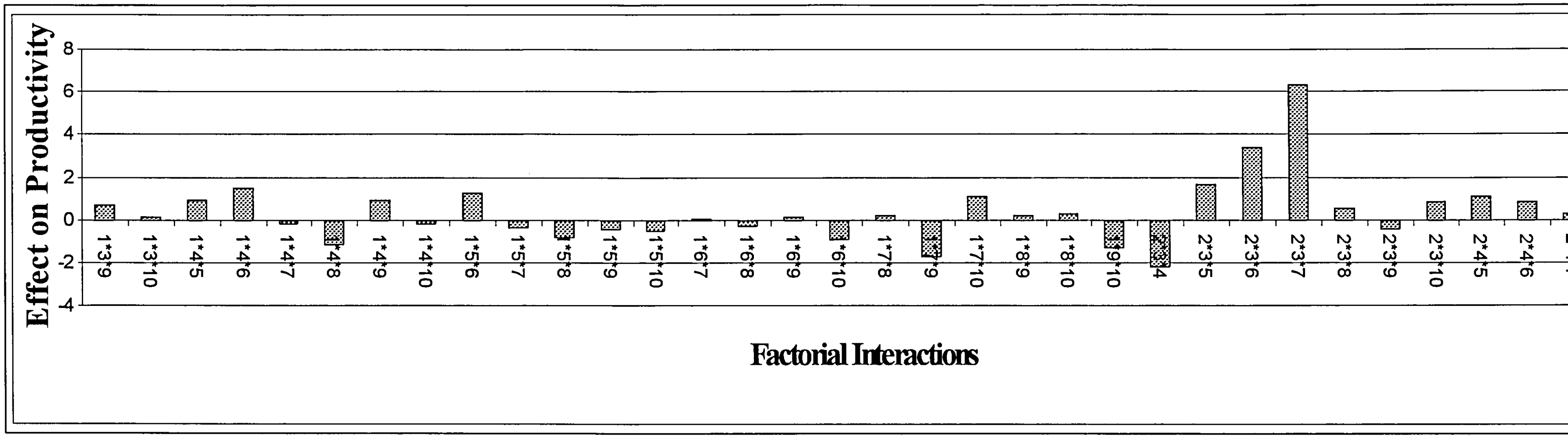
6*7*9
6*7*10
6*8*9
6*9*10
7*8*10
Factorial Interactions


Effect on Productivity
8
6
4
2
0
-2
-4
1*3*9
1*3*10
1*4*5
1*4*6
1*4*7
1*4*8
1*4*9
1*4*10
1*5*6
1*5*7
1*5*8
1*5*9
1*5*10
1*6*7
1*6*8
1*6*9
1*6*10
1*7*8
1*7*9
1*7*10
1*8*9
1*8*10
1*9*10
2*3*4
2*3*5
2*3*6
2*3*7
2*3*8
2*3*9
2*3*10
2*4*5
2*4*6
Factorial Interactions