# FLEET SELECTION FOR EARTHMOVING OPERATIONS USING QUEUEING METHOD

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# ABSTRACT

## FLEET SELECTION FOR EARTHMOVING OPERATIONS USING QUEUEING METHOD

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Earthmoving operation is an important task in any construction project. It is considered a major cost item in a heavy civil project. Normally it is carried out using excavators as production units and trucks as the hauling unit. In planning such operations it is important to determine the "optimum combination" of trucks and excavators such as the number and sizes of the haulers and the production units, in order for the project to be completed at least total cost or duration. The determined combination of haul units and production units can be called the "optimal combination".

To determine the optimal combination of earthmoving equipment is a complex task, this is mainly attributed to the variability of the time components of earthmoving operations. In earthmoving operations queues are commonplace to form when the capacity of the service facility or server is exceeded by the demand of service. In such cases queuing theory is a suitable model that reflects the stochastic or variable nature of the operations.

This research concentrates on presenting a methodology for equipment fleet selection for earthmoving operations. The methodology is incorporated in a developed computer module "**FLSELECTOR**", FLeet SELECTOR, capable of

assisting the users in making management decisions required for earthmoving operations, such as determining the size and number of trucks and excavators, haul road lengths and surface conditions, etc...These decisions are based on the calculated output for all feasible fleets.

Mathematical solutions of queuing models that apply to excavation work were derived and coded using commercially available tools, Microsoft Excel 2000 and Visual Basic for Application (VBA), a subset of the popular application development language, Visual Basic.

Two case studies, an actual project and a hypothetical case, are presented in order to illustrate the effectiveness and performance of the proposed model with a comparison of the results with deterministic and simulation methods.

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Finally, I wish to dedicate this thesis to my parents and parents-in-law for their continuous support and encouragement now as before.

## TABLE OF CONTENTS

## TABLE OF FIGURES

# LIST OF TABLES

# General Notation

**B** bank carrying capacity of haul unit ($m^3$ or $yd^3$)

**c** number of servers

**$c_f$** units conversion factor

**$C_1$** the cost per hour of the loader

**$C_2$** the cost per hour of the truck

**$C_h$** truck capacity in units of cubic meters (yards) or tonnes

**D** constant distribution

**$D_f$** Deration factor

**$E_l$** Erlang distribution with shape parameter $l$

**$F_e$** cold environment factor for equipment task

**$F_m$** reflects the probability of either one server is working or both servers are working in the two-server-case

**$F_o$** haul unit manufacturer's rated rim pull (kN)

**G** general distribution

**$G_o$** effective resistance grade (grade plus rolling) (%)

**K** population or source size (finite source case)

**$K_o$** a coefficient determined by regression analysis

**m** total number of phases in the queue and being served

**M** Exponential distribution

**n** The system is in state n if it contains n units or haulers (including both units being served and queuing to be served). The state of the system equals thenumber of units in the queuing system.

**$n'$** an exponent determined by regression analysis

**$P_m(t)$** the probability that the system is in state m at time t

**$P_n$** probability that there are n units in the queuing system

**$P_s$** Snow fall precipitation

**P(j, t)** probability that the system is in state j at time t

**RP** rim pull (kN)

**T** air temperature

**$U_w$** bank unit weight of material ($t/m^3$ or $kip/yd^3$)

**V** wind speed

**$V_h$** haul-unit speed (km/hr)

**$V_L$** Velocity at level "L"

**Vs** Velocity at sea level

**$W_e$** empty weight of haul units (t or kip)

**$\lambda_m$** average or mean arrival rate of new units when m phases are in system

**$\lambda_n$** average or mean arrival rate of new units when n units are in system (customer arrival per time). $1/\lambda$ may be interpreted as an expected inter-arrival time.

**$\mu_m$** average or mean service rate for the whole system when m phases are in the system

**$\mu_n$** average or mean service rate for the whole system when n units are in the system (customer servicing per time), it is a combined rate for all busy servers in parallel server system. $1/\mu$ may be interpreted as an expected service time

**$\eta$** utilization of the servers; the expected proportion of time the servers are busy

**$\Theta$** system output (customers per time), or output rate

# CHAPTER 1

# INTRODUCTION

## 1.1 General

In general, earthmoving operation in most large construction projects is a major bid item, which affects the overall cost and time of the project. In order for a contractor to win a job and to maximize profit, and for owner to minimize costs, accurate planning and estimating should be considered in this item. Careful selection of equipment, haul routes, and dumping points can yield to a significant savings in both time and cost. For small projects where a single loader and several trucks are required, equipment selection can be accomplished by simple deterministic methods that take in consideration the production rate and are constrained by the availability of equipment. While for large projects where multiloader-truck fleets are required, the selection process can be more complicated, and costs can vary severely.

Normally the selection of equipment aims to minimize cost, maximize production, reduce the idle time of the equipment, work in a safe environment, and meet the requirement of the project. The difficulty with production analysis in construction operations is that the variability in the components of the operations' cycles complicates the analysis. The presence of bunching of machines, equipment idle times, queues and other-non-deterministic events all must be accounted for in any rational analysis. Consequently, choosing between the different available equipment can be a complex task and an inexperienced person may fail to select the best fleet.

To make this task easier, a computer prototype with a methodology based on Queuing method is used to model the multiloader-truck systems assuming the trip times follow the negative exponential distribution, and the service times follow the Erlang distribution of degree *l* with a number of servers less than or equal to three. In the proposed methodology project conditions and factors should be carefully identified then appropriate equipment fleet selection is to be made.

## 1.2 Research Objectives:

Most of the construction projects incorporate earthmoving operations, which varies from small tasks as in foundation work to large ones as in dams and highway constructions. Careful selection of equipment to carry out these tasks may have a critical effect on the cost and duration of the whole project.

The main objective of this research is to study the current practices and methods of equipment selection used in earthmoving projects. Aiming at modeling the process of earthmoving equipment selection in a computerized environment.

The research objectives can be listed as follows:

- Understanding the earthmoving equipment selection process and classifying the different selection methods
- Analyzing the factors affecting the equipment and their selection in earthmoving projects.
- Establishing a methodology for earthmoving equipment selection.

- Developing a computer based tool capable of advising on the selection of the most appropriate equipment for earthmoving projects.

**1.3 Methodology:** To achieve the stated objectives the following steps were followed:

**1.3.1 Literature Review**: An intensive review of literature in the area of earthmoving equipment selection is presented in chapter (2).

**1.3.2 Interview:** Interviewing a representative from Caterpillar Corporation to discuss the matching factors between equipment, in addition to time components and factors that should be consider in the selection process.

**1.3.3 Proposed Methodology:**

The methodology used in the developed model is based on the queuing method with $M/E_l/c$ model at steady state, finite population source, and number of servers less than or equal to three, as illustrated in chapter (3).

**1.3.4 Development of the Model:**

A computer prototype model is presented; two case studies and an output comparison with the deterministic method and a simulation system were done for verification, as shown in Chapter (4).

**1.4 Thesis Organization**

Chapter 2 includes a summary of the literature review. Factors and the nature of earthmoving equipment selection process are discussed. A review of the applications of Knowledge-based expert systems (KBES), Linear Programming (LP), Simulation method, and Queuing theory in the construction industry in general and to the equipment selection in earth-moving operations in particular is presented.

Chapter 3 explains the methodology used in developing the proposed system, derivation of the equations and data flow is also presented.

Chapter 4 covers the computer implementation of the methodology with the case studies. It illustrates the system modules, input, output, and its main features.

Chapter 5 is the thesis conclusion and recommendations for future work.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Careful selection of equipment fleets for earthmoving projects can yield substantial savings in both time and cost. Equipment selection for an earth-moving operation is usually based on the production rate required and is often constrained by the equipment on hand. This deterministic method is simple and can provide satisfactory results for small projects requiring a single loader and several trucks. For large projects requiring multi-loader-truck fleets, however, the selection process can be more complicated, and cost can fluctuate widely (Farid and Koning, 1994).

Shovel-truck type operation may be represented schematically as shown in Figure 2.1, which is a variation of the classic queuing system-for example, a bank or a car wash. The term shovel here is used to generally mean a shovel(s), loader(s), excavator(s), dragline(s), or similar as employed in earthmoving, quarrying and open cut mining operations. Trucks are used in this system to transport material from the cut area to the fill area, and these are (in queuing-theory terminology) the customers. The service time is built up from individual component times that are the maneuver or spot time, which is the time the truck takes to get from the queue to its position by the loader, and the load time, which is made up of individual load pass times. The trucks, once loaded, haul to the dump area, dump the load and return to the queue.

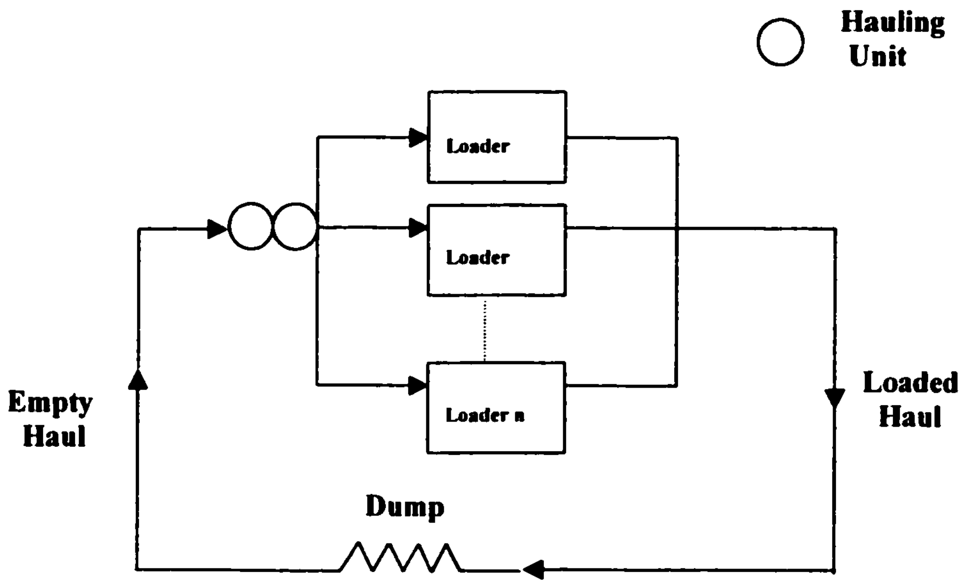



**Figure 2.1 Schematic Representation of Shovel-Truck Operation**

The length of time of this "back-cycle" (or time out of service) is heavily dependent on the speed of the trucks and the length of the haul; the haul and return times have been collectively classified as travel time. The final time component is the dump time. The queue forms whenever a truck arrives and finds the shovel busy loading another truck.

The primary objective in the analysis of such operation is for the analysis to aid the forecasting of production or the forecasting of the effectiveness of any given configuration of hauling units-loaders-haul-routes-dump facility, leading to a configuration with the desired performance characteristics (maximum productivity, minimum cost). Planning involves the engineer determining haul routes and grades, determining the fleet configurations (type, number and capacity of hauling units and loading equipment) and determining the location and capacity of the dump point.

## 2.2 Earthmoving Productivity

Gransberg (1996) indicated that it is "the critical characteristics of the loading facility which ultimately impact on the overall system production." The maximum possible productivity of a system is dependent on the output from the loader (or prime mover)- this maximum can only be increased by changing the characteristics of this prime mover or by increasing the number of teams. In real terms, however, this maximum productivity is rarely reached, at least not in an efficient manner- it being reduced by mismatch and bunching (Smith 1999). An earthmoving system's productivity is limited by the production of the loading facility (Farid and Koning 1994). In other words, regardless of the size, number, and speeds of the hauling units, the ability of the loading facility to load the haul units will determine the maximum productivity of the system. As a result, the loading facility characteristics must be carefully considered in the planning of a hauling operation (Gransberg, 1996).

## 2.3 Factors That Affect The Output Of An Earth-Moving System.

### 2.3.1 Earthmoving System

Smith et al. (1995) presented the parts of an earth-moving system to which the output is most sensitive. He used response-surface methodology to indicate the relationship between the factors. His work attempts to determine which factors, and what levels of these factors, affect the output responses of an earthmoving model the most. He stated that the output of the model is sensitive to six factors: number of trucks, passes per load, load pass time, spot time, travel time, and dump time. He found that the correct number of trucks matched to the loader is essential for maximum efficiency of an earthmoving operation, despite the increase in load time, in certain situations extra bucketfuls per load are advantageous, this must never overload the truck for safety and plant longevity. He also found that spot and load pass time both have the same effect on the output, travel time will become the dominant factor as haul length increases, and keeping the component times to a minimum is essential if maximum production is to be achieved.

### 2.3.2 Payload

Payload is the load a vehicle can carry, exclusive of the vehicle weight. Typically, the limiting factor is the tire's ability to carry the load (Karshenas 1989). Payload can be expressed as gravimetric capacity in mega grams or metric tons (pounds or tons), or as volumetric capacity in either struck or heaped loose-volume cubic meters (loose cubic yards) (Schexnayder et al.1999).

Schexnayder et al. (1999) found from field studies that payload weight affects the incremental production of a fleet. This is most evident as the payload weight approaches and/or exceeds the rated capacity of the haul unit.

### 2.3.3 Rounding Based On Productivity

The decision of rounding off the optimum number of haul units up or down can have a marked effect on the system's productivity (Ringwald 1987). Rounding the number up maximizes the loading facility productivity. Rounding the number down maximizes haul unit productivity. Therefore, it is logical to check both and select the higher of the two In practice, engineers tend to always round down, as it is easier to add another truck when necessary than to delete one that is not required (Gransberg 1996).

## 2.4 Applications In Earthmoving Field

This section describes the methods and current practices used in the area of equipment selection for construction projects. In addition, a review of the applications of Knowledge-based expert systems (KBES), Linear Programming (LP), Simulation method, and Queuing theory in the construction industry in general and to the equipment selection in earth-moving operations in particular.

### 2.4.1 Expert Systems

In spite of the need and potential benefits, there are currently very few operational expert systems (i.e. in routine use by persons other than developers) in the field of construction. One reason for this may be a lack of awareness by the industry about what expert systems currently exist, what their capabilities are, and who their developers and vendors are (Sahish and Mohan 1990).

Expert system and its application in earthmoving operations were discussed in the work of (Amirkhanian and Baker, 1992; Alkass and Harris, 1988).

Alkass and Harris (1988) presented a model for selecting earth-moving equipment in road construction. They developed a prototype computer program called **ESEMPS** (Expert System for Earth-Moving Plant Selection). The essence of this prototype, as in all expert systems, is encoding of expert knowledge in a form usable by non-experts. It is based on the combination of the experience judgments of experts in the field for road construction and equipment rental specialists, known facts on ground conditions, weather conditions from past records, machine performance, work study, and cost data. A consultation begins by the user responding to questions posed by the system. Having received an answer to a question, the system locates the applicable rules by comparing the answers with the knowledge base and produces a decision giving a likely solution to the problem in hand.

**Earthmoving E.S.P** (Amirkhane and Baker, 1992) is a system for selecting earth-moving equipment. It was developed using a rule-based expert system (i.e VP-Expert). The system interprets information concerning a particular projects, soil conditions, operator performance, and required earth-moving operations. The knowledge for the development of the system was obtained from several experts. The system provides the user with a printed spreadsheet for each type of equipment that is being selected by the system to perform the operations the user indicated. The job conditions and soil properties that were selected during the consultations are outlined on each spreadsheet. The estimated productivity of the piece of equipment at the productivity required to complete the project in the designated number of workdays is also outlined. The system has some limitations including the scope of the project (i.e. maximum of 4,000,000 BCY [3,060,000$m^3$], not performing balancing the selected fleet, and the limited number of the equipment manufacturers used (i.e. 2).

### 2.4.2 Linear Programming

Linear optimization, or linear programming as it is popular is a tool used by managers to aid their decision. Although linear programming (LP) is not entirely new to the construction industry as Critical Path Methods, which driven from linear programming, have been popular since the 1950s, but LP doesn't have the prominent role in construction that it has in other industries (Stark and Mayer 1983).

Implementation of linear programming in earthmoving operations can be found in the work of (Easa1988, Jayawardane and Harris 1990, Easa 1987, Mayer and Stark 1981).

Easa (1987) developed computer software program (**EARTHN**), which solves a mixed-integer linear model of earthwork allocation to determine the quantities of material to be moved from each cut section (or borrow pit) to each fill section (or disposal pit).

### 2.4.3 Simulation

Simulation is applied widely as a practical tool for planning and analysis in many industries. However, in the case of construction processes, it has not yet emerged from the research stage into practice (Fente et al. 2000)

Shi and AbouRizk (1997) stated that construction simulation has been mostly successful in academic research with limited successful applications in the industry. They attributed that to the complexities involved in constructing a model and the resultant time requirement.

Simulation and its various applications in the construction operations have been described in the work of (Kannan and Vorster 2000, Martinez and Ioannou 1999, Smith et al. 1995, Farid and Koning 1994, Shi and AbouRizk 1997, Paulson et al 1987).

Two general types of simulation systems exist; general-purpose and Special-purpose simulation systems. General-purpose simulation tools and languages target a very broad domain and can be used to model almost any type of operation (Martinez and Ioannou, 1999). General-purpose simulation tools for construction modeling were developed, CYCLONE (Halpin and Woodhead 1976) its implementations such as Mainframe CYCLONE (Halpin and Woodhead 1976), STEPS (McCahill and Bernold 1993), and STROBOSCOPE (Martinez, 1996).

In contrast, special-purpose simulations are tools that target a narrow domain such as ductile iron pipe installation (Martinez and Ioannou, 1999). For the special-purpose simulation tools in earthwork; **SCRAPESIM** (Clemmens and Willenbrock 1978), which is a specialized program, developed at the Pennsylvania State University for simulation of scraper earthwork operations; AbouRizk and Mather (2000) proposed an integration approach that enabled the composition of simulation models for earthmoving operations from high-level descriptions in CAD; and **SimEarth** (Marzouk and Moselhi 2001), a simulation system developed to model earthmoving operations utilizing object-oriented features and discrete event simulation, fuzzy clustering is used to provide realistic estimates of haulers' travel time. Two databases have been developed to support *SimEarth*, the first stores equipment characteristics and the second stores haulers' maximum speed across different grades and under different loading conditions.

### 2.4.4 Queuing Theory

Queuing theory (or waiting line) theory describes the stochastic or variable behavior of an operation or system that provides service for arriving demands. When the capacity of the service facility or server is exceeded by the demand for service, a queue or waiting line forms. A queue is then a collection of arrivals or arriving units (customers) waiting for service (Cox and Smith, 1961).

Queues are commonplace in construction and mining operations, effective planning or management of the operations involves an examination of this queuing behavior. It is remarkable that queuing theory enjoyed a certain amount of popularity among engineers in the 1960's and 1970's but that the technique of simulation has been favored in more recent years. There are several reasons for this shift in popularity. Firstly, early work in applying queuing theory to civil engineering and mining engineering struggled mainly with the exponential time distribution assumption. Secondly, the solution of the relevant queuing equations for every application was not feasible. Thirdly, simulation offers the prospect of being able to solve all operational problems.

While acknowledging that simulation is a very useful technique, for many problems queuing theory can provide insight that is at times complementary to and at other times additional to that offered by simulation because of its fundamental analytical base (compared with a numerically based technique). As such queuing theory should be regarded as a basic tool in the repertoire of any civil or mining engineer (Carmichael 1986).

Early applications of queuing theory to earthmoving, open-cut mining were concerned with determining a production index (equivalently, sever utilization) from which the production of the operation could be evaluated. Generally, attention centered on (i) the use of exponential distributions for both the loading and traveling, and (ii) the single loader case, for example the work of O'Shea et al (1964), Maher and Cabrera (1973), Cabrera and Maher (1973), Carmichael 1986, and Carmichael 1987.

The **FLEET** (Karshenas and Farid, 1988) program models multiloader-truck operations using queuing theory and a systematic evaluation of all cost and production factors that influence construction operations at the steady state. Graphical solutions for a specified range of independent variables are provided. These variable include the following: Loader bucket size, truck capacity, number of loading units, and the truck's average travel time (Haul, Dump, and Return) referred to in their paper as "the project factors". FLEET computer program is an accurate model of the steady state, multiloader-truck process if exponential distribution did accurately fit load- and travel- time distributions. But, Erlang or Beta distribution more closely fits actual load and travel times in construction.

### 2.4.5 Other Methods:

Other methods were used for the equipment selection in earth-moving operations:

Touran et al. (1996) introduced a methodology for evaluating a dozer's capability to excavate a certain soil type based on specific soil properties. A set of decision charts were introduced that can be used by the users to estimate the tractor dozer's ability to excavate various types of soils.

Smith (1999) presented a method to estimate earthmoving productivity using regression techniques. (Smith 1999) investigated the results obtained from over 140 separate earthmoving operations taken from four different construction projects. Initially, the effects of bunching were determined, and many factors that influence productivity were identified. The development of a deterministic model that allows for the variability of the cycle times of a haulage plant was outlined. This model can then be used to assist in the estimation of earthmoving productivity. The model is based on data obtained from U.K highway construction projects and was developed using stepwise multiple regression techniques.

Gransberg (1996) Optimized haul unit size and number based on loading facility characteristics. He presented an improved model that relies on the derivation of a cost number (CIN) to determine the optimum size and number of haul units for a given loading facility. He concluded that the use of this model provides a means to design the construction equipment fleet for a wide range of material moving projects.

Haidar et al. (1999) used the genetic algorithms application for equipment selection. He research was directed into the development of a decision support system XpertRule for the selection of open cast mine equipment (XSOME), which was designed using a hybrid knowledge-base system and generic algorithms. The knowledge base relates mainly to the selection of equipment in broad categories. XSOME also applies advanced genetic algorithms search techniques to find the input variables that can achieve the optimal cost.

Of the above-mentioned methods for earthmoving equipment selection, only the simulation method and the queuing theory describe the variability in the time components of the earthmoving operations. However, few attempts to model earthmoving operations using queuing method can be found (**FLEET**, Karshenas and Farid, 1988), this can be attributed to assumptions underlying the queuing theory that are unrealistic in construction. Specifically, the exponential distribution does not accurately model load- and travel-time duration, and the transient effects of the process start-up and shutdown must be included to more closely model real-world construction processes (Farid and Koning 1994).

This research shows that the queuing theory with the required modifications to better represent the earthmoving operations offers a reliable and consistent means of predicting the production.

Further information about this method is given in the following section.

## 2.5 Queuing Method

### 2.5.1 Introduction:

A queuing system may be described as one having a service facility at which units of some kind (generically called "customers") arrive for service and, whenever there are more units in the system than the service facility can handle simultaneously, a queue, or waiting line, develops. The waiting units take their turn for service according to a preassigned rule, and after service they leave the service, and the output is the serviced customers (Srivastava and kashyap, 1982). The word queue has a somewhat negative connotation stemming from its association with waiting, a familiar experience of everyday life, such as that encountered in banks, postal offices, airports, gas stations, automobile traffic, mail backorders, telephone traffic, dental and medical offices, hospitals, and organ transplants ( Dshalalow, 1995).

Queuing theory is a branch of applied mathematics utilizing concepts from the field of stochastic processes. It has been developed in an attempt to predict fluctuating demands from observational data and to enable an enterprise to provide adequate service for its customers with tolerable waiting. However, the theory also basically improves understanding of a queuing situation, enabling better control. The theory provides one with predictions about waiting times, the number waiting at any time, the length of a busy period and so forth (Saaty, 1961).

### 2.5.2 Background:

At the beginning of this century, the practical requirements of telephone traffic, physics and rational organization of mass service (theatrical agencies, stores, automatic ticket machines, etc.) gave rise to a new type of mathematical problems. These problems were concerned primarily with questions of priority service to telephone subscribers, regulation of stock in stores to ensure continuous supply to customers, and determination of an adequate number of shop assistants and cash desks in stores. The first impetus to development of this theory was given by the famous Danish scientist A.K.Eralng (1878-1929), of the Copenhagen Telephone Company. His basic research in the field dates from the years 1908-1922, from then on, interest in the problems formulated by Erlang increased rapidly. More and more mathematicians, engineers, and also economists, became interested in similar problems and developed them accordingly. It turned out that problems arising in telephone traffic are also relevant for various other fields of research: science, engineering, economics, transport, military problems, and organization of industry (Gnedenko and Kovalenko, 1968).

Nowadays queuing theory is a well-developed branch of applied probability theory. A vast amount of literature, which is still growing rapidly, exists on this subject. Until about 1940 the development of queuing theory has mainly been directed by the needs encountered in the design of automatic telephone exchanges. After the Second World War, when applications of mathematical models and methods in technology and organization rose to a level hitherto unknown, it was soon recognized that queuing theory had a very broad field of application (Cohen, 1982).

### 2.5.3 Fundamental Characteristics Of Queuing Models

Elementary queuing models may be characterized by:

- The system input source.
- The queue discipline.
- The service discipline.
- The service mechanism.

#### 2.5.3.1 Input Source:

Units entering the system derive from some calling population or input source. The primary characterization of the population or source of the potential customers is whether it is finite or infinite. An infinite source system is easier to describe mathematically than one with a finite source. The reason for this is that, in a finite source system, the number of customers in the system affects the arrival rate; indeed, if every potential customer is already in the system, the arrival rate drops to zero. For infinite population systems the number of customers in the system has no effect on the arrival pattern. If the customer population is finite but large, we sometimes assume infinite source to simplify the mathematics (Allen, 1990). In an earthmoving operation the fleet of trucks will be finite in number and hence it has a finite input source (O'Shea et al 1964).

The two primary descriptors of customer arrivals involve the probability distribution function of the arriving customers and the probability distribution function of the time interval between successive customer arrivals (Gorney, 1981). The most common and most mathematically tractable assumption is that units arriving at the queuing system follow a *Poisson* distribution. Equivalently this may be rephrased to state that the time between unit arrivals (inter-arrival time) follows an exponential distribution. The Poisson assumption corresponds to units arriving randomly yet at an average rate, which is constant. Other common assumptions regarding the probability distribution of the unit arrivals are the Erlang distribution and constant distribution among others (Carmichael, 1987). Farid, and Koning (1994) stated that erlang or beta distribution more closely fits actual load and travel times in construction than exponential distribution.

An important parameter of the *Poisson* probability distribution is that which measures the average number of customer arrivals in a given period of time. This measure, known as the mean customer arrival rate, is denoted by the letter lambda ($\lambda$). If the unit of time (t) when this mean customer arrival rate is being considered is in, say, minute. If we were interested in knowing the probability of having *n* customers arrivals in *t* minutes of time, where customer arrivals are distributed in a *Poisson* manner,

We would use the equation,

$$P_n(t) = (\lambda t)^n \exp^{-\lambda t} / n! \tag{2.1}$$

Where parameter λ is a positive integer and parameter *n* corresponds to the integer values 0,1,……… customers (Gorney, 1981).

(Cox and Smith, 1961) proved that if the customer arrival process follows a *Poisson* probability distribution, the corresponding customer inter-arrival process will follow the exponential probability distribution.

#### 2.5.3.2 Queue Characteristics:

The queue of units waiting to be served is taken as either restricted (finite) or unrestricted (infinite) the former occurs where there is insufficient space for an unlimited length queue to form. In such a case, units arriving when the queue has reached its maximum length are turned away (Carmichael, 1987).

Infinite queue capacity; that is, every arriving customer is allowed to wait until service can provided; other queuing systems, called "loss systems," have zero queue capacity, thus if a customer arrives when the service facility is full utilized (all the servers are busy), the customer is turned away (Allen, 1990)

#### 2.5.3.3 Service Or Queue Discipline:

Queue discipline specifies how customers are to be selected for service from the pool of customers who have arrived at the queuing point (Cox and Smith, 1961).

The most natural prescription seems to be: "first-come, first-served" (FCFS), also called "first-in, first-out" (FIFO), which holds for most actual queuing in a physical sense (Kosten, 1973). Other common queue disciplines include "last-come, first-served," (LCFS) or ("last-in, first-out," LIFO); "random-selection-for-service," RSS (or "service-in-random order," SIRO), that means that each customer in the queue has the same probability of being selected for service; or "priority service," PRL. Priority service means that some customers get preferential treatment (Allen, 1990).

Typically, for construction and mining operations, the service discipline is FCFS (O'Shea et al 1964). It is customary to include under this heading queuing phenomena, like balking and reneging, depicting the behavior of the waiting customers. Customers are said to *balk* when, looking at the size of the queue, and estimating therefore the time they may have to wait before service, they do not join the queue. After joining the queue, the customers are said to *renege* if they fed up with waiting and leave the queue before service starts (Srivastava and Kashyap, 1982). Several customers may be in collusion whereby only one-person waits in line while the rest are then free to attend to other things. Some may even arrange to take turns waiting. Units may jockey from one line to another, as in bank (Saaty, 1961).

#### 2.5.3.4 Service Mechanism:

The manner of servicing the units may be characterized according to the number of servers. The servers will usually be arranged in parallel or in series as shown in Figure 2.2. Other queue types include cyclic and network queues (Carmichael, 1987).

A service facility may consist of several channels in parallel, some of which may be in series with other channels, or several parallel channels may all lead to one or more channels in series. In the case of channels in series, a queue may or may not be permitted before each channel. In supermarket, an arriving customer serves himself immediately on arrival and thus the number of service channels (though not the number of check-out counters) varies with the number of arrivals. All customers queue before the checkout counters for a second service (Saaty, 1961).

In servicing operation, there are three aspects of this that need description. First, there is the length of time taken to serve an individual customer, the service time. In the great majority of cases we assume that the service-times of different customers are independent random variables, all with the same probability distribution, to be called the service time distribution. In more complicated cases the customers may be of several types, each with its own distribution of service-time (Cox and Smith, 1961). The exponential distribution is often used to describe the service time of a server The Erlang and constant distributions, among others are also adopted (Allen, 1990).

The second aspect of service is that of the capacity of the system. This is defined as the maximum number of customers that can be served at any time. For example, in the single-server queue the capacity is one, for the m-server queue, the capacity is m (Cox and Smith, 1961).

The third property of service is its availability. To describe this we must state both when service facility are available and also any restrictions which reduce the number of customers that can be served together, below the full capacity of the system (Cox and Smith, 1961).

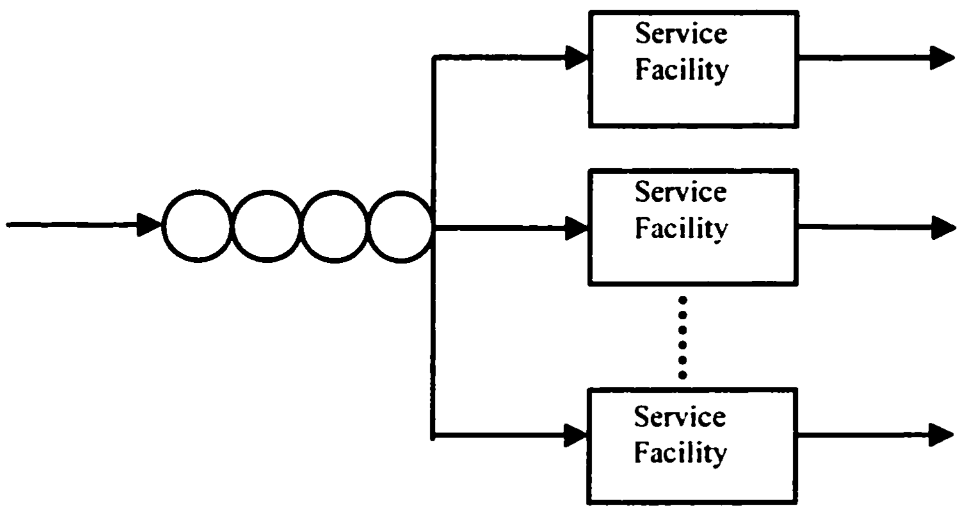



**Figure 2.2A Parallel servers (multichannel) queuing system.**

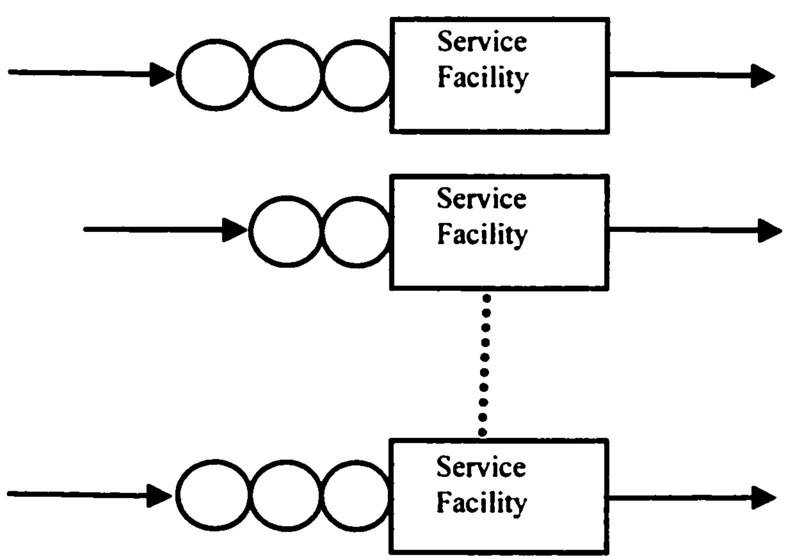



**Figure 2.2B Parallel servers (multichannel) queuing system.**


**Figure 2.2C Series servers (multistage) queuing system (with queuing allowed between servers or stages).**

### 2.5.4 Steady State:

At the initial start-up of a queuing system, the system behavior is affected by this initial condition and the system is said to be operating in a transient condition. At other times of operation of the system where the behavior is essentially unaffected by this initial condition, that is after the system has been operating for some time, the system is said to be operating in a steady state (or equilibrium) condition. Equilibrium may never be attained if, for example, the service time is longer than the arrival time. In practice, many operations attain this equilibrium status and are therefore studied for equilibrium. Note that equilibrium means that the probabilities are independent of time but not that the system becomes deterministic. The queue continues to fluctuate but the distributions describing it are fixed in time. One can compute averages, deviations, etc. (Saaty 1961). Queuing theory primarily concentrates on the steady state case for two reasons, Firstly the transient case is the more difficult analytically. Secondly, and fortunately, the steady state case represents the case of most interest, namely that involving the long-term operation of the system (Carmichael, 1987). However, a study done by (Farid and Koning 1994) shows that models which consider only the steady state may experience only a 1-2% increase in production.

### 2.5.5 Queuing Models:

A commonly adopted notation for finite source is (--/--/--/)/-- where the slots refer to:

(i) The probability distribution describing the back cycle time.

(ii) The probability distribution describing the service time.

(iii) The number of shovels.

(iv) The source (truck fleet) size.

For the probability describing the service times and back cycle times, the usual assumptions are that the distributions are either exponential (denoted *M*), Erlang (denoted $E_l$, where $l$ is the Erlang shape parameter) or constant (denoted *D*). Other distributions tend not to be as tractable and are not favored. The family of Erlang distribution in Figure 2.3. The exponential and constant distributions correspond to Erlang distributions with $l$=1 and $l \rightarrow \infty$ respectively, (Carmichael, 1986).

Solutions are available for some finite source queuing models. The solution to the most tractable model, the *(M/M/c)/K* model, has been available for many years. The *M* represents the extreme variability case where both the service times and back cycle times have coefficient of variation of 1. At the other extreme, the solution to the *(D/D/c)/K* is also easily obtained. This model represents the case of extreme lack of variability or extreme regularity where both the service times have a coefficient of variation. There are some available intermediate queuing models but not a full range discussed in the work of (Carmichael, 1986), and (Bunday and Scraton, 1980).

Various authors have examined different finite source queuing models as applied to shovel-truck operations. Exponential models have been used. O'Shea et al., (1964), Maher and Cabrera (1973), Halpin and Woodhead (1976). More general probability distributions for the service times have been discussed by Carmichael (1986), Morgan (1966), and Cabrera and Maher (1973).

### 2.5.6 Establishing The Suitability Of A Particular Distribution

Both the input source and the service mechanism are characterized by probability distributions, which reflects the underlying statistical qualities of the process. Conventionally, queuing theory models the probability distribution as exponential, Erlang or constant distributions although other distributions are possible (Carmichael, 1987).

Stochastic simulation of construction processes and other systems requires modeling the underlying random processes of the durations of various activities and tasks in the system. All simulators of construction systems agree that the key to a successful simulation experiment includes accurate modeling of input (AbouRizk and Halpin 1992). Probability distributions serve as input model for most stochastic simulations, when a random sample of an input process is available, we can use a variety of approaches to identify and fit an appropriate statistical distribution. One often recommended approach is to create a histogram of the sample data, select candidate distributions suggested by the histogram's shape, fit the associated parameter values to the data, and then choose the parameterized distribution that best represents the data set (Debrota et al 1988).

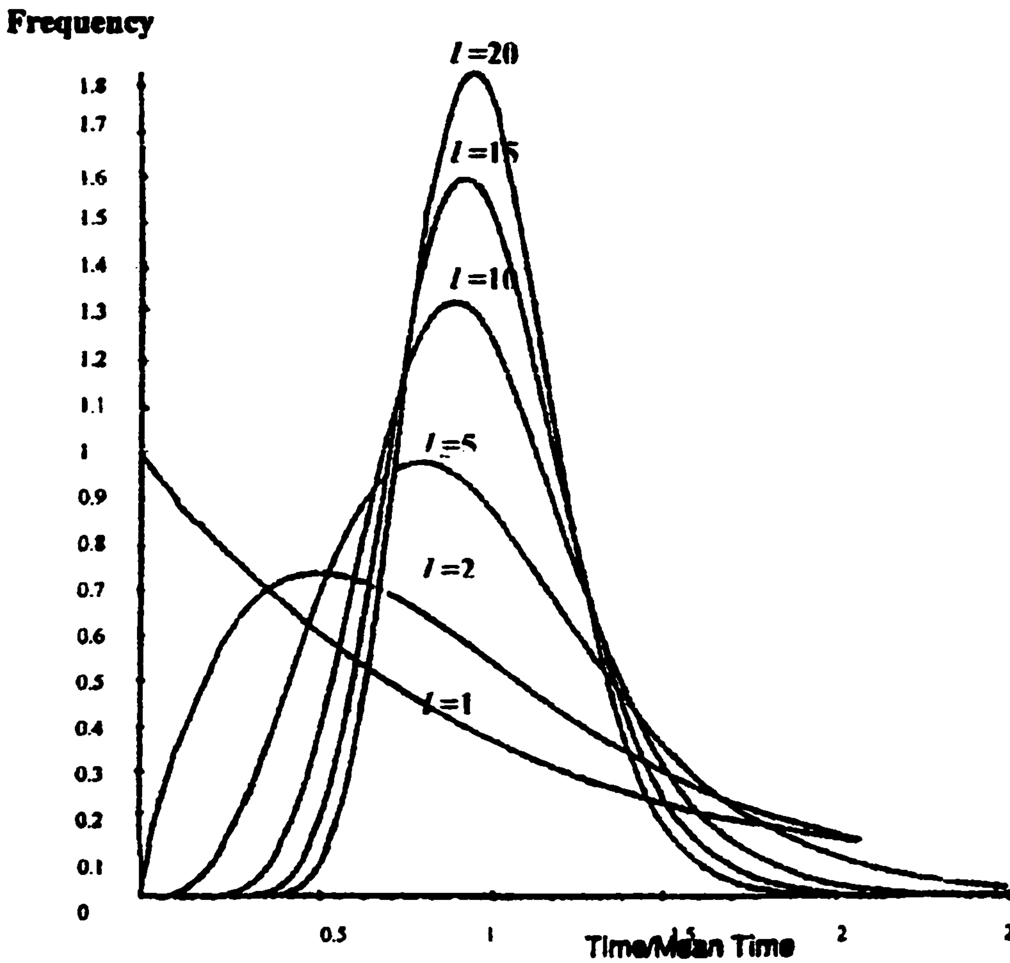



**Fig.2.3 Probability density functions of the Erlang distribution.**

AbouRizk and Halpin (1990) described a procedure for selecting input model for the simulation of repetitive construction operations. They stated that the duration input to a simulation experiment in construction is classically approached by fitting a statistical distribution to a collected sample of observations. A simulator can fit any of the classical statistical distributions to the sample of observations. In any case, a check for goodness of fit should be performed. This is often done in the form of statistical goodness-of-fit tests like the chi-square test, the Kolmogorov-Simirnov (K-S0 test), q-*q* plots, and visual inspection of the quality of the fit of the empirical cumulative density function (CDF) and the fitted (theoretical) CDF. One can also consider visual inspection of the theoretical probability density function (PDF) and the histogram of the sample data.

### 2.5.7 Field Investigations:

O'Shea et al. (1964) conducted field studies on the campus of the university of Illinois, Urbana. The operations studied involved the foundation excavation for three-campus building. They studied queuing theory and cycle-time distributions, and they concluded that the exponential distribution did not accurately fit real-world construction processes. Their field data collected for loader-tuck operations suggested that the Erlang distribution with $l$ = 10 and 16 better modeled load and haul activities, respectively

AbouRizk and Halpin (1992) concluded after analyzing samples of durations of different construction activities that while families of the flexible distributions-namely, the Johnson translation system and the Pearson system-were appropriate, the beta distribution-part of the Pearson system-was most suitable for modeling durations of construction activities.

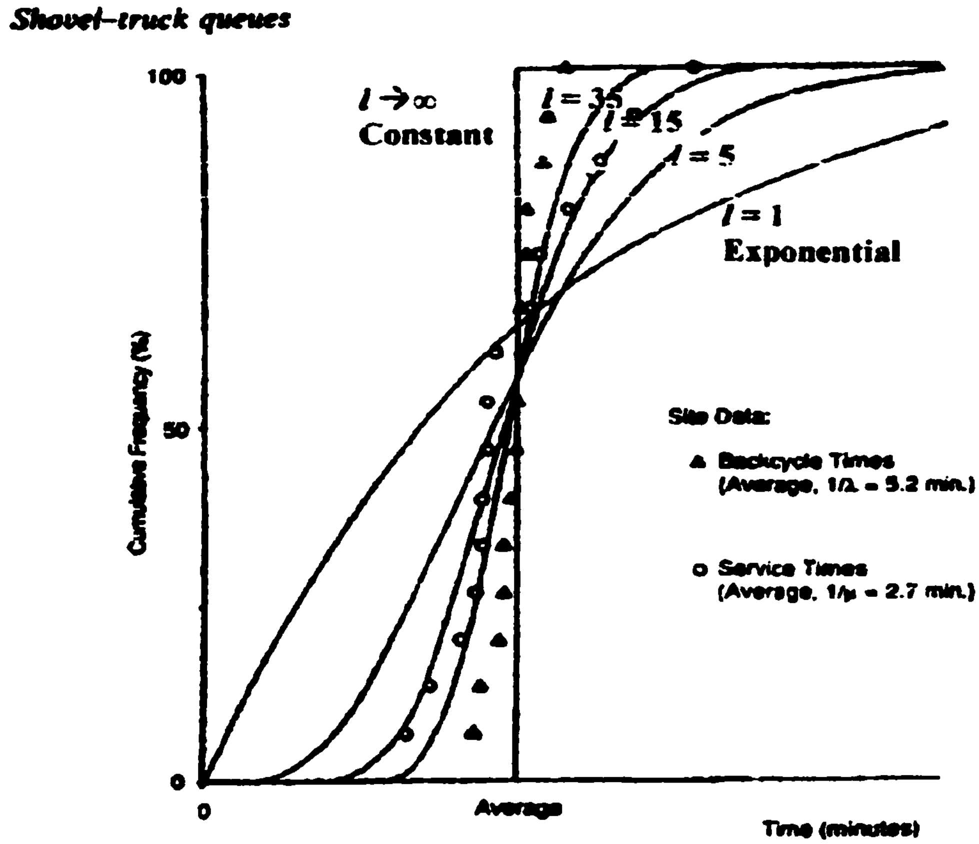



**Fig.2.4 Typical block of field data superimposed on some Erlang distribution (Carmichael, 1986)**

Carmichael (1986) studied thirty individual records of field data for earthmoving projects, he found that the best fit distribution to model back cycle times and service times follow Erlang distribution. Figure 2.4 gives a typical plot of field data for one truck in the quarrying operation superimposed on some Erlang distributions. He stated that an exponential (*l*=1) interval time distribution can be considered generally a good approximation as it reflects the phenomenon of bunching of trucks, on the other hand this distribution is considered unrealistic for service times and it leads to an underestimation of production as large as 10%. In general he concluded that using exponential production as large as 10%. In general he concluded that using exponential assumptions for the back cycle and service times, underestimates the production up to 9% and with an average of 3 %, on the other hand using conventional (deterministic) method showed an average overestimate errors of 12.5% when compared with site values. Queuing model with exponential distribution and Erlang distribution for arrival and service rate respectively would produce acceptable output error, and that the output of this model has very little differences for $l$ values above 10. It is noticed that multi-server models lead to lower errors than the single server models. It appeared that the assumptions on the probability distributions for the service times and back cycle times become less important as the number of servers increases.

## 2.6 Summary:

This chapter has reviewed previous theories and practical work in the field of equipment selection. A review of the applications of Knowledge-based expert systems (KBES), Linear Programming (LP), Simulation method, and Queuing theory in the construction industry in general and to the equipment selection in earth-moving operations in particular was presented. Queuing analysis provides an effective tool in assisting the decision making process for earthmoving equipment selection. From various field investigations it is found that Erlang or beta distribution more closely fits actual load and travel times in construction than exponential distribution, and that using queuing model with exponential distribution and Erlang distribution for arrival and service rate respectively would produce acceptable output error.

# CHAPTER 3

# PROPOSED METHODOLOGY FOR FLEET SELECTION

## 3.1 Introduction

This chapter describes a proposed methodology for earthmoving fleet selection. The queuing theory of model $(M/\ E_l\ /c)/K$ at the steady state is adopted to represent earthmoving process. In this model the stochastic variations of the server loading rate and that of the travel and dump times of hauling units are considered respectively by exponential and Erlang probability distributions, in addition the number of customers (haulers) is regarded as finite. Solutions for this queuing model are derived for forecasting the production of the one, two, and three servers excavation operation. The solution of this model yields among other items the percent of time the server system is busy (i.e. server utilization), this measure is used in the system production forecasting.

## 3.2 Equipment Selection.

The common practice in fleet selection for earthmoving operations is to choose a loader and then select proper haulers to serve the loader. The reliability of the selection depends on the level of the experience of the one who is selecting the equipment. This process is incorporated in the methodology. After choosing the loader and specifying the bucket type, a set of selected matching haulers is automatically listed. Two criteria should be taken in consideration (according to

Caterpillar's expert, who was interviewed) when matching between loaders and haulers: 1) the ratio of the capacity of haulers to the capacity of loaders; 2) the difference between the dumping height of loaders (B) and the loading height of haulers (D) as shown in Figure 3.1.

It is desirable to use haul units whose capacities balance the output of the excavator. If this is not achieved, operating difficulties will develop and the combined cost of excavating and hauling material will be higher than when balanced units are used. The loader should take between three and six bucketfuls to fill a hauler for an efficient operation with good balance (Day and Benjamin, 1991). Matching the dumping clearance of the loader with the loading height of the hauler units is to make sure that the combination of the equipment is feasible, and no field problems will be faced.

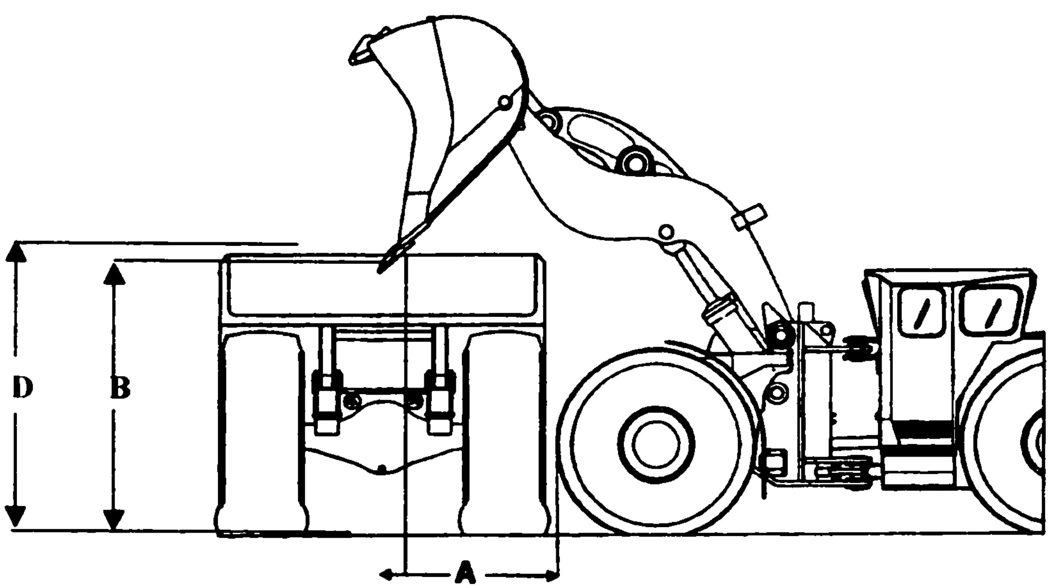



**Figure. 3.1 (Dumping and Loading Height)**
**Where D is the loading height (empty), (Day and Benjamin, 1989).**

The process of equipment selection requires to determine, haul unit performance, rolling resistance, traction force, tipping load, travel and service time, and servers' output. In addition other factors are considered such as, weather condition, altitude, and operator efficiency; this is shown in the following sections:

### 3.3 Haul-unit Speed Calculation

In practice a haul-unit performance is determined using manufacturer's alignment charts. This is time consuming process and may result in errors. In addition the specification sheet or performance handbook may not be available. To avoid this deficiency equation (3.1) is adopted from (Hicks, 1993).

Some of the advantages using an equation are: (1) It is easy to program for computer applications; (2) it is faster to use than the alignment charts; (3) it eliminates the alignment-chart measurement errors; and (4) it does not require continuous access to specifications.

The speed (velocity) of a hauler can be calculated using the following equation (Hicks, 1993):

$$V_h = K_o \, [0.01 \, C_f (W_e + U_w B) \, G_o]^{n'} \tag{3.1}$$

Where:

$V_h$ = haul-unit speed (km/hr);

$K_o$ = a coefficient determined by regression analysis;

$C_f$ = units conversion factor;

$W_e$ = empty weight of haul unit (t or kip[mass]);

$U_w$ = bank unit weight of material (t/$m^3$ or $yd^3$);

$B$ = bank carrying capacity of haul unit ($m^3$ or $yd^3$);

$G_o$ = effective resistance (grade plus rolling) (%); and

n' = an exponent determined by regression analysis.

The coefficients used in equation (3.1) are determined for each different machine based upon the manufacturer's specifications. Detailed information on this is shown in Appendix A.

### 3.4 Rolling Resistance

Rolling resistance is the resistance to movement of a vehicle over the travel surface due to internal friction, tire flexing, and penetration of vehicle into the travel surface. The rolling resistance of an earth-surface will probably not remain constant under varying climatic conditions or/and for varying types of soil (Peurifoy, Ledbetter, and Schexnader, 1996). Values for rolling resistance will be entered manually in the system.

The values of rolling resistance for various types of wheels and surfaces are shown in Table 3.1 in Appendix B.

### 3.5 Traction Force:

Traction force is the driving force developed by a wheel or track as it acts upon a surface. It is expressed as usable Drawbar Pull or Rimpull. The following factors affect traction: weight on the driving wheel or tracks, gripping action of the wheel or track, and ground conditions. The coefficient of traction (for any roadway) is the ratio of the maximum pull developed by the machine to the total weight on the drivers (Caterpillar performance book):

$$\text{Coefficient of traction} = \frac{\text{Pull}}{\text{Weight on drivers}} \tag{3.2}$$

The usable pull for a given machine is calculated using equation (3.3):

Usable pull= Coefficient of traction * weight on drivers. (3.3)

The Coefficients of traction for different types of wheels and surfaces are shown in Table 3.2 in Appendix B

### 3.6 Fill Factor

The percentage of an available volume in a body, bucket, or bowl that is actually used is expressed as the fill factor. A fill factor of 87% for a hauler body means for example that 13% of the rated volume is not being used to carry material. Buckets often have fill factors of 100% (Day and Benjamin, 1991).

Fill factors are shown in Table 3.3 in Appendix B.

### 3.7 Speed Correction:

For each hauler there is a standard tire. At times, user may not wish to use tires of the standard size for the selected hauler. User may prefer to use an optional tire configuration. The speed correction factor is the ratio of the revolutions per mile for the standard tire to the revolutions per mile for the optional tire. Speed correction factor can be calculated if both of these figures are known.

$$\text{Multiplier} = \frac{\text{Standard Tire Revolutions per Mile}}{\text{Optional Tire Revolutions per Mile}} \tag{3.4}$$

For example, to find the multiplier for the hauler type "773" with 24*25 $E_3$ optional tires (21*35 $E_3$ tires are standard):

Find the revolutions per mile for the standard tire: 254

Find the revolutions per mile for the optional tire: 243

Multiplier = 254/243= 1.05

(Caterpillar Software manual)

Values of the multipliers for the different types of tires are obtained from FPC and used in the model.

### 3.8 Safety Against Tipping

The bucket for front-end loaders range in size from 1/4 cubic yard (cy) to more than 20 cy heaped capacity. A careful balance between the size of the bucket and the size of the tractor should be considered. The safety against tipping forward when a full bucket is supported in a raised position with the arms fully extended in front of the tractor in the case of straight-ahead position, and in the maximum turned position, is based on the static tipping load. A safety factor of 2.5-3.5 can be suggested (Day and Benjamin, 1989), meaning that the tipping load, is two and a half to three and half times what a bucket loaded to its nominal heaped capacity. This high safety is needed to protect against the more sever load condition when moving. The model will calculate the bucket load for each selection and compare it with the tipping load according to the selected safety factor. Another way to check for tipping is through bucket rated load, which is limited to 75% of the load that would cause the machine to tip, and furnished by the manufacturers for each bucket.

### 3.9 Effect Of Altitude

The calculated speed of the hauler equipment is for standard conditions, which generally means sea level. At higher altitudes internal combustion engines lose power because of the decreased density of the air, which affects the fuel-to-air ratio in the combustion chamber of the engine, the available drawbar or rimpull and therefore the speed will be less. One method of accounting for altitude deration is to decrease the calculated speed by percentage equal to the percent of horsepower deration due to altitude (Day and Benjamin, 1989). Satisfying equation (3.5), which is used by the model:

$V_L = Vs^* D_f$ (Hicks, 1993) (3.5)

Where:

$V_L$ = Velocity at level "L".

$V_s$ = Velocity at sea level.

$D_f$ = Deration factor furnished by the manufacturer.

Sample of altitude deration factors are shown in Table 3.4 in Appendix B.

In the proposed model the travel distance of the loaders is considered minimum, thus the altitude effect on loaders is negligible, and it will be considered for the haulers only.

## 3.10 Cycle Time Calculations:

### 3.10.1 Hauling Units:

The number of trips per hour of the hauling units will depend on the weight of the vehicle, the engine horsepower, the haul distance, and the condition of the haul road. The cycle time of the hauler is calculated using Equation (3.6):

Cycle time = (empty haul travel time/return + loaded haul travel time) + (load with exchange time+ queue waiting time at the loading system) + (dump and maneuver time). (3.6)

Having the hauling distance in addition to the calculated speeds, for both empty and loaded trucks, simple motion methods can be used to calculate the time required for hauling.

Load with exchange time = Loader cycle time * (System passes/hauler –1) + First Bucket Dump + Hauler exchange time.

Where Hauler exchange time should be equal or bigger than Loader cycle time (Caterpillar FPC software). First Bucket Dump and hauler exchange time are fixed values for each machine and are obtained from FPC software. (O'Shea et al. 1964) defined that back cycle time or trip time of the hauling units in the finite systems includes the haul phases and the dump phase only.

**3.10.2 Loaders**: basic cycle times are considered for loaders, which include load, dump, four reversals of directions, and minimum travel. These basic cycle times are extracted from Caterpillar Performance Book and FPC Software.

## 3.11 Production Loss.

The potential production of loading and hauling equipment is generally much higher than the achieved on a long-term basis. In the proposed model the loss in production is considered to be due to:

- Weather condition
- Operator efficiency
- Equipment availability

### 3.11.1 Weather Conditions

The impact of weather condition will be taken mainly according to two situations; cold weather, moderate weather or hot weather.

#### 3.11.1.1 Cold Weather Conditions:

For the cold weather condition a nomograph (Figure.3.2) presented by McFadden and Bennett (1991) will be used, this nomograph originally constructed by Abele (1986) and based on the work of U.S. Army Cold Regions Research and Engineering Laboratory.

A cold environment factor ($F_e$), which indicates the effect of cold weather characteristics on equipment task efficiency, is obtained from the nomograph at any temperature, wind and snow fall condition, Where:

$$F_e = 1 / \text{Efficiency (E)} \qquad (3.7)$$

Where a factor of $F_e$=1, the base value, represents productivity under idea conditions; i.e. at a temperature equal or superior to 40° F, no wind and precipitation. As the work efficiency decrease with the adversity of weather conditions, the cold environment factor increases thereby giving the value or factor by which the work optimum effort (in terms of time) would have to be multiplied to determine the length of time required to perform the task in a specific cold environment condition. The variables used in nomograph are indicated as follows:

T=Air temperature

V=Wind speed

$P_s$=Snowfall precipitation

$F_e$=Cold environment factor for equipment task.

In this nomograph, we see that an ambient temperature of 20° F (-6.667 ° C), a moderate snowfall precipitation as well as a 20 mph (32.2 km/h) wind velocity result in a cold environment factor of 1.3, this means that an equipment task, which under normal or ideal conditions requires 2 hours to complete, would take 2.6 hours in the above-mentioned conditions.

### 3.11.1.2 Moderate and hot weather conditions:

For this weather condition a study presented by McFadden and Bennett (1991), is adopted. This study, done by Roberts (1976), presented data pertaining to machine efficiency for hauling and excavation equipment as related to temperature, lighting and precipitation as shown in Table 3.5 in Appendix B. As the main concern is the weather effect, the lighting effect is ignored.

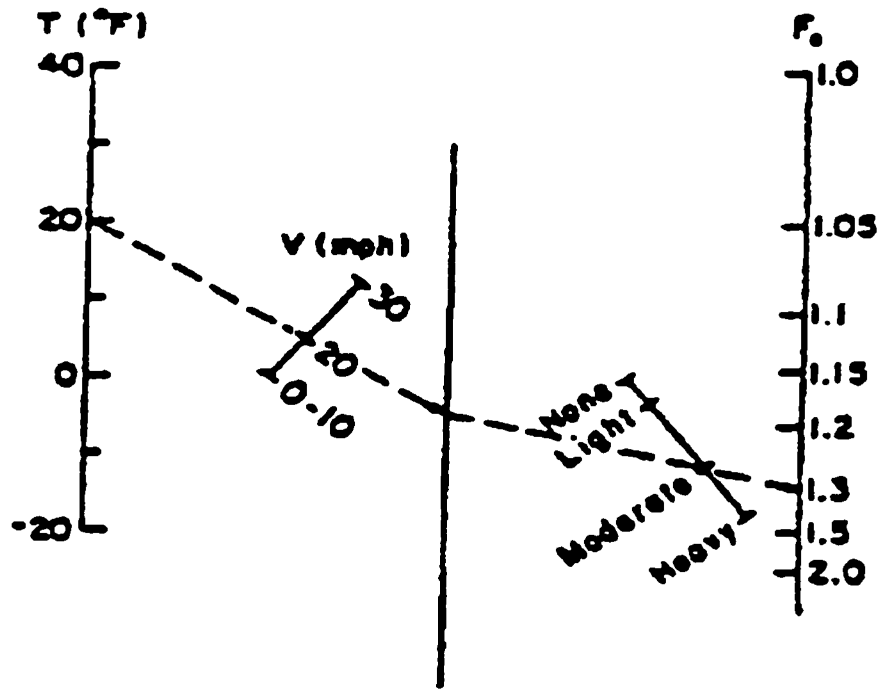



**Figure 3.2 Nomograph for estimating cold environment factors for equipment task.**

### 3.11.2 Operator Efficiency:

Unlike other equipment, the earthmoving machine operators generally achieve maximum performance of the equipment. Generally the shorter the haul rout is, the higher time is spent maneuvering by the operator. Therefore the shorter haul routs have more effect on operator efficiency and can lower productivity more than longer hauls (Caterpillar software manual).

Sample of operator efficiencies used by this methodology are shown in Table 3.6 in Appendix B

### 3.11.3 Fleet Availability:

Production may be reduced since equipment is not always available to operate when scheduled. Since loading and hauling equipment must work together, downtime has a compounding effect. Fleet production is reduced by the product of the loader and hauler availability. That is, if the loader on-shift availability is 90 percent and the average Hauler availability is 90 percent, then the fleet is 90 times 90, or 81 percent (Caterpillar FPC software).

## 3.12 Arrival and service rate:

Since the source or calling population of earthmoving operations is finite, when "n" units are in the system there are only (K-n) units remaining in the input source (where K is the total number of customers). The units alternate between being in the queuing system and being in the input source. The arrival rate ($\lambda$) is taken proportional to the number of units in the input source, namely $\lambda_n$ = (K-n) $\lambda$ for n = 0,1,2,3...K (Hillier and Lieberman, 1980) ($\lambda$ applies to an individual unit).

Where:

1/ $\lambda$ is the mean out-of-system time, which includes travel and dump times.

If the trucks have different traveling characteristics, that is, the source is *heterogeneous*, the back cycle time should be computed separately corresponding to each truck or truck type.

$\mu$ is the service rate for an individual server where $1/\mu$ is the mean service time. All servers are identical (homogeneous case). If the trucks have different servicing characteristics (for example trucks have different capacities), that is, the source is *heterogeneous*, the service time should be computed separately corresponding to each truck or truck type.

Generally,

$$\text{Arrival rate} = \begin{cases} (K-n)\,\lambda & n = 0,1,2,\ldots K \\ 0 & n \geq K \end{cases}$$

(Gross and Harris, 1985).

In practice not all the trucks that are used in the same operation have identical characteristics and that is the case for the servers too. Construction and mining equipment organizations are usually forced to use whatever equipment is available.

In this methodology the heterogeneity will be limited to the customers only.

Gross and Ince (1981) suggested an approximation for converting a heterogeneous system into an equivalent homogeneous one.

For a population with j types of customers, each with different mean back cycle and service times, let

$1 / \lambda_i$ = back cycle time of truck type i, i= 1,2,3...j

$1/\mu_i$ = service time of truck type i, i= 1,2,3...j

Let there be $K_1$ trucks of type 1 and $K_2$ trucks of type 2... $K_j$ trucks of type j such that $K_1 + K_2 + .... + K_j = K$. let $1/\lambda^-$ be the approximate back cycle time and $1/\mu^-$ be the approximate service time.

The approximation is based on a weighted average of rates.

$\lambda^- = (K_1 \lambda_1 + K_2 \lambda_2 + .... + K_j \lambda_j)/(K_1 + K_2 + ... + K_j)$

$\mu^- = (K_1 \mu_1 + K_2 \mu_2 + ..... + K_j \mu_j)/(K_1 + K_2 + .... + K_j)$

### 3.13 Matching Number of Haulers

Gransberg (1996) recommended that the optimum number of haul units is equal to its cycle time divided by the loading time. (Carmichael 1987) suggested that the optimal number of trucks will be close to the case where the production or cycle times of the loader matches the production or cycle times of the trucks. For the deterministic case, the service time is $1/\mu$ and the back cycle time is $1/\lambda$. For K' trucks traveling and 1 in service (that is the total number of trucks, K= K'+1), then the production is matched when

$1/\lambda = K' (1/\mu)$ or $K' = \mu/\lambda$

and the total number or trucks, $K = K' + 1 = \mu/\lambda + 1$. That is, $K = \mu/\lambda + 1$ and the optimum number of trucks should be in range of K - 1 to K + 1.

### 3.14 Output calculation:

The methodology followed in this work uses $(M/E_l/c)/K$ model, in which the trip times follow the negative exponential distribution, and the service times follow the

Erlang distribution of degree $l$ and the number of servers is less than or equal to three. Note that the value of $l$ for the Erlang distribution describing the service time distribution is equal to 20 for the cases of one and two servers. For the three-server-case, since using Erlang distribution with parameter ($l$) equal to 20 results an extremely large number of equations, and the effect of the selected type of time distribution decreases with larger number of servers as Carmichael (1986) noticed from field investigations, then erlang distribution with parameter $l$ equal to 3 will be used instead.

The assumptions that consequent from the selection of the Poisson distribution for arrivals are (Gross and Harris, 1985):

(i) The probability that an arrival occurs between time t and time $t + \Delta t$ is equal to $\lambda \Delta t + o(\Delta t)$. We write this as Pr {arrival occurs between t and $t + \Delta t$} = $\lambda \Delta t + o(\Delta t)$, where $\lambda$ is mean arrival rate, and $o(\Delta t)$ denotes a quantity that becomes negligible when compared to $\Delta t$ as $\Delta t \rightarrow 0$.

(ii) Pr {more than one arrival between t and $t + \Delta t$} = $o(\Delta t)$;

(iii) The numbers of arrivals in no overlapping intervals are statistically independent.

By using $E_l$, the Erlangian distribution, as the service distribution, (Hillier and Lieberman, 1980) illustrated that:

If we have $T_1, T_2, T_3 \ldots\ldots T_l$ which are $l$ independent variables with an identical exponential distribution whose mean is $1/\mu l$ . Then their sum,

$T = T_1 + T_2 + \ldots + T_l,$

has an Erlang distribution with parameters μ and $l$. The total service required by a customer may involve the server performing not just one specific task but also a sequence of $l$ tasks. If the respective tasks have an identical exponential distribution for their duration, the total service time would have an Erlang distribution, which would be the case, for example, if the server must perform the same exponential task $l$ times for each customer (Figure 3.3).

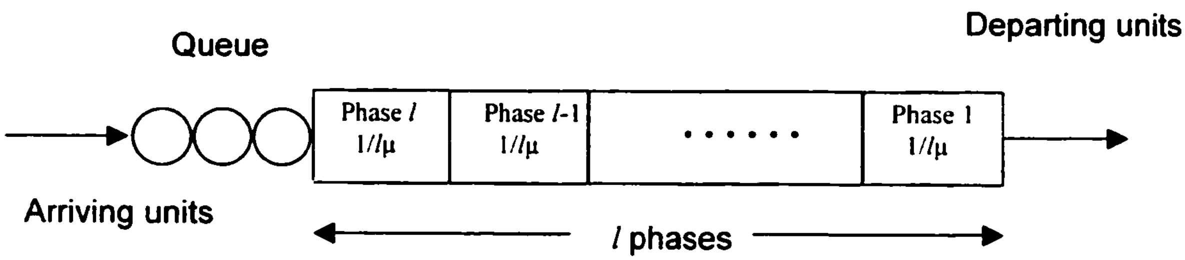



**Figure 3.3 Erlang Distribution for service time**

For the Erlang service time model, it is found convenient in its development to define the state as the number of "phases" that are waiting for service plus (for units receiving service) the number of phases left in the service operation. That is, each customer/unit arrival is viewed as $l$ phases that have to be serviced before the unit may depart the system. For example (for the single server case), if there are "q" units in the queue and the unit receiving service still requires "s" more phases in the system, or equivalently the state, $m = lq + s$; $s = 1,2...l$; $q = 0,1,2...K$. thus $m = 0,1,2...Kl$. The possible state transitions are from "m" to $(m + l)$ with the arrival of one customer or from "m" to $(m - 1)$ with the carrying out of the service on one phase for the customer with server(s) Carmichael (1987).

### 3.14.1 One-Server-Case:

If $P_m(t)$ is the probability that the system is in state m (the total number of phases in the queue and being served) at time t, then $P_m(t + \Delta t)$ is the probability that the system is in state m at time $t + \Delta t$, where $\Delta t$ is a small increment in time. Saaty (1961) proposed an equation to solve $P_m(t + \Delta t)$ for *infinite* input source, but since earthmoving operations require *finite* input source (limited number of trucks) as shown in the literature review section, this equation is modified as follows:

The probability that the system is in state m at time $t + \Delta t$ is therefore:

$$P_m(t + \Delta t)= P_m(t)[1-( \lambda (K-m/l) + l\mu) \Delta t] + P_{m+1}(t)\, l\mu\, \Delta t + P_{m-l}(t)\, \lambda\, (K-(m-l)/l)\, \Delta t \qquad (3.8)$$

As the arrival rate follows the Poisson distribution, the probability of one arrival during $\Delta t$ is $\lambda_m \Delta t$ (plus negligible terms) and hence the probability of no arrival during $\Delta t$ is $1- \lambda_m \Delta t$.

Where: $\lambda_m = \lambda (K-m/l)$, and $m/l$ is rounded up to the nearest integer.

By transposing $P_m(t)$ from the right-hand side to the left, dividing through by $\Delta t$ and taking the limit as $\Delta t \rightarrow 0$ .

$$P_m(t + \Delta t)- P_m(t)= -P_m(t)[( \lambda (K-m/l) + l\mu) \Delta t] + P_{m+1}(t)\, l\mu\, \Delta t + P_{m-l}(t)\, \lambda\, (K-(m-l)/l)\, \Delta t$$

$$[P_m(t + \Delta t)- P_m(t)]/ \Delta t = -P_m(t)[( \lambda (K-m/l) + l\mu)] + P_{m+1}(t)\, l\mu + P_{m-l}(t)\, \lambda\, (K-(m-l)/l)$$

$$d P_m(t)/dt = P_{m+1}(t)\, l\mu + P_{m-l}(t)\, \lambda\, (K-(m-l)/l) -P_m(t)[( \lambda (K-m/l) + l\mu)]$$

Since $P_m(t)$ is to be independent of time (steady state condition) :

$d P_m(t)/dt$ is zero (O'Shea et al. 1964)

Therefore;

$$0 = P_{m+1}(t)\, l\mu \;+ P_{m-l}(t)\, \lambda\, (K-(m-l)/l) \;- P_m(t)[(\lambda\, (K-m/l) + l\mu)]$$

Where:

For m = 0

$$K\lambda\, P_0 = l\mu\, P_1$$

Which is obtained from the equation by substituting m = 0, it is realized that no departures are possible during the time interval $\Delta t$ if the system was in state m = 0 at time t, and that $P_j = 0$ if $j < 0$.

For m =1

$$0 = P_2(t)\, l\mu \;+ P_{1-l}(t)\, \lambda\, (K-(1-l)/l) \;- P_1(t)[(\lambda\, (K-1/l) + l\mu)]$$

$$P_2\, l\mu \;=\; P_{1-l}(t)\, \lambda\, (K-(1-l)/l) \;- [(\lambda\, (K-1/l) + l\mu)]\, P_1$$

For m= 2

$$0 = P_3(t)\, l\mu \;+ P_{2-l}(t)\, \lambda\, (K-(2-l)/l) \;- P_2(t)[(\lambda\, (K-2/l) + l\mu)]$$

$$P_3(t)\, l\mu \;=\; P_{2-l}(t)\, \lambda\, (K-(2-l)/l) \;- P_2(t)[(\lambda\, (K-2/l) + l\mu)]$$

$$\vdots \qquad\qquad \vdots$$

For m = K*l*,

$$0 = P_{Kl+1}(t)\, l\mu \;+ P_{Kl-l}(t)\, \lambda\, (K-(Kl-l)/l) \;- P_m(t)[(\lambda\, (K- Kl/l) + l\mu)]$$

$$P_{Kl-l}(t)\, \lambda\, l = \;- l\mu\, P_{Kl}\,(t)$$

Sample of probability calculations for one server is shown in Appendix C.

After evaluating, $P_m$ , m = 0, 1, 2,......, K$l$, to determine the steady state probabilities that there are, for example, $n$ trucks in the system. The relationship between m and n is as follows (Saaty 1961):

$$P_n = \sum_{m=nl-l+1}^{nl} P_m \qquad n=1,2,........,K \qquad (3.9)$$

Where:

$P_{(n=0)} = P_{(m=0)}$

Knowing $P_n$ , n = 0, 1, 2,......K, allows the utilization of the system to be determined, from the following equation.

$$\eta = P_1 + P_2 + ... \qquad (3.10)$$

Or

$\eta = 1-P_0$

The system output is proportional to the percentage or proportion of time that the servers are busy. For the single server case, Allen (1978):

$$\Theta = \mu\,(1-P_0) = \mu\,(P_1 + P_2 + ...) \qquad (3.11)$$

With units the same as $\mu$, that is, customer per time.

### 3.14.2 Two-Server-Case:

The same general equation can be used for the two-server-case with some modification with the arrival and service rate:

$$P_m(t + \Delta t) = P_m(t)[1 - (\lambda_m + l\mu_m)\Delta t] + P_{m+1}(t)\, l\mu_m\, \Delta t + P_{m-l}(t)\, \lambda_{m-l}\, \Delta t \qquad (3.12)$$

For this case where a customer arrival gives a jump upward of $l$ phases, and either server 1 or server 2 completes a phase giving a jump downwards of 1 phase;

Carmichael (1987) suggested values for $\lambda_m$ and $\mu_m$ as follows:

$$\lambda_m = \begin{cases} (K - F_m)\,\lambda & \text{For } m \le l \\ [K - (j+1) - (i-1)/l]\,\lambda & \text{For } m > l;\ \text{(i and j can be obtained from } m = jl + i) \end{cases}$$

And

$$\mu_m = F_m\,\mu \qquad (3.13)$$

Where:

$$F_m = \begin{cases} 2m/(m+1) & \text{For } m \le l \\ 2 & \text{For } m > l \end{cases}$$

Where $F_n$ reflects the probability of either one server is working or both servers are working.

$$P_m(t + \Delta t) = P_m(t)[1-(\lambda_m + l\mu_m)\,\Delta t] + P_{m+1}(t)\, l\mu_{m+1}\,\Delta t + P_{m-l}(t)\,\lambda_{m-l}\,\Delta t$$

$$0 = P_{m+1}(t)\, l\mu_{m+1} + P_{m-l}(t)\,\lambda_{m-l} - P_m(t)[(\lambda_m + l\mu_m)]$$

$$P_m(t)[(\lambda_m + l\mu_m)] = P_{m+1}(t)\, l\mu_{m+1} + P_{m-l}(t)\,\lambda_{m-l}$$

For $m = 0$

$F_m = 0$ thus $\mu_m = 0$

$\lambda_m = (K - 0)\,\lambda = K\,\lambda$

$F_{m+1} = 2(1)/(1+1)=1$ thus $\mu_m = \mu$

$\lambda_{m+1} = (K - 1)\,\lambda$

As $l$ =20 therefore $P_{m-l} = 0$

Therefore:

$P_0[(\lambda_m + l\mu_m)] = P_1\, l\mu_{m+1}$

$P_0(K\lambda) = P_1\, l\mu$

For $m = 1$

$F_m = 2(1)/(1+1)=1$ thus $\mu_m = \mu$

$\lambda_m = (K - 1)\,\lambda$

$F_{m+1} = 2(2)/(1+2)= 4/3$ thus $\mu_{m+1} = 4/3\,\mu$

$\lambda_{m+1} = (K - 4/3)\,\lambda$

As $l$ =20 therefore $P_{m-l} = 0$

Therefore:

$P_1[((K - 1)\,\lambda + l\mu)] = P_2\, l\,(4/3)\,\mu$

And so on for all values of m ($m = 0,1,2,3\ldots Kl$).

To determine the probability of having n customers in the system Carmichael (1987) presented the following relationship between $P_n$, $n = 0,1,\ldots\ldots.,K$ and $P_m$, $m = 0,1,\ldots\ldots\ldots,Kl$:

Equations (3.14):

$$P_{(n=0)} = P_{(m=0)}$$

$$P_1=\sum_{m=1}^{l} \frac{2}{m+1} P_m$$

$$P_2=\sum_{m=l}^{l} \frac{m+1-2}{m+1} P_m + \sum_{m=l}^{2l} \frac{2l-m+1}{m+1} P_m$$

$$P_h=\sum_{m=(h-2)l}^{l}\left( 1-\frac{(h-1)l-m+1}{l} \right) P_m + \sum_{m=(h-1)l+1}^{hl} \frac{hl-m+1}{l} P_m$$

$$h = 3,4,\ldots\ldots,K-1$$

$$P_K=\sum_{m=(K-2)l+1}^{(K-1)l}\left( 1-\frac{(K-1)l-m+1}{l} \right) P_m + \sum_{m=(K-1)l+1}^{Kl} P_m$$

Sample of probability calculations for two servers is shown in Appendix C.

The utilization for the two server case, namely

$$\eta = P_1 + 2(P_2+P_3+\ldots) \tag{3.15}$$

Or

$$\eta=2-2P_0 - P_1$$

The output becomes

$\Theta = \mu\eta$

Allen (1978)

### 3.14.3 Three-Server-Case:

For three servers the derivation of the steady state equations is based on the lexicographic order used by Mayhugh and McCormick (1968) to solve $M/E_l/c$ with *infinite* population of customers. The procedure has been modified to make it suitable for application to earthmoving operations, where the number of customers is *finite*.

As in the first two cases, the Erlang distribution of parameter $l$ of the service time can be considered as the sum of $l$ independent random variables each having the same negative exponential distribution with parameter $\mu$, and that the loading of each hauler is consisting of $l$ ordered stages. The $l$ stages of service have no physical significance. They are to represent the service system as a stochastic process.

Mayhugh and McCormick (1968) presented that the state of the stochastic service system can be showed as:

$$n\text{: } x_l x_{l-1} \ldots\ldots x_1 \qquad (3.16)$$

Where $n$ is the number of haulers waiting to be loaded or being loaded, and $x_i$ is the total number of customers in $i^{th}$ stages of service (summed across all service channels) with $x_1$ is the total number customers in the last or exit stage and $x_l$ is the total number customers in the first or entry stage. The symbols will be ordered lexicographically as follows: (1) by $n$ in ascending numerical order; (2) for constant $n$, by $x_1$ in descending numerical order; (3) for constant $x_1$, by $x_2$ in descending numerical order; *etc.* then label the symbols in lexicographic arrangement serially by the integer $j = 0,1,2.......$ In the following the integer $j$ will be used to refer to the corresponding states of the system.

The modified total number of states in the system for the finite population of customers is as follows:

The total number of states in which there are $n$ customers, where $n \le c$, is

$$\binom{n+l-1}{n} \tag{3.17}$$

If $n > c$, the number of states in which $n$ customers are present is constant and equal to

$$y = y(c,l) = \binom{c+l-1}{c} \tag{3.18}$$

We shall call "y" the repetitive cycle length because if $j$ is a state wherein $n > c$, then the symbol for state $j$-y is identical with that of $j$ except that the number of customers in the system is ($n$-1) shown in table 3.6.

Therefore the total number of states in the system is:

$$\sum_{n=1}^{c} \binom{n+l-1}{n} + \binom{n+l-1}{n}(K-c)+1 \tag{3.19}$$

| Symbol | j | Symbol | j | Symbol | j |
|---|---|---|---|---|---|
| 0:000 | 0 | 4:003 | 20 | 6:003 | 40 |
| 1:001 | 1 | 4:012 | 21 | 6:012 | 41 |
| 1:010 | 2 | 4:102 | 22 | 6:102 | 42 |
| 1:100 | 3 | 4:021 | 23 | 6:021 | 43 |
| 2:002 | 4 | 4:111 | 24 | 6:111 | 44 |
| 2:011 | 5 | 4:201 | 25 | 6:201 | 45 |
| 2:101 | 6 | 4:030 | 26 | 6:030 | 46 |
| 2:020 | 7 | 4:120 | 27 | 6:120 | 47 |
| 2:110 | 8 | 4:210 | 28 | 6:210 | 48 |
| 2:200 | 9 | 4:300 | 29 | 6:300 | 49 |
| 3:003 | 10 | 5:003 | 30 | 7:003 | 50 |
| 3:012 | 11 | 5:012 | 31 | 7:012 | 51 |
| 3:102 | 12 | 5:102 | 32 | 7:102 | 52 |
| 3:021 | 13 | 5:021 | 33 | 7:021 | 53 |
| 3:111 | 14 | 5:111 | 34 | 7:111 | 54 |
| 3:201 | 15 | 5:201 | 35 | 7:201 | 55 |
| 3:030 | 16 | 5:030 | 36 | 7:030 | 56 |
| 3:120 | 17 | 5:120 | 37 | 7:120 | 57 |
| 3:210 | 18 | 5:210 | 38 | 7:210 | 58 |
| 3:300 | 19 | 5:300 | 39 | 7:300 | 59 |

**Table 3.6 System's different states**

The states of the system for *M/M/1/k* model were identified by O'Shea (1964); this work was modified by Mayhugh and McCormick (1968) to work with the Erlang service time distribution and infinite source population:

Let si = si(*j*), i=0,1,2,.......*l*+1 be the serial number of the states from which transition of one customer can bring the system to state *j*, and let p(*j*, t) denote the probability that the service system is in state *j* at time t.

The list of the possible symbols as proposed is: (3.20)

| symbols | number |
|---|---|
| $n: x_l x_{l-1} \ldots\ldots x_2 x_1$ | $j$ |
| $(n-1): (x_l-1) x_{l-1} \ldots\ldots x_2 x_1$ | $s_0$ |
| $(n+1): x_l x_{l-1} \ldots\ldots x_2 (x_1+1)$ | $s_1$ |
| $n: x_l x_{l-1} \ldots\ldots (x_2+1)(x_1-1)$ | $s_2$ |
| $n: x_l x_{l-1} \ldots\ldots (x_3+1)(x_2-1) x_1$ | $s_3$ |
| $\vdots$ | $\vdots$ |
| $n: (x_l+1)(x_{l-1}-1) \ldots\ldots x_2 x_1$ | $s_l$ |
| $(n+1): (x_l-1) x_{l-1} \ldots\ldots x_2 (x_1+1)$ | $s_{l+1}$ |

On the assumption that the probability of more than one transition of a customer from any stage to the succeeding stage in any time interval (t, i + Δt) is 0(Δt), Mayhugh and McCormick (1968) derived equations to calculate p(j, i + Δt), the probability that the system in state j at time t+Δt , these equations will be modified to reflect the case of *finite input source* as follows:

Equations (3.21)

$n < c$,

$p(j, i + \Delta t) = p(s_0,t)[\, k-(n-1)]\lambda\, \Delta t + [1-(k-n)\, \lambda + n\, \mu]\, \Delta t]\, p(j, t) + E(t, j{:}\ n<c)\, \mu\, \Delta t + 0(\Delta t)$

$n = c$

$p(j, i + \Delta t) = p(s_0,t)[\, k-(n-1)]\lambda\, \Delta t + [1-(k-n)\, \lambda + c\mu]\, \Delta t]\, p(j, t) + E(t, j{:}\ c \le n \le k)\, \mu\Delta t + 0(\Delta t)$

$c < n \le k$

$p(t, i + \Delta t) = p(j\text{-}y, t)[\, k-(n-1)]\lambda\, \Delta t + [1-(k-n)\lambda + c\mu]\, \Delta t]\, p(j, t) + E(t, j{:}\ c \le n \le k)\mu\Delta t + 0(\Delta t)$

Where the coefficients E(t, $j$: $n$<r) and E(t, $j$: r≤ $n$ ≤ k) are the expected number of customers at time t (considering all possible states of the system) such that the transition of the customer to the succeeding stage of service brings the system to state $j$: $n$<c or c≤ $n$ ≤ k respectively. Thus,

Equations (3.22)

$$E(t, j: n<c) = \sum_{i=1}^{i=l} (x_l + 1)\, p(s_i, t)$$

$$E(t, j: c \le n \le K) = \sum_{i=2}^{i=l+1} (x_l + 1)\, p(s_i, t)$$

From equations (3.21) and (3.22) we obtain the equations for the steady state probabilities p($j$),and then dividing by μ and setting α= λ/ μ:

Equations (3.23)

$$p(s_0)\,[\,k-(n-1)]\alpha - [\alpha(\,k-n) + n]\,p(j) + \sum_{i=1}^{i=l} (x_l + 1)\, p(s_i) = 0 \qquad n < c$$

$$p(s_0)\,[\,k-(n-1)]\alpha - [\alpha(\,k-n) + c]\,p(j) + \sum_{i=2}^{i=l+1} (x_l + 1)\, p(s_i) = 0 \qquad n = c$$

$$p(j-y)\,[\,k-(n-1)]\alpha - [\alpha(\,k-n) + c]\,p(j) + \sum_{i=2}^{i=l+1} (x_l + 1)\, p(s_i) = 0 \qquad c < n \le k-1$$

1:010 $j = 2$

0:(-1)10 $s_0$

2:011 $s_1=5$

1:02(-1) $s_2$

1:100 $s_3=3$

Any symbol with a negative element, corresponds to an impossible state of the system and is to be assigned probability zero as the case for $s_0$ and $s_2$.

Equation $j = 2$ is

$$p(s_0)\,[\,k-(n-1)]\alpha - [\alpha(\,k-n) + n]\,p(j) + \sum_{i=1}^{i=l} (x_l + 1)\,p(s_i) = 0 \qquad n < c$$

$$p(s_0)\,[\,k-(n-1)]\alpha - [\alpha(\,k-n) + n]p_1 + (x_1 + 1)\,p(s_1) + (x_2 + 1)\,p(s_2) + (x_3 + 1)\,p(s_3) = 0$$

$$0 - [\alpha(\,k-n) + n]p_2 + (x_1 + 1)\,p(s_1) + 0 + (x_3 + 1)\,p(s_3) = 0$$

$$-[\alpha(\,k-1) + 1]p_2 + (\,1)\,p(s_1) + 0 + (\,1)\,p(s_3) = 0$$

$$-[\alpha(\,k-1) + 1]p_2 + p_5 + p_3 = 0$$

Again, from table 3.6 the symbol for $j = 13$ is 3:021, since $n = c$, we compute the quantities needed to substitute in the last of equations (3.25)

3:021 $j = 13$

2:(-1)21 $s_0$

3:030 $s_2=16$

3:111 $s_3=14$

4:(-1)22 $s_4$

Since $s_0$ and $s_4$ corresponds to nonexistence states, equation $j$ = 13 is

$$p(s_0)\,[\,k-(n-1)]\alpha - [\alpha(\,k-n) + c]\,p(j) + \sum_{i=2}^{i=l+1} (x_i + 1)\,p(s_i) = 0 \qquad\qquad n = c$$

$$p(s_0)\,[\,k-(n-1)]\alpha - [\alpha(\,k-n) + c]\,p(j) + (x_2 + 1)\,p(s_2) + (x_3 + 1)\,p(s_3) + (x_4 + 1)\,p(s_4) = 0$$

$$0 - [\alpha(\,k-n) + c]\,p(13) + (3)\,p(s_2) + (1)\,p(s_3) + 0 = 0$$

$$-[\alpha(\,k-3) + 3]\,p_{13} + 3\,p_{16} + p_{14} = 0$$

The same process is repeated for all the values of $j$, and the obtained set of equations can be arranged as: (a) a set of initial equations (for $n \le c$), (b) system of y equations repeated K-c times (for $n > c$).

Dividing the equations by $p_0$ and then substituting $q_j = p_j / p_0$, the equations can be rearranged as follows:

Initial equations:

$$q_1 = K\alpha$$

$$2q_4 = [(K-1)\,\alpha+1]q_1 - q_2$$

$$q_5 = [(K-1)\,\alpha+1]q_2 - q_3$$

$$q_5 + 3q_{10} = [(K-2)\,\alpha+2]q_4$$

$$q_6 = [(K-1)\,\alpha+1]q_3 - K\alpha$$

$$q_6 + 2q_7 + 2q_{11} = [(K-2)\,\alpha+2]q_5$$

$$q_{11} = [(K-3)\,\alpha+3]q_{10}$$

$$q_8 + 2q_{12} = [(K-2)\,\alpha+2]q_6 - (K-1)\,\alpha q_1$$

$$q_8 + q_{13} = [(K-2)\,\alpha+2]q_7$$

$$q_{12} + 2q_{13} = [(K-3)\,\alpha+3]q_{11}$$

$$2q_9+q_{14}=[(K-2)\ \alpha+2]q_8-(K-1)\ \alpha q_2$$

$$q_{14}+3q_{20}=[(K-3)\ \alpha+3]q_{12}-(K-2)\ \alpha q_4$$

$$q_{14}+3q_{16}=[(K-3)\ \alpha+3]q_{13}$$

$$q_{15}=[(K-2)\ \alpha+2]q_9-(K-1)\ \alpha q_3$$

$$2q_{15}+2q_{17}+2q_{21}=[(K-3)\ \alpha+3]q_{14}-(K-2)\ \alpha q_5$$

$$q_{17}=[(K-3)\ \alpha+3]q_{16}$$

$$q_{21}=[(K-4)\ \alpha+3]q_{20}-(K-3)\ \alpha q_{10}$$

Repetitive equations:

First cycle:

$$q_{18}+2q_{22}=[(K-3)\ \alpha+3]q_{15}-(K-2)\ \alpha q_6$$

$$2q_{18}+q_{23}=[(K-3)\ \alpha+3]q_{17}-(K-2)\ \alpha q_7$$

$$q_{22}+2q_{23}=[(K-3)\ \alpha+3]q_{21}-(K-2)\ \alpha q_{11}$$

$$q_{19}+q_{24}=[(K-3)\ \alpha+3]q_{18}-(K-2)\ \alpha q_8$$

$$q_{24}+3q_{30}=[(K-4)\ \alpha+3]q_{22}-(K-3)\ \alpha q_{12}$$

$$q_{24}+3q_{26}=[(-4)\ \alpha+3]q_{23}-(K-3)\ \alpha q_{13}$$

$$q_{25}=[(K-3)\ \alpha+3]q_{19}-(K-2)\ \alpha q_9$$

$$2q_{25}+2q_{27}+2q_{31}=[(K-4)\ \alpha+3]q_{24}-(K-3)\ \alpha q_{14}$$

$$q_{27}=[(K-4)\ \alpha+3]q_{26}-(K-3)\ \alpha q_{16}$$

$$q_{31}=[(K-5)\ \alpha+3]q_{30}-(K-4)\ \alpha q_{20}$$

Second cycle:

$$q_{28}+2q_{32}=[(K-4)\ \alpha+3]q_{25}-(K-3)\ \alpha q_{15}$$

$$2q_{28} + q_{33} = [(K-4)\ \alpha+3]q_{27} - (K-3)\ \alpha q_{17}$$

$$q_{32} + 2q_{33} = [(K-4)\ \alpha+3]q_{31} - K-3)\ \alpha q_{21}$$

$$3q_{29} + q_{34} = [(K-4)\ \alpha+3]q_{28} - (K-3)\ \alpha q_{18}$$

$$q_{34} + 3q_{40} = [(K-5)\ \alpha+3]q_{32} - (K-4)\ \alpha q_{22}$$

$$q_{34} + 3q_{36} = [(K-5)\ \alpha+3]q_{33} - (K-4)\ \alpha q_{23}$$

$$q_{35} = [(K-4)\ \alpha+3]q_{29} - (K-3)\ \alpha q_{19}$$

$$2q_{35} + 2q_{37} + 2q_{41} = [(K-5)\ \alpha+3]q_{34} - (K-4)\ \alpha q_{24}$$

$$q_{37} = [(K-5)\ \alpha+3]q_{36} - (K-4)\ \alpha q_{26}$$

$$q_{41} = [(K-6)\ \alpha+3]q_{40} - (K-5)\ \alpha q_{30}$$

The repetitive equations consist of (K-c) cycles, each cycle has y=10 equations.

We can represent the sequence of all repetitive subsystems by (3.26):

$$E_iQ_i = D_iQ_i^* \qquad 1 \le i \le \binom{n+l-1}{n}(K-c)/10$$

Where:

$$E_i = \begin{bmatrix}
1 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \\
-[K-(i+2)]\alpha-3 & 3 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -[K-(i+3)]\alpha-3 & 0 & 1 & 0 & 0 & 0 & 3 & 0 \\
0 & 0 & 0 & -[K-(i+2)]\alpha-3 & 1 & 0 & 3 & 0 & 0 & 0 \\
0 & -[K-(i+2)]\alpha-3 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -[K-(i+2)]\alpha-3 & 2 & 0 & 2 & 0 & 2 \\
0 & 0 & 0 & 0 & 0 & 0 & -[K-(i+2)]\alpha-3 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -[K-(i+2)]\alpha-3 & 0
\end{bmatrix}$$

$$
D_i = \left[\begin{array}{ccccccccccccc}
-[K-(i+1)]\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 & [K-(i+2)]\alpha+3 & 0 & 0 & 0 & 0 \\
0 & -[K-(i+1)]\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & [K-(i+2)]\alpha+3 & 0 & 0 \\
0 & 0 & 0 & 0 & -[K-(i+1)]\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 & [K-(i+2)]\alpha+3 \\
0 & 0 & -[K-(i+1)]\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -[K-(i+2)]\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -[K-(i+2)]\alpha & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -[K-(i+1)] & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -[K-(i+2)] & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -[K-(i+2)]\alpha & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -[K-(i+4)]\alpha & 0
\end{array}\right]
$$

$Q_i = [q_{8+10i}, q_{9+10i}, q_{12+10i}, q_{13+10i}, q_{14+10i}, q_{15+10i}, q_{16+10i}, q_{17+10i}, q_{20+10i}, q_{21+10i}]$

$Q_i^* = [q_{6+10(i-1)}, q_{7+10(i-1)}, q_{8+10(i-1)}, q_{9+10(i-1)}, q_{11+10(i-1)}, q_{12+10(i-1)}, q_{13+10(i-1)}, q_{14+10(i-1)}, q_{15+10(i-1)}, q_{16+10(i-1)}, q_{17+10(i-1)}, q_{20+10(i-1)}, q_{21+10(i-1)}]$

with

$Q_1 = [q_{18}, q_{19}, q_{22}, q_{23}, q_{24}, q_{25}, q_{26}, q_{27}, q_{30}, q_{31}]$

$Q_1^* = [q_6, q_7, q_8, q_9, q_{11}, q_{12}, q_{13}, q_{14}, q_{15}, q_{16}, q_{17}, q_{20}, q_{21}]$

By considering the relation:

$$q_j = \mu_j q_2 + v_j q_3 + z_j \qquad 1 \le j \le \sum_{n=1}^{c} \binom{n+l-1}{n} + \binom{n+l-1}{n}(K-c)$$

Thus equations (3.27) are:

$$\begin{aligned}
q_1 &= \mu_1 q_2 + v_1 q_3 + z_1 \\
q_2 &= \mu_2 q_2 + v_2 q_3 + z_2 \\
q_3 &= \mu_3 q_2 + v_3 q_3 + z_3 \\
q_4 &= \mu_4 q_2 + v_4 q_3 + z_4 \\
q_5 &= \mu_5 q_2 + v_5 q_3 + z_5 \\
q_6 &= \mu_6 q_2 + v_6 q_3 + z_6 \\
q_7 &= \mu_7 q_2 + v_7 q_3 + z_7 \\
q_8 &= \mu_8 q_2 + v_8 q_3 + z_8 \\
&\vdots \\
q_j &= \mu_j q_2 + v_j q_3 + z_j
\end{aligned}$$

Which can be written by:

$$Q_i = H_1 \bar{A} \quad \& \quad Q_i^* = H_1^* \bar{A} \tag{3.28}$$

Where:

$$\bar{A} = \begin{bmatrix} q_2 \\ q_3 \\ 1 \end{bmatrix}$$

$$H_i = \begin{bmatrix} u_{8+10i} & v_{8+10i} & z_{8+10i} \\ u_{9+10i} & v_{9+10i} & z_{9+10i} \\ u_{12+10i} & v_{12+10i} & z_{12+10i} \\ u_{13+10i} & v_{13+10i} & z_{13+10i} \\ u_{14+10i} & v_{14+10i} & z_{14+10i} \\ u_{15+10i} & v_{15+10i} & z_{15+10i} \\ u_{16+10i} & v_{16+10i} & z_{16+10i} \\ u_{17+10i} & v_{17+10i} & z_{17+10i} \\ u_{20+10i} & v_{20+10i} & z_{20+10i} \\ u_{21+10i} & v_{21+10i} & z_{21+10i} \end{bmatrix}$$

$$H_i^* = \begin{bmatrix} u_{6+10(i-1)} & v_{6+10(i-1)} & z_{6+10(i-1)} \\ u_{7+10(i-1)} & v_{7+10(i-1} & z_{7+10(i-1)} \\ u_{8+10(i-1)} & v_{8+10(i-1} & z_{8+10(i-1)} \\ u_{9+10(i-1)} & v_{9+10(i-1} & z_{9+10(i-1)} \\ u_{11+10(i-1)} & v_{11+10(i-1} & z_{11+10(i-1)} \\ u_{12+10(i-1)} & v_{12+10(i-1} & z_{12+10(i-1)} \\ u_{13+10(i-1)} & v_{13+10(i-1} & z_{13+10(i-1)} \\ u_{14+10(i-1)} & v_{14+10(i-1} & z_{14+10(i-1)} \\ u_{15+10(i-1)} & v_{15+10(i-1} & z_{15+10(i-1)} \\ u_{16+10(i-1)} & v_{16+10(i-1} & z_{16+10(i-1)} \\ u_{17+10(i-1)} & v_{17+10(i-1} & z_{17+10(i-1)} \\ u_{20+10(i-1)} & v_{20+10(i-1} & z_{20+10(i-1)} \\ u_{21+10(i-1)} & v_{21+10(i-1} & z_{21+10(i-1)} \end{bmatrix}$$

From equations (3.26) and (3.28):

$E_i H_i = D_i H_i^*$

Therefore:

$E_i u_i = D_i u_i^*$, $E_i v_i = D_i v_i^*$ & $E_i z_i = D_i z_i^*$ (3.29)

$1 \le i \le \binom{n+l-1}{n}(K-c)/10$

Where:

$u_i = [u_{8+10i}, u_{9+10i}, u_{12+10i}, u_{13+10i}, u_{14+10i}, u_{15+10i}, u_{16+10i}, u_{17+10i}, u_{20+10i}, u_{21+10i}]$

$u_i^* = [u_{6+10(i-1)}, u_{7+10(i-1)}, u_{8+10(i-1)}, u_{9+10(i-1)}, u_{11+10(i-1)}, u_{12+10(i-1)}, u_{13+10(i-1)}, u_{14+10(i-1)}, u_{15+10(i-1)}, u_{16+10(i-1)}, u_{17+10(i-1)}, u_{20+10(i-1)}, u_{21+10(i-1)}]$

$v_i = [v_{8+10i}, v_{9+10i}, v_{12+10i}, v_{13+10i}, v_{14+10i}, v_{15+10i}, v_{16+10i}, v_{17+10i}, v_{20+10i}, v_{21+10i}]$

$v_i^* = [v_{6+10(i-1)}, v_{7+10(i-1)}, v_{8+10(i-1)}, v_{9+10(i-1)}, v_{11+10(i-1)}, v_{12+10(i-1)}, v_{13+10(i-1)}, v_{14+10(i-1)}, v_{15+10(i-1)}, v_{16+10(i-1)}, v_{17+10(i-1)}, v_{20+10(i-1)}, v_{21+10(i-1)}]$

$z_i = [z_{8+10i}, z_{9+10i}, z_{12+10i}, z_{13+10i}, z_{14+10i}, z_{15+10i}, z_{16+10i}, z_{17+10i}, z_{20+10i}, z_{21+10i}]$

$z_i^* = [z_{6+10(i-1)}, z_{7+10(i-1)}, z_{8+10(i-1)}, z_{9+10(i-1)}, z_{11+10(i-1)}, z_{12+10(i-1)}, z_{13+10(i-1)},$

$z_{14+10(i-1)}, z_{15+10(i-1)}, z_{16+10(i-1)}, z_{17+10(i-1)}, z_{20+10(i-1)}, z_{21+10(i-1)}]$

By solving the initial equations in terms of $q_2$ and $q_3$, $u_i^*$, $v_i^*$, $z_i^*$ can be evaluated. After solving equation (10) for all values of "i",we calculate $u_j$, $v_j$, $z_j$ for all values of $q_j$. Sample of $u_j$, $v_j$, $z_j$ calculations is shown in Appendix C.

By direct substitution in the relations:

$$q_j = \mu_j q_2 + v_j q_3 + k_j \qquad 1 \le j \le \sum_{n=1}^{c} \binom{n+l-1}{n} + \binom{n+l-1}{n}(K-c)$$

And for the condition that $q_j = 0$ for all $j \ge \sum_{n=1}^{c} \binom{n+l-1}{n} + \binom{n+l-1}{n}(K-c)$

The variables $q_2$, $q_3$ are evaluated from two of the remaining final and then $q_j$'s are calculated from the equation.

A guess is made for $p_0$, then the different values of $p_j$ are calculated by substituting $q_j = p_j / p_0$, and finally the equation:

$$\sum p_j = 1, \qquad 0 \le j \le \sum_{n=1}^{c} \binom{n+l-1}{n} + \binom{n+l-1}{n}(K-c)$$

is used for scaling the solution

The probability $P_n$ of n machines waiting to be served or being served are given by the formula Mayhugh and McCormick (1968):

Equations (3.30)

$$P_0 = p_0$$

$$P_n = \sum_{j=a(n,l)}^{j=b(n,l)} p_j \qquad 0 < n \leq c$$

$$P_n = \sum_{j=d(n,l,c)}^{j=e(n,l,c)} p_j \qquad c < n \leq N$$

Where

$$a(n,l) = \binom{n+l-1}{l}$$

$$b(n,l) = \binom{n+l}{l} - 1$$

$$d(n,l) = \binom{n+l}{l} + (n-c-1)y$$

$$e(n,l) = \binom{n+l}{l} + (n-c)y - 1$$

Once the probabilities $P_n$ have been evaluated, the server utilization is calculated from

$$\eta = 3 - 3P_0 - 2P_1 - P_2 \quad (3.31)$$

### 3.15 Production forecasting model:

In this model the equipment matching will be achieved based on the operating cost of the equipment, so as to produce an operation of minimum total cost per unit output or production.

For an operation involving c loaders and K trucks, the total operating cost/hour is

$$cC_1 + C_2K \quad (3.32)$$

Where C1 is the cost per hour of the loader and $C_2$ is the cost per hour of a truck. Both costs include those of the operators, maintenance, ownership cost and other charges.

For an operation output of $\mu\eta$, the production per hour is $\mu\ \eta\ C_h$ (O'Shea 1964) in units of cubic meters (or tones) per hour. Here the $\mu$ is in units of trucks per hour and $C_h$, the capacity of a truck is in units of cubic meters (or tones) per truck.

The total cost per cubic meter of earth moved is then

$$C_t = \frac{cC_1 + C_2K}{\mu\eta\, C}$$

### 3.16 summary

This chapter proposed a methodology for earthmoving equipment fleet selection model, using queuing theory of model *(M/E$_r$/c)/k* at steady state with a number of servers up to three and finite number of customers, the distributions used for the arrival and service times are exponential and erlang respectively. The queuing model is solved to obtain among other items the percent of time the server system is busy (i.e. server utilization), this item will be used for the calculation of the system production. Items needed to determine the equipment output are calculated such as: the haul unit performance, rolling resistance, traction force, tipping load, travel and service time...etc. Additional factors were taken in consideration such as, weather condition, altitude, and operator efficiency. Heterogeneity of the trucks was taken in consideration by using an approximation for converting a heterogeneous system into an equivalent homogeneous one.

The model implementation phase in addition to the system performance is shown n chapter 4 through two case studies, validation of the outputs is done by comparison with the results of the simulation and deterministic methods.

# Chapter 4

## MODEL IMPLEMENTATION

### 4.1 Introduction:

This chapter presents the computer implementation stage of the proposed methodology to select the optimum equipment fleet using queuing method. This computer module is called **FLSELECTOR**, which represents FLEET SELECTOR, and is implemented using Visual Basic for Application (VBA) and Microsoft Excel 2000. **FLSELECTOR** consists of one main module, with multi-page tab controls. This module is used to assist in selecting the appropriate fleet of equipment, which is technically feasible, and allowing for the choice of the fleet with optimum output (least cost, maximum production, or minimum project duration). **FLSELECTOR** provides the user with a list of the best ten fleet alternatives.

### 4.2 System's Architecture:

The FLeet SELECTOR (**FLSELECTOR**) is a prototype computer model designed as a stand-alone module. **FLSELECTOR** is used as a decision support tool to assist engineers and contactors in their decisions to select the best fleet combination of loaders and haulers that can complete an earthmoving operation with maximum production (minimum duration) or minimum cost.

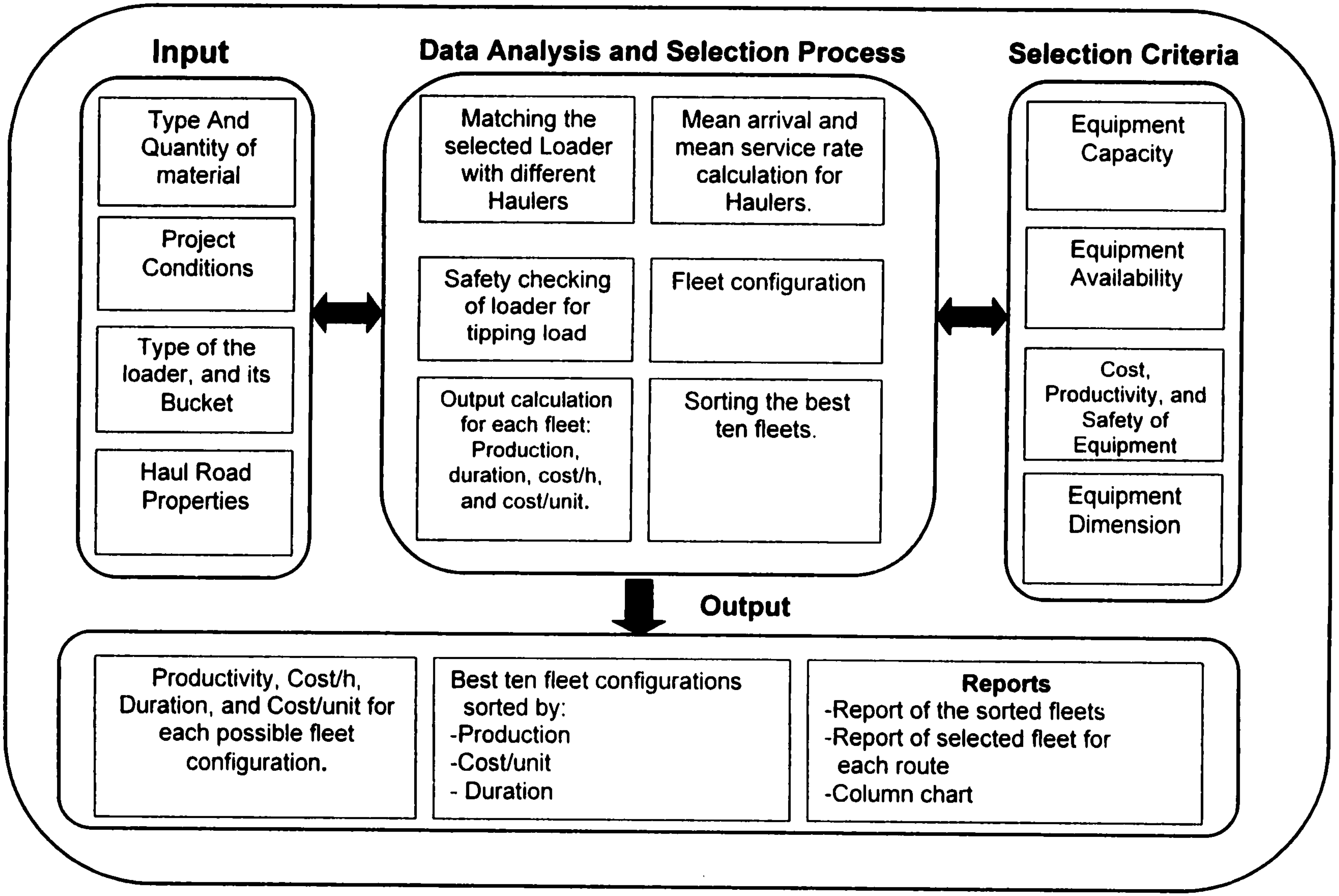



**Figure 4 Fleet selection process and Data analysis**

In addition to the fleet selection, **FLSELECTOR** allows the user to compare between the outputs of the different hauling routes from the loading to the dumping area.

**FLSELECTOR** consists of one main module, which is subdivided into sub modules to help in entering the project's information, selecting equipment, executing the different calculation phases, and manipulating the outputs. The model is not limited to specific types of equipment, furthermore it allows for using customized (own) equipment.

As shown in Figure (4), the process starts with entering the project information, weather condition, haul road conditions, and the type of material to be hauled in addition to its quantity. Loader selection with its components should be completed before launching the matching process to select the appropriate haulers to work with the loader, in this selection process dimensional, capacity, and safety criteria should be satisfied. Time components for all equipment are calculated, and different fleet configurations are listed. Using queuing method the production, duration, and cost/unit are calculated for each fleet, and the best ten fleets can be listed according to a selected criterion. The user can select the suitable fleet from the list and then repeat the process again for the different hauling routes.

**FLSELECTOR**'s options are explained in the following sections.

### 4.3 Adding Customized Equipment:

The system's database doesn't cover all the existing types of excavators and haulers, also it is normal that the users may want to use different types of equipment in their projects, due to many factors, such as the availability of the equipment, and whether the operators are familiar with a specific type of equipment. Therefore, it is essential that the system must have the option of adding customized equipment and not limit the users with specific types. **FLSELECTOR** with its user-friendly interface make this task simple. Using the same tap-page the user can customize both haulers and loaders; each machine has details of capacity, cost, weight, dimensions, and availability to be entered.

### 4.3.1 Adding Customized Hauler:

To add customized hauler a set of textboxes must be filled in with relevant data (Figure 4.1). All the boxes allow direct text entry, and all the required data can be obtained from the manufacturer.

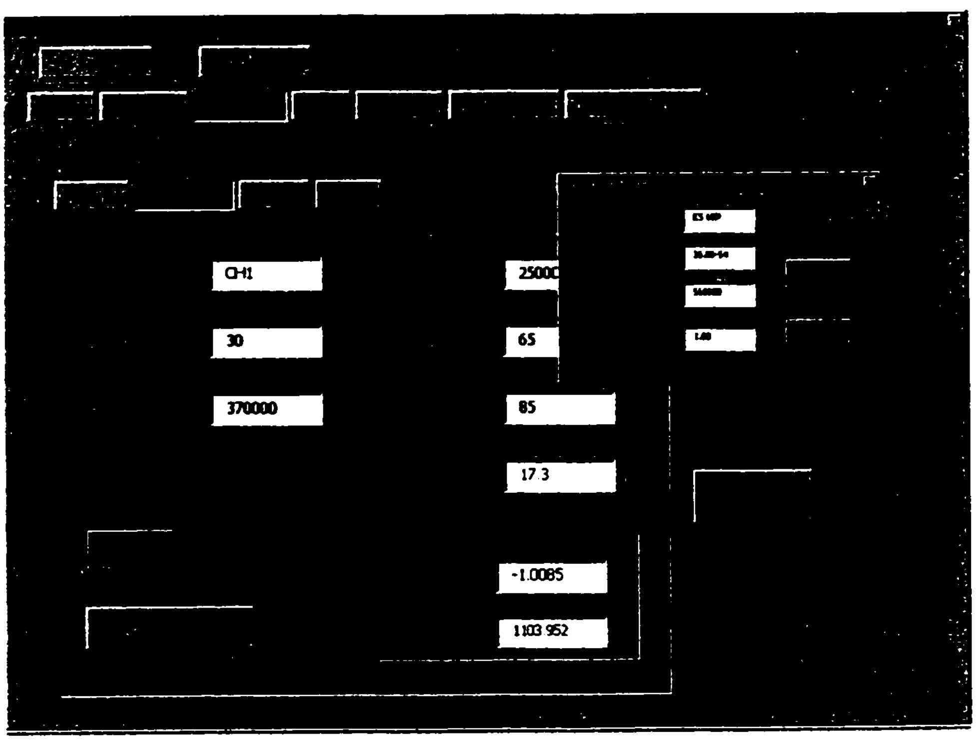



**Figure 4.1 Adding customized hauler to the module database**

Chart coefficients, which will be used in the performance equations, should be extracted from the performance charts for each hauler as shown in Appendix A. These coefficients are vital to calculate the hauler speed and they should be as accurate as possible. Data on Tires can be entered through sub-form, which appears when clicking the Tires button. The hourly cost and availability can be modified later during the selection process.

### 4.3.2 Adding Customized Loaders:

Similarly, customized loaders can be added. All boxes must be filled, including the average cycle time, which can be obtained from the manufacturer and it includes load, dump, four reversals of direction, and minimum travel; other information is required such as dumping height, bucket capacity, and the tipping load (Figure 4.2).

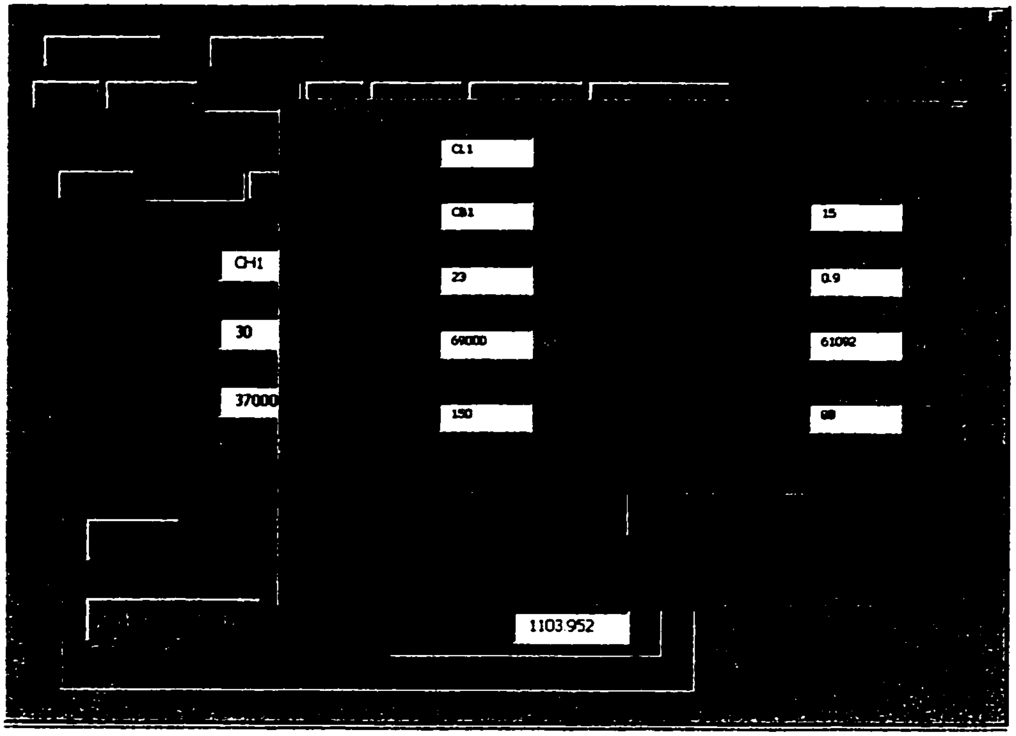



**Figure 4.2 Adding customized Loader to the module database**

### 4.4 Fleet Selection:

Fleet selection is a complex task that needs to correlate different set of data together, to follow several steps, and to use inputs obtained from manufacturers and field. Data about the haul road, equipment to be used, excavated material, weather conditions, altitude, and equipment availability will be considered in the calculation process, as shown in the flow diagram (Figure 4.3).

For each fleet there will be only one type of loader with different types of haulers that match with the loader. This will provide more flexibility in the field since all haulers will match and work with all loaders in the pit, and no hauler will be waiting while a loader is idle due to a mismatch. In addition contractors prefer to have one type of loader, as it is much easier for workers to deal with than having different types. The module provides the users with the flexibility to mix between customized and standard equipment.

The maximum number of loaders per fleet is set for three loaders, for the following two reasons:

1) It is impractical to have more than 3 loaders in one pit (According to a construction expert).

2) It is difficult to solve using queuing method.

The number of haulers is only limited by the capability of the system (loaders) to handle.

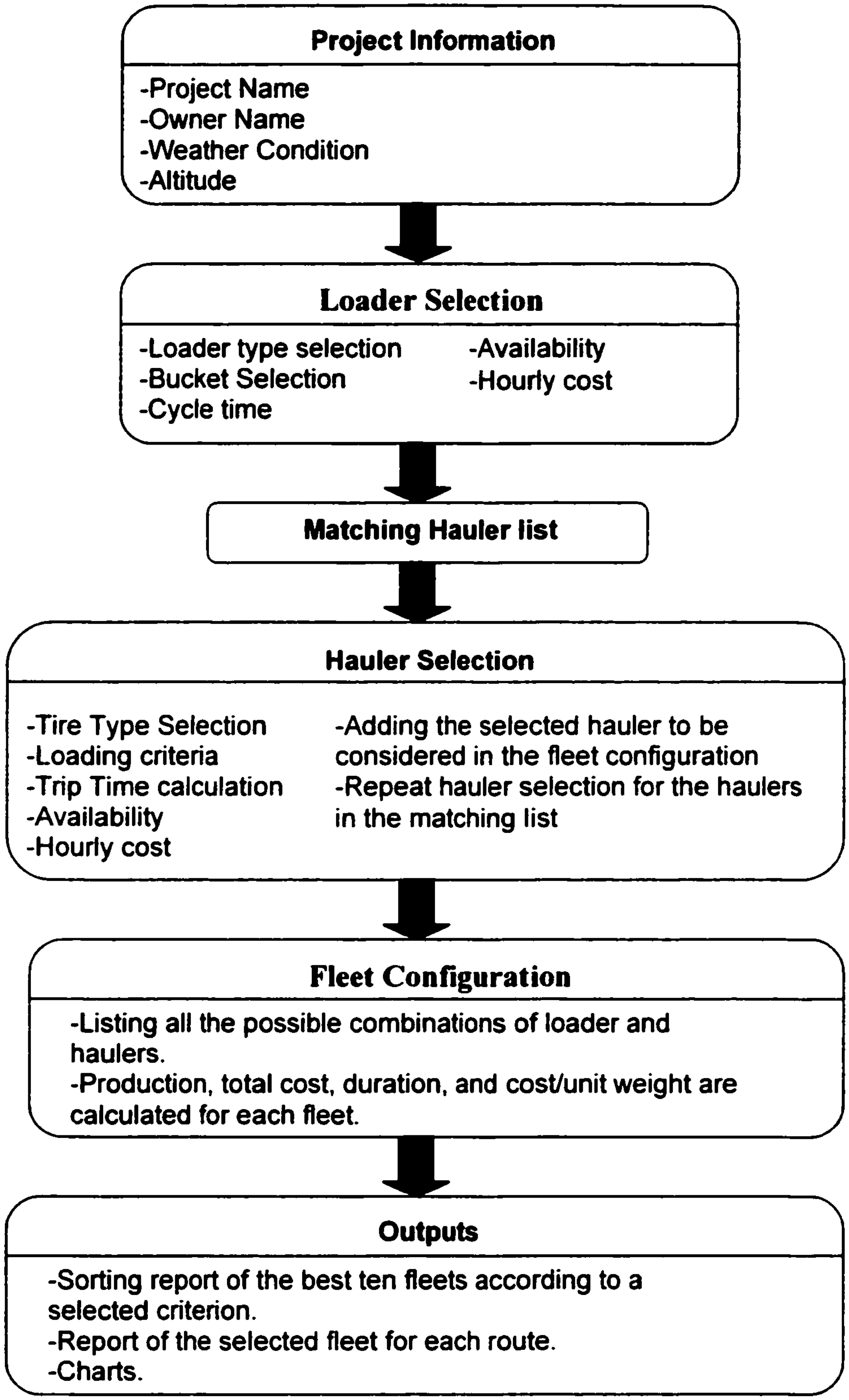



**Figure (4.3) Model's flow diagram**

General information about the project including weather condition and altitude is first required as shown in Figure (4.4).

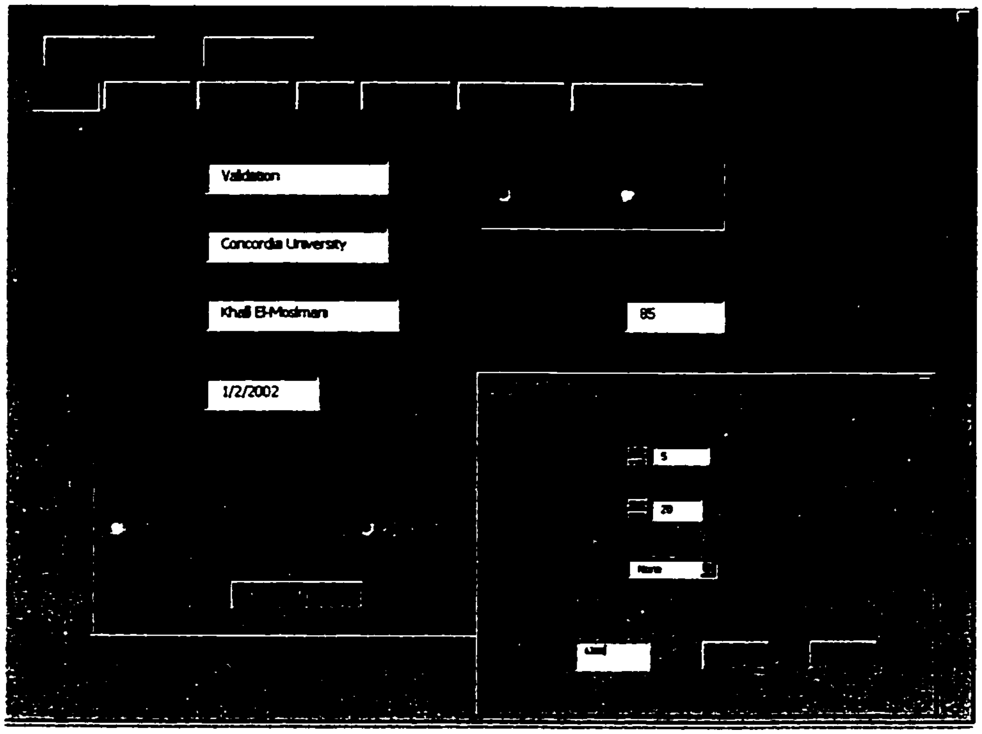



**Figure 4.4 Project General Information, Weather condition and Altitude**

In order to calculate the hauling time (the time required to haul the material from the loading point to the dumping point), detailed information should be provided regarding the haul road. As the road characteristics (slope, condition...) may change along the traveling distance, the route is divided into segments.

Figure (4.5) shows that for each segment the user must specify the distance, rolling resistance, grade, speed limit, and surface type (Figure 4.6).

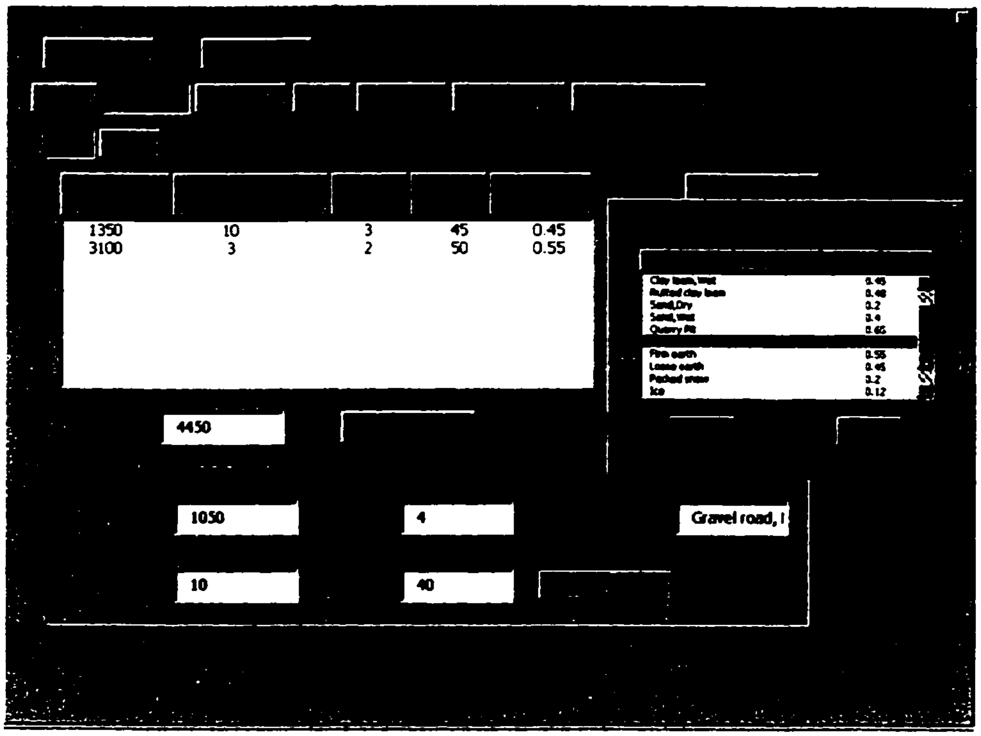



**Figure 4.6 Surface Type Selection**

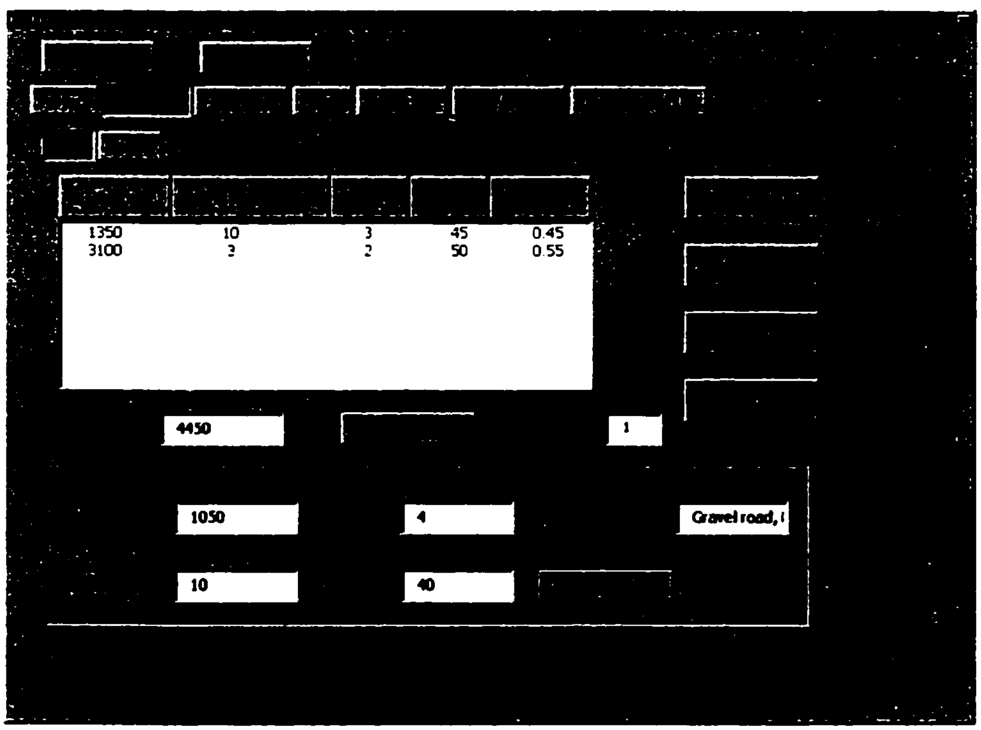



**Figure 4.5 Haul Road Data**

**FLSECTOR** provides the user with the following three options 1) change the sequence of the segments, 2) delete any segment, and 3) mirror any haul segment into the return road box with the same grade but of opposite sign. For the return road, the user can add to the mirror segments additional segments if the return road is not totally symmetrical to the haul road (Figure 4.7).

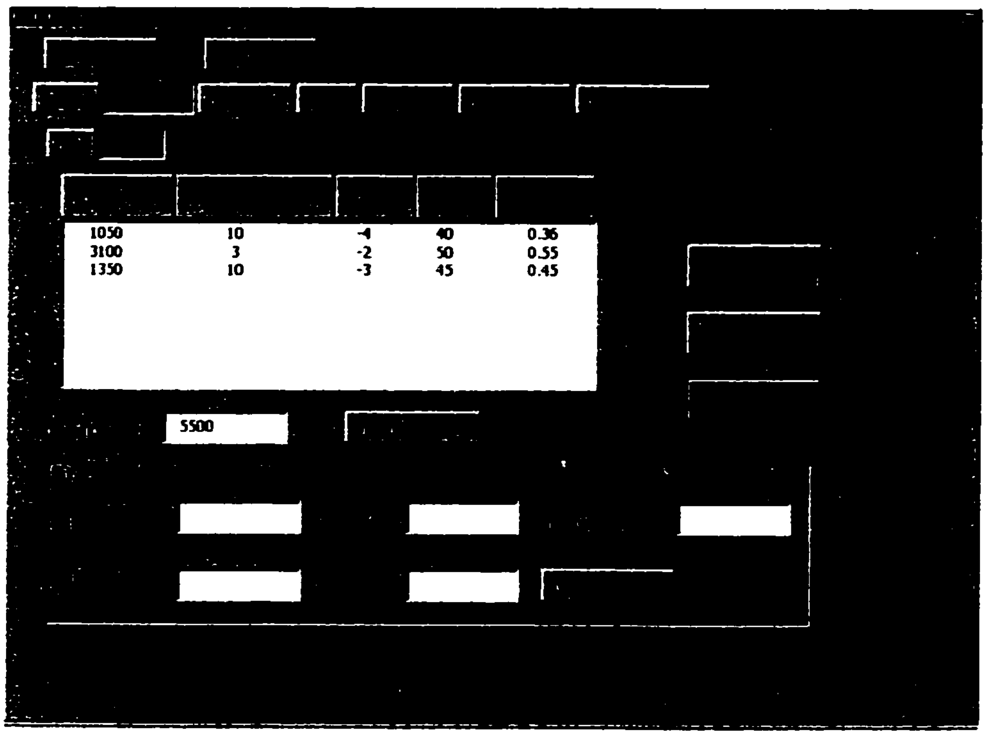



**Figure 4.7 Return Road data Entry**

The material database contains information on fifty-two different types of material as shown in Appendix B table 4.1. The user has the option to either select from the existing list as shown in Figure (4.8) or alternatively enter a new type manually.

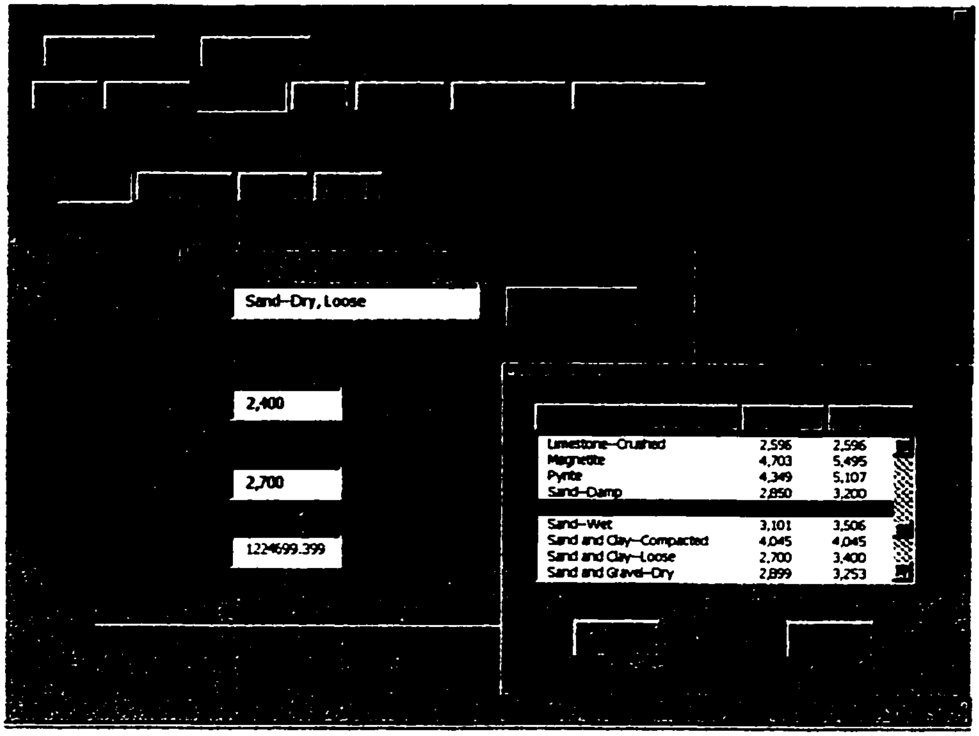



**Figure 4.8 Material Selection List.**

### 4.4.1 Loader Selection:

The loader database contains information on six different commercially available loaders as shown in Figure (4.9). Loaders have the capability of working with different types and sizes of buckets; information about these buckets is stored as a different list for each loader, a list will be called according to the selected loader (Figure 4.10). The selected bucket type affects the loader productivity and the hauler types that the loader can serve (matching the dumping height and capacity). The user has the option for a customized loader selection.

Tipping Load is a very important safety factor for loaders and it is a function of two components, material unit weight and the bucket capacity. The user has the option to specify the Tipping Load Safety Factor or alternatively accept the default value of 2.5.

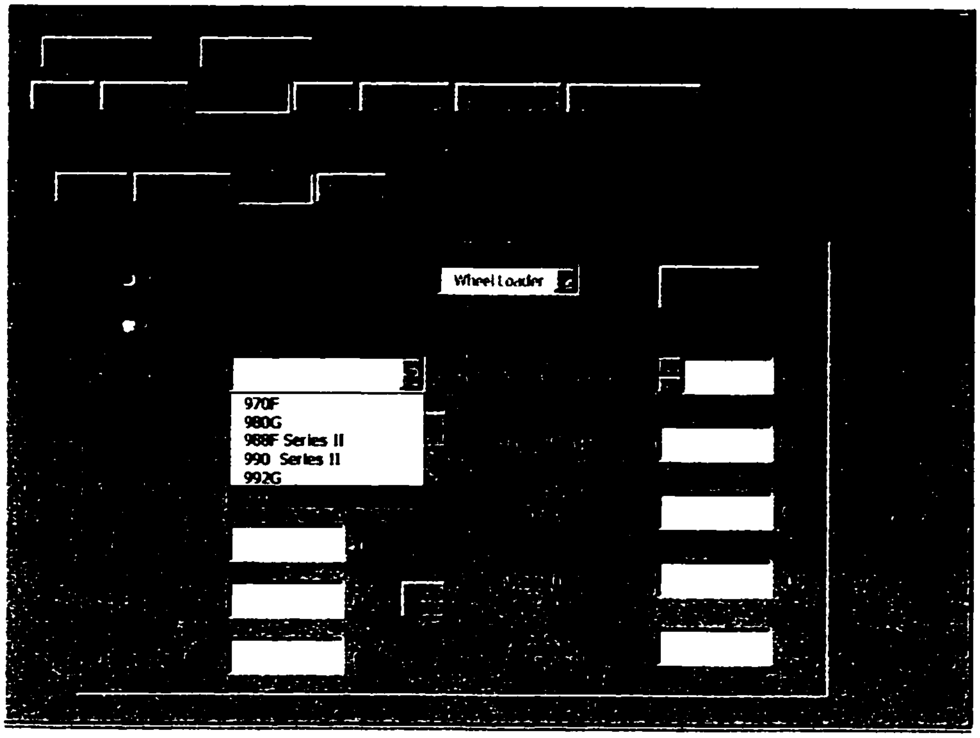



**Figure 4.9 Loader Selection screen**

### 4.4.2 Loader Cycle Time

Loader cycle time includes the time required for loading, dumping, four reversals of direction, and minimum travel (Figure 4.11). For each loader there is a specified cycle time. First dump time and the hauler exchange time are fixed for all loaders; user can modify these values manually.

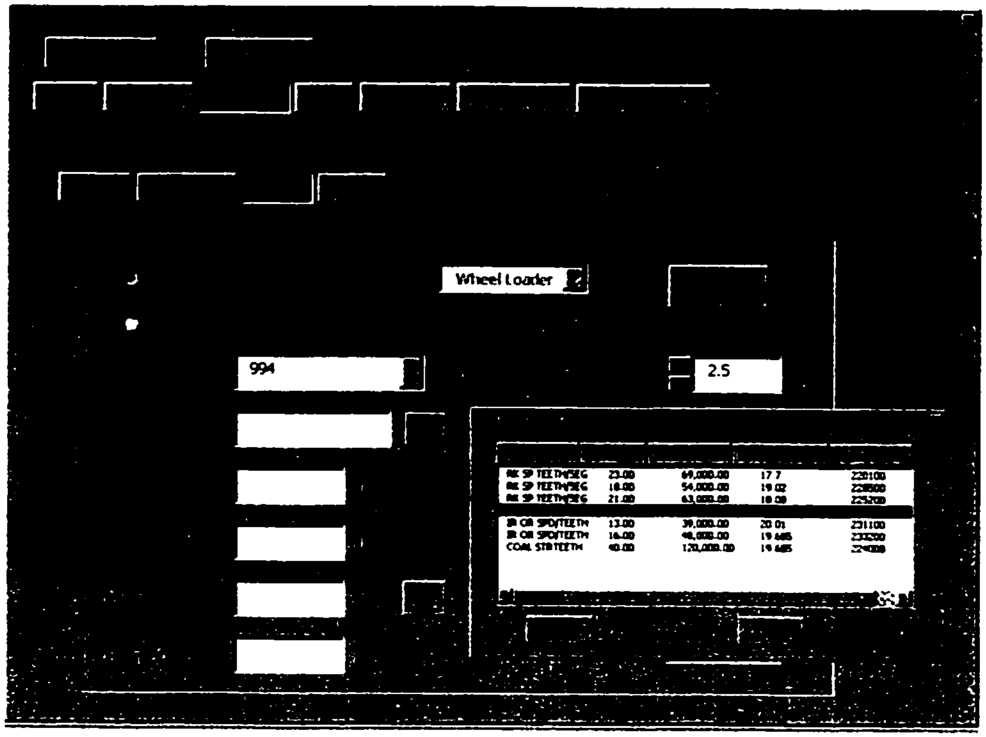



**Figure 4.10 Bucket Selection Screen**

### 4.4.3 Matching:

Two factors govern the matching between the loader and the haulers (Figure 4.12):

1) The difference between a loader's loading height and haulers' dumping height, taking into consideration the difference in level that may take place between the two equipment

2) The ratio of a hauler's capacity to loaders capacity.

The process of matching is to select the appropriate haulers in order to work with the loader after having satisfied the above conditions (Figure 4.13). The flow chart of the equipment matching process is shown in Figure (4.14).

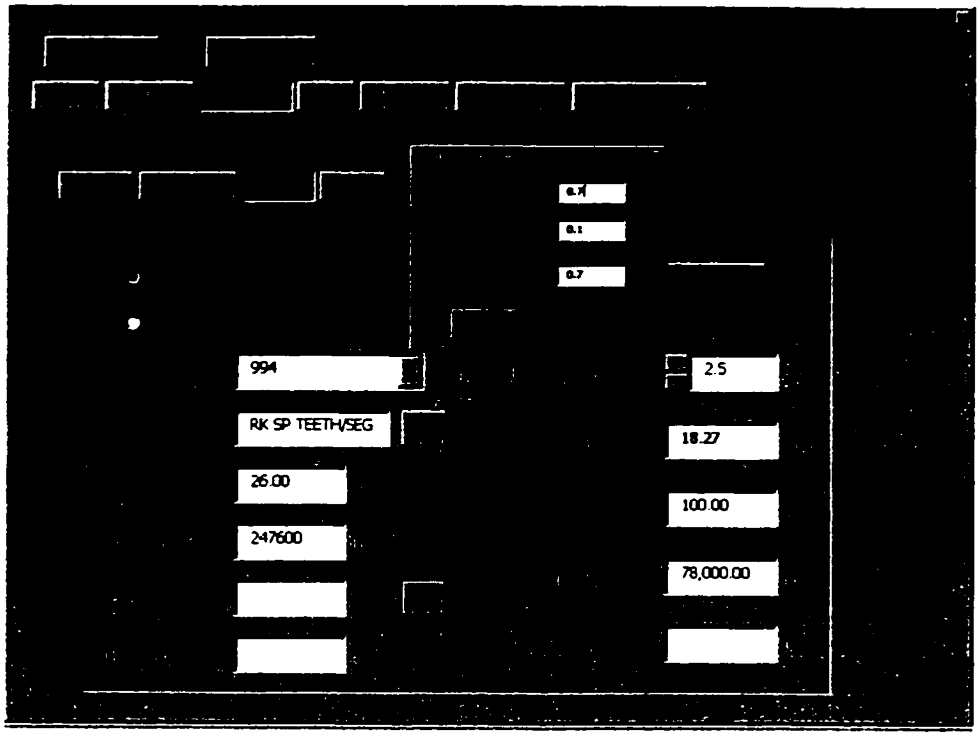



**Figure 4.11 Loader cycle time**

### 4.4.4 Hauler Tire Selection

Tire type selection specifies related hauler's data such as Payload index, Empty Weight, and Correction Speed Factor (Figure 4.15).

Hauler weight distribution on the driving wheels should be specified when tire type is selected. This value is very vital in the calculation of Maximum Usable Traction Force and it may affect the speed of the hauler and consequently the time of trip.

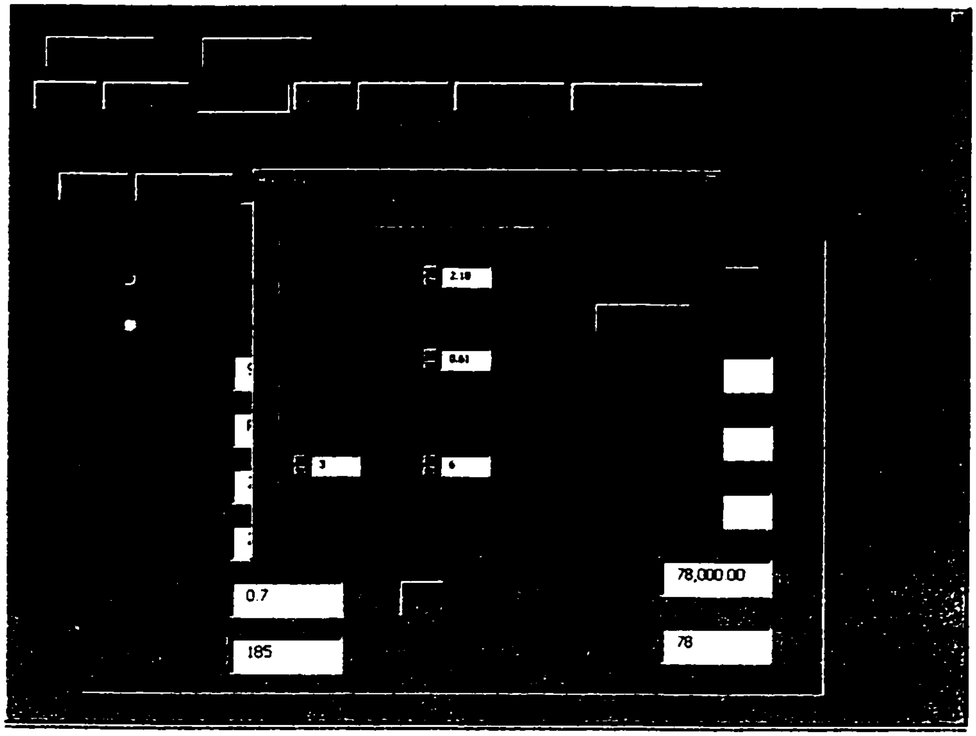


**Figure 4.12 Specifying the Matching Factors**

### 4.4.5 Loading Time

The system calculates the number of passes required for the loader to fill the hauler to 100% capacity. The calculated number of passes will not be in integer increments. Field Practicing suggests that a loader operator will not make a pass with less than a full bucket; therefore, this number will require manual rounding. This will result in the hauler being filled to either slightly less or slightly higher than the rated capacity.

As the hauler's exchange time (maneuvering time at the loading area) is normally larger than loader's cycle time, the loader will make a cycle (fill the bucket) and wait for the next hauler to maneuver after it finishes loading the hauler (Figure 4.16). Thus loading time of the hauler is equal to: (number of buckets needed to the hauler −1) multiplied by the loader's cycle time, plus the time needed to dump the first bucket.

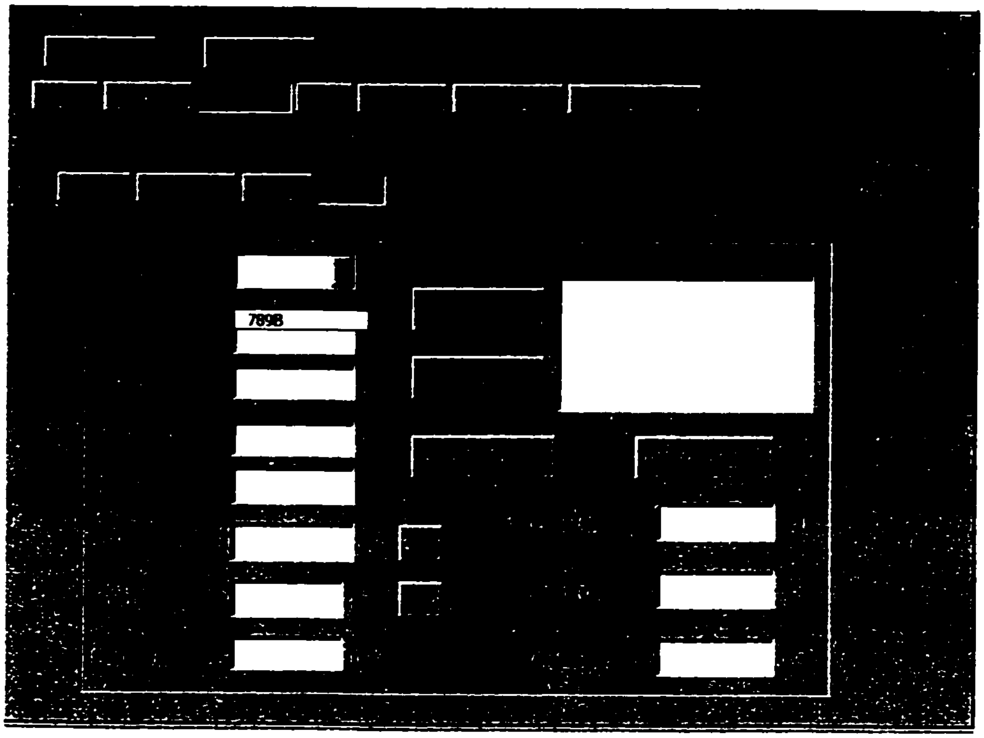


**Figure 4.13 List of Matching Haulers**

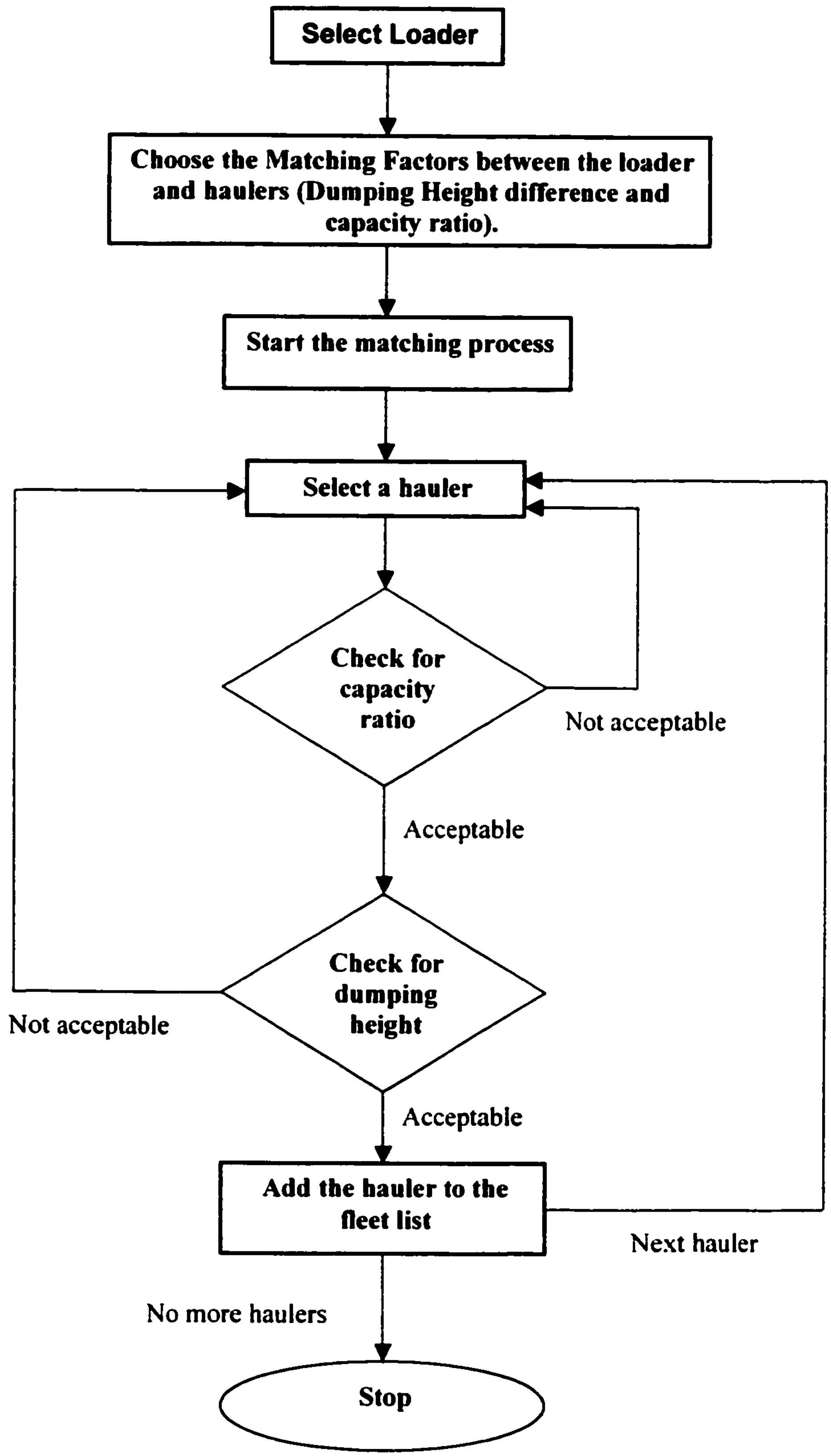



**Figure (4.14) Flow chart of the equipment matching process.**

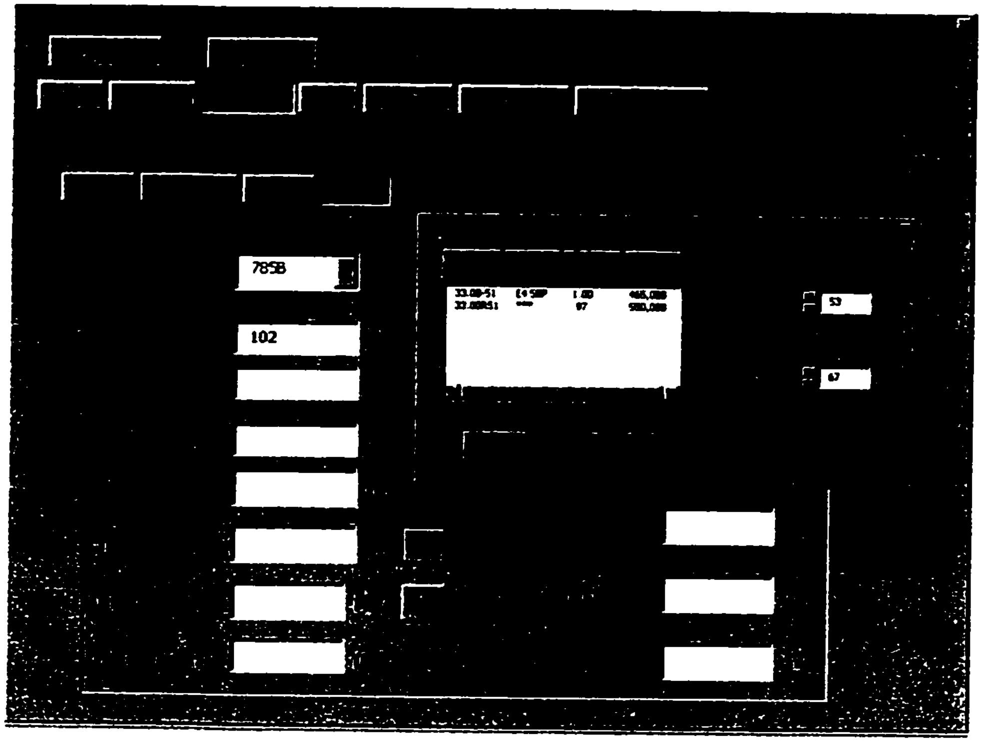



**Figure 4.15 Tire selection for the hauler**

Hauler's payload and the volume of material loaded into the hauler are a function of the number of passes of the loader per hauler (Figure 4.17). In many circumstances, 87% of body fill is ideal (Day and Benjamin, 1989). To change this result, the number of passes per hauler must be changed.

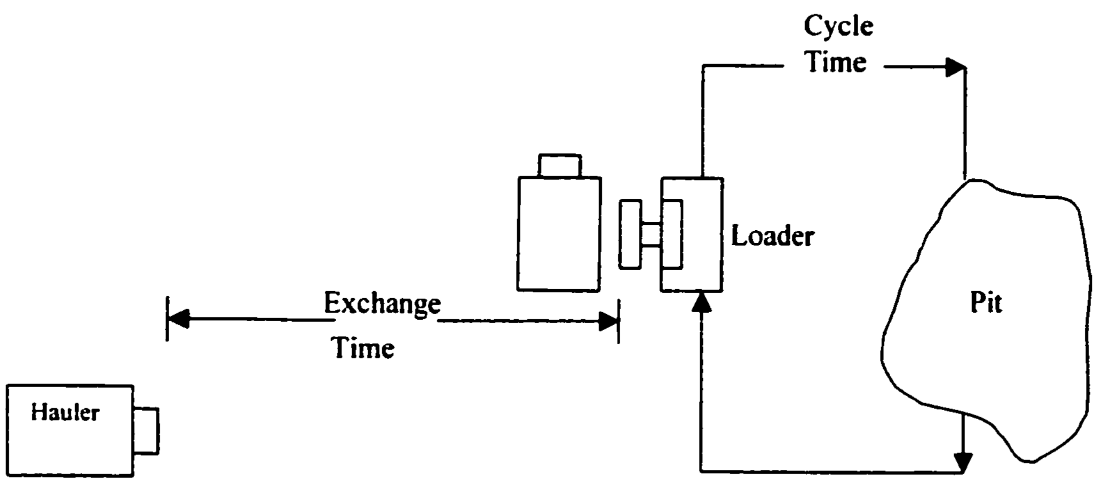



**Figure 4.16 Loader cycle time**

### 4.4.6 Hauler Cycle Time:

Cycle time calculation for haulers depends on many factors such as hauler's performance, hauling road, loader cycle time, hauler exchange time, and hauler's and loader's capacity.

Hauling and returning time are calculated according to the hauler's performance and the hauling road conditions. Dumping and maneuvering time is an editable value hence the default value can be changed to correctly represent the real value in the field as shown in Figure (4.18).

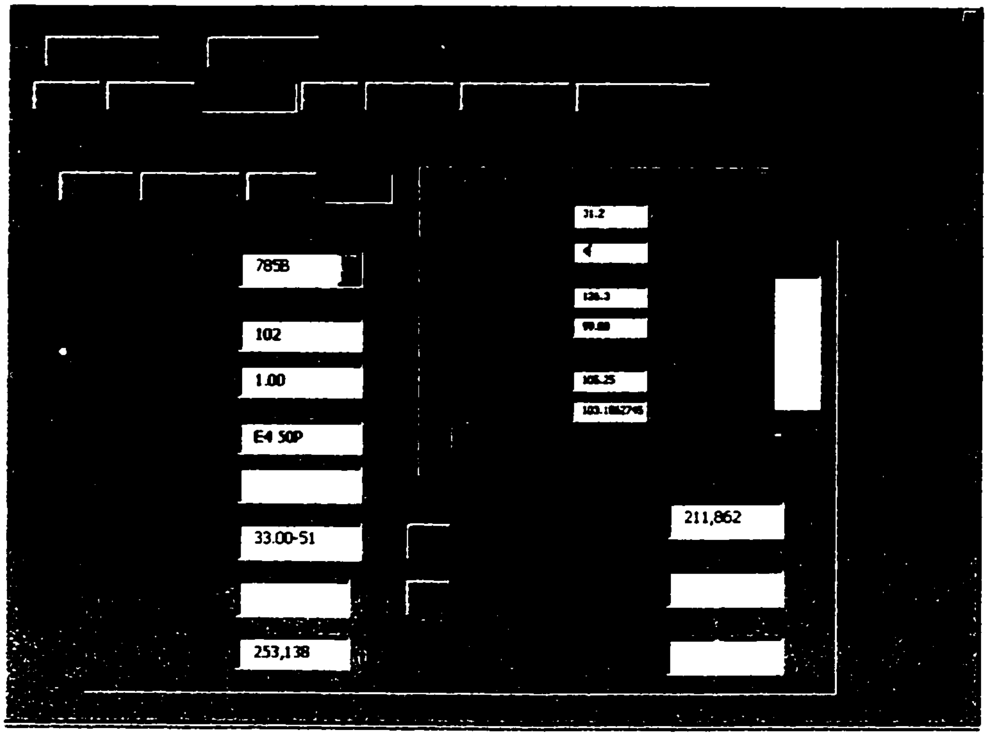




**Figure 4.17 Loading Criteria of the hauler.**

### 4.4.7 Calculating the Time Components of Hauler Cycle

In order for a hauler to be considered in the fleet configuration in latter steps, it should be added to a special list (Figure 4.19). In addition to the hauler's name, the tire type will be displayed. The same type of a hauler can't be added to the list unless it has a different type of tires. The user has the option of removing haulers from the list.

Before the fleet configuration step, **FLSELECTOR** displays the fleet components from haulers and loaders (Figure 4.20). Additional information is displayed in this step such as the appropriate number for each type of haulers matched with the selected loader, the loading time, and the hauler's trip time.

### 4.3.8 Fleet output Calculations

After all the information is added for each required component of the project, the user can begin the process of calculating the production for each fleet. This step is very complex because it needs to solve a large number of equations especially in the case of three servers (refer to Appendix C).

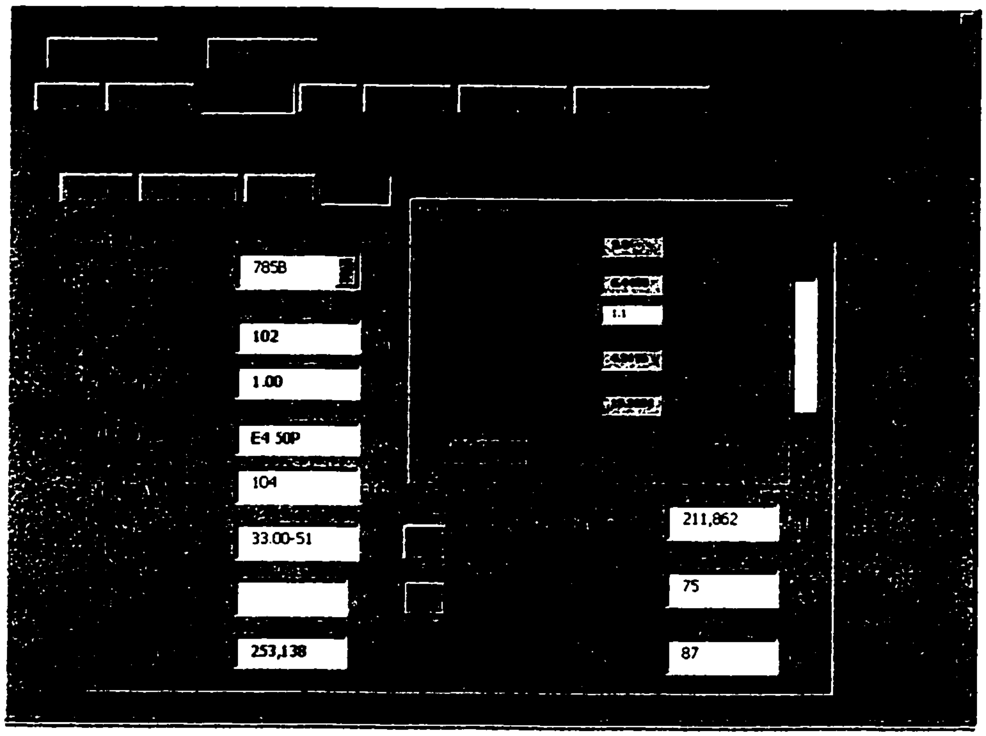



**Figure 4.18 Hauler Cycle time**

The process starts by presenting all possible fleet configurations for one, two, and three servers (Figure 4.21). The number of fleets depends mainly on two factors; the optimum number of trucks matching with the loader production and the number of different types of haulers. In order to cover a wider range of possible fleets, **FLSELECTOR** will consider, for each type of hauler, a range that starts with a number below the optimum number of haulers and ends with a number above this number.

To illustrate, if we have three types of haulers working with a type of loader, and the optimum number of the first truck is 3 (the selection range will be from 2 to 4), the second is 5 (the selection range will be from 4 to 6), and the third is 7(the selection range will be from 6 to 8). In this case we have a fleet ranging from 2 to 8 haulers.

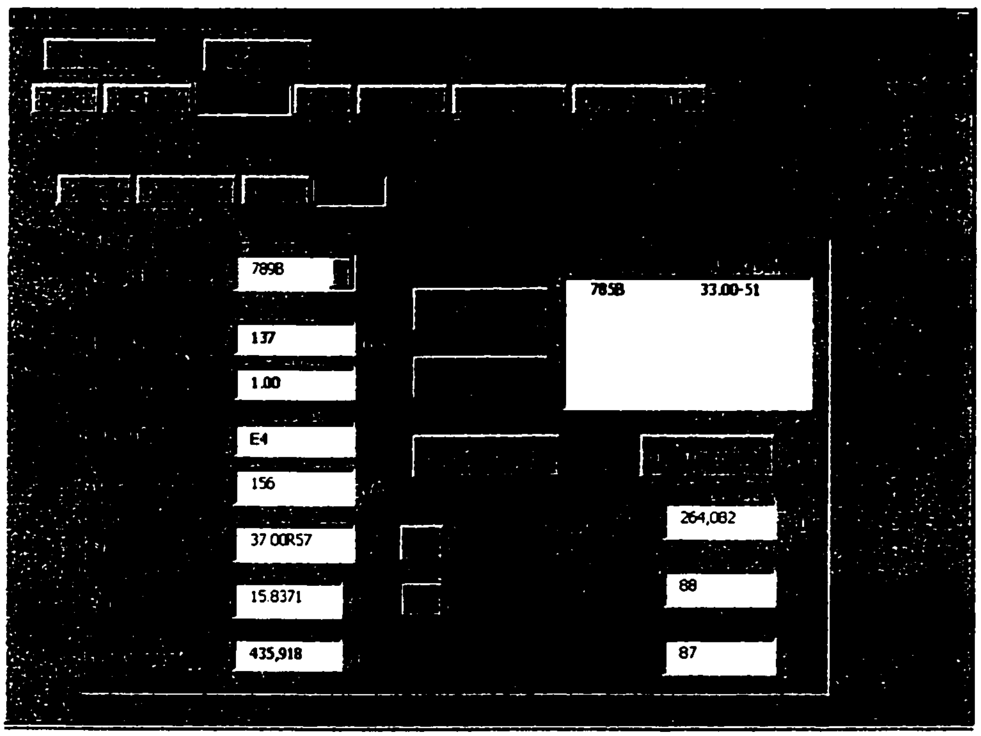



**Figure 4.19 Adding hauler to the fleet**

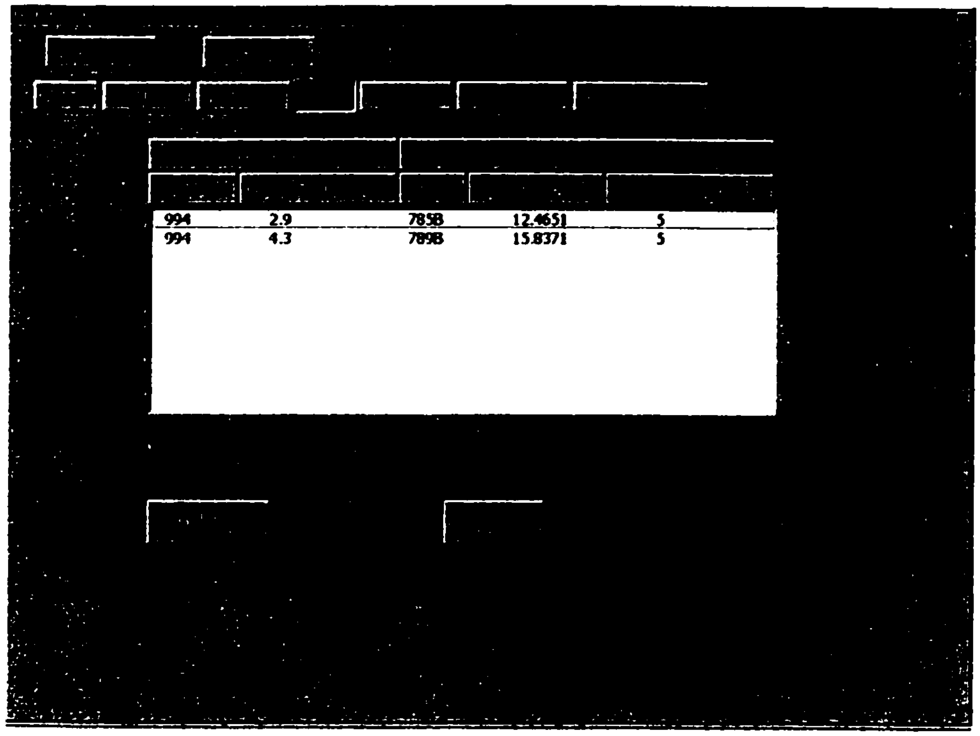



**Figure 4.20 Time components of the fleet equipment**

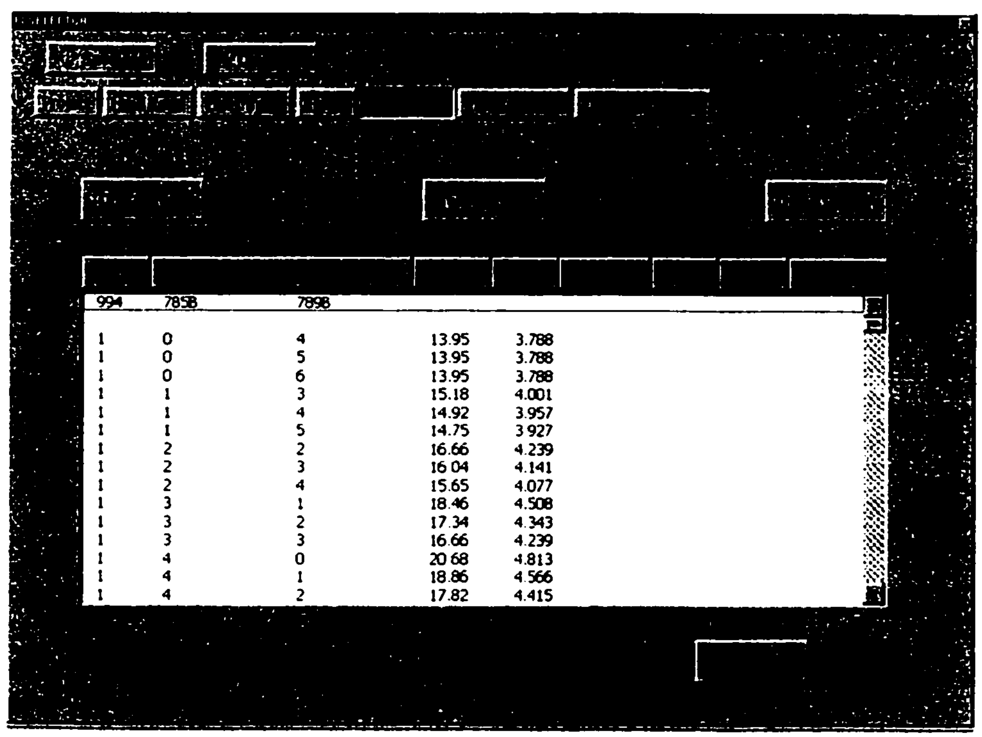



**Figure 4.21 Fleet configuration**

**FLSELECTOR** will consider all the possible alternatives of hauler distribution. It is noticeable that the number of fleets can be very large (for 3-type haulers it may exceed 2500 different fleets). These fleets will be listed in order, so that they start with all the one-server fleets and their possible configuration and end with the three server ones as Shown in Appendix D, Table 4.1.

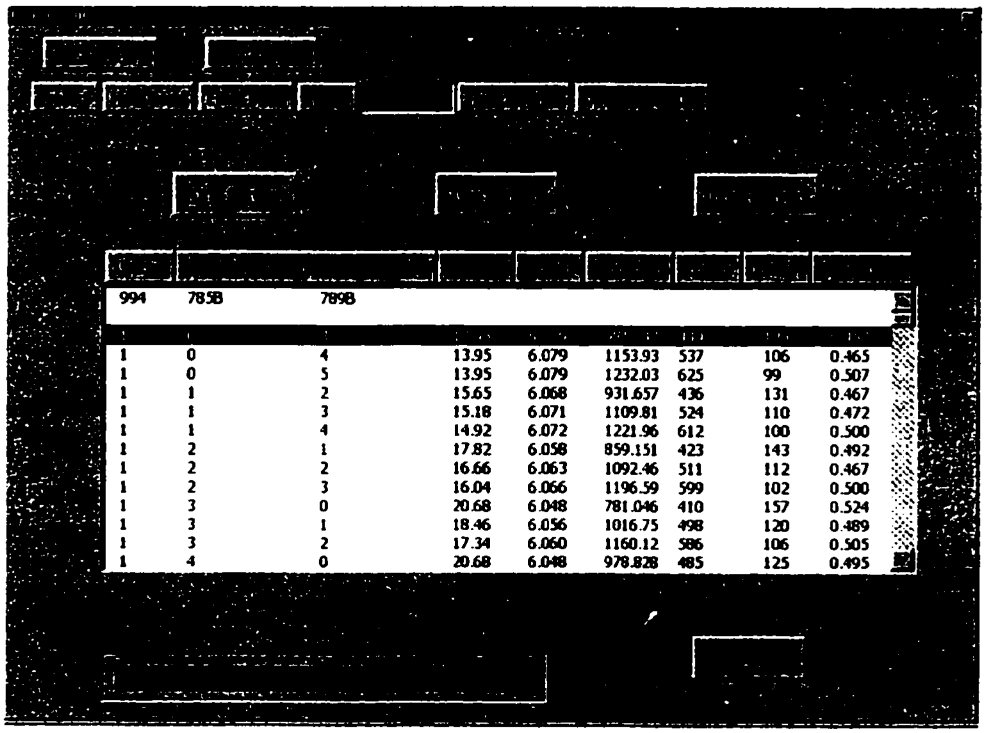



**Figure 4.22 Calculation for One-server Fleets**

Arrival rate, service rate, utilization, production, cost, duration, and cost per unit will be calculated for each fleet (Figure 4.22). A progress indicator will be displayed to show the progress of calculation, the process may take as short as few seconds (one server with one type of trucks) or as long as 10 minutes (three servers with more than two types of haulers).

### 4.3.9 Fleet Sorting

A very useful tool that **FLSELECTOR** provides is the capability of sorting the fleets. **FLSELECTOR** sorts the best ten fleets in a descending or ascending order according to the selected criterion of sorting. This criterion is the production, project duration, or the cost/unit as shown in Figure (4.23). A list of the best ten fleets will appear (Figure 4.24, Figure 4.25, and Figure 4.26), with the user having the choice of selecting the favorite one.

It is noticeable that two fleets may have very close production while the number of haulers is not the same. This is due to the fact that it is the loading system that governs the production. A report of this list can be created and printed out.

Charts for production, duration, and cost/unit of the ten fleets can be viewed and printed out.

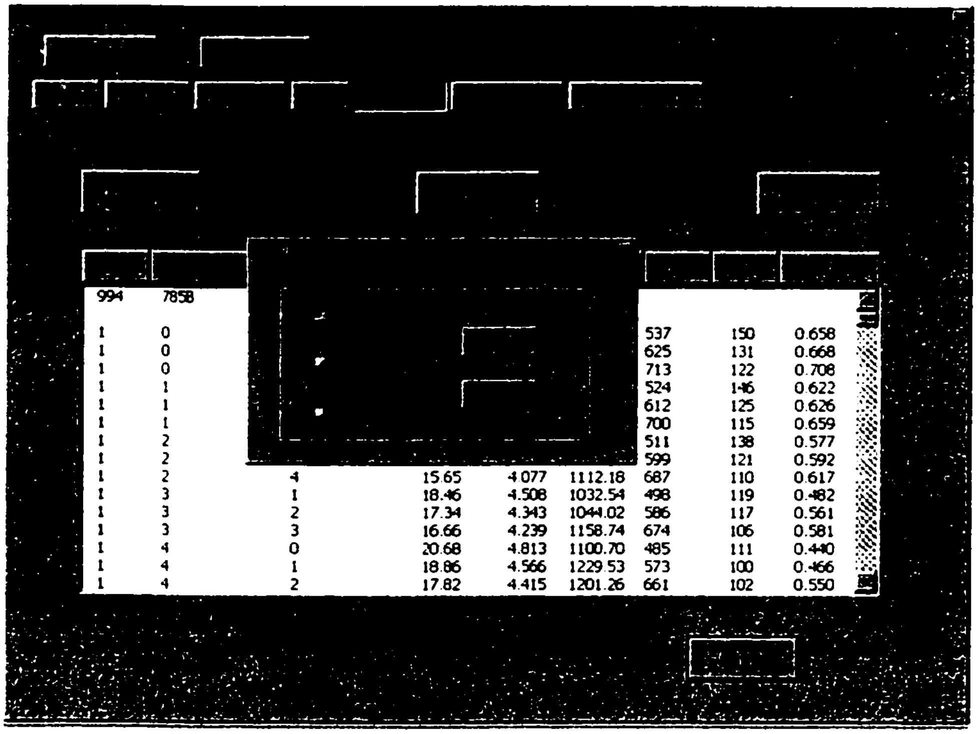



**Figure 4.23 Sorting Criterion Selection**

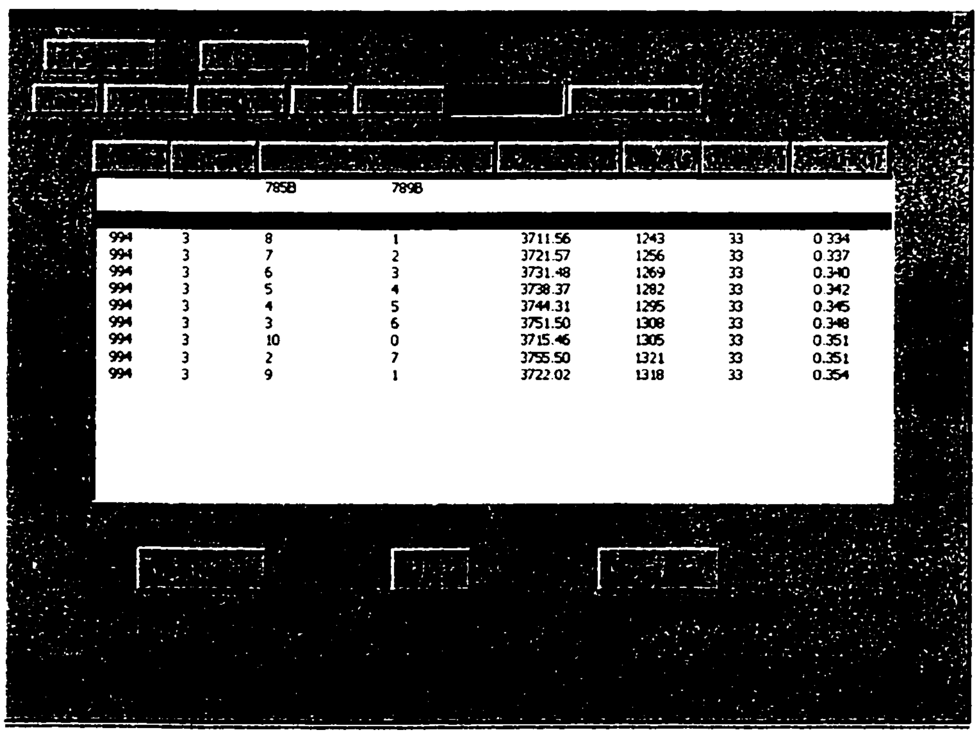
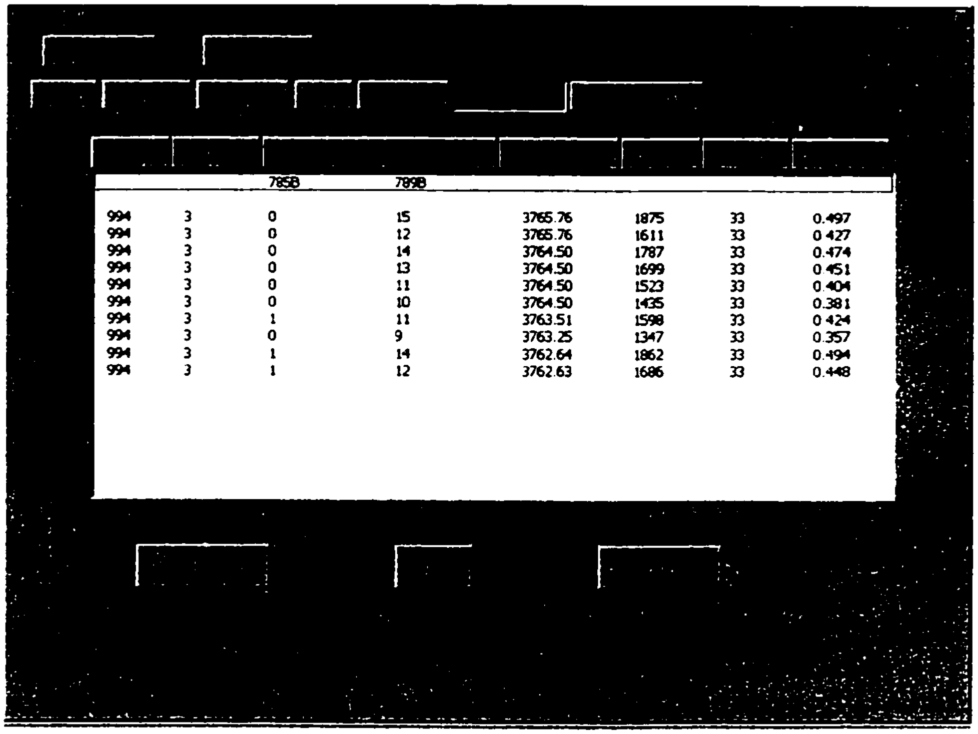



**Figure 4.24 Cost/unit Sorting**

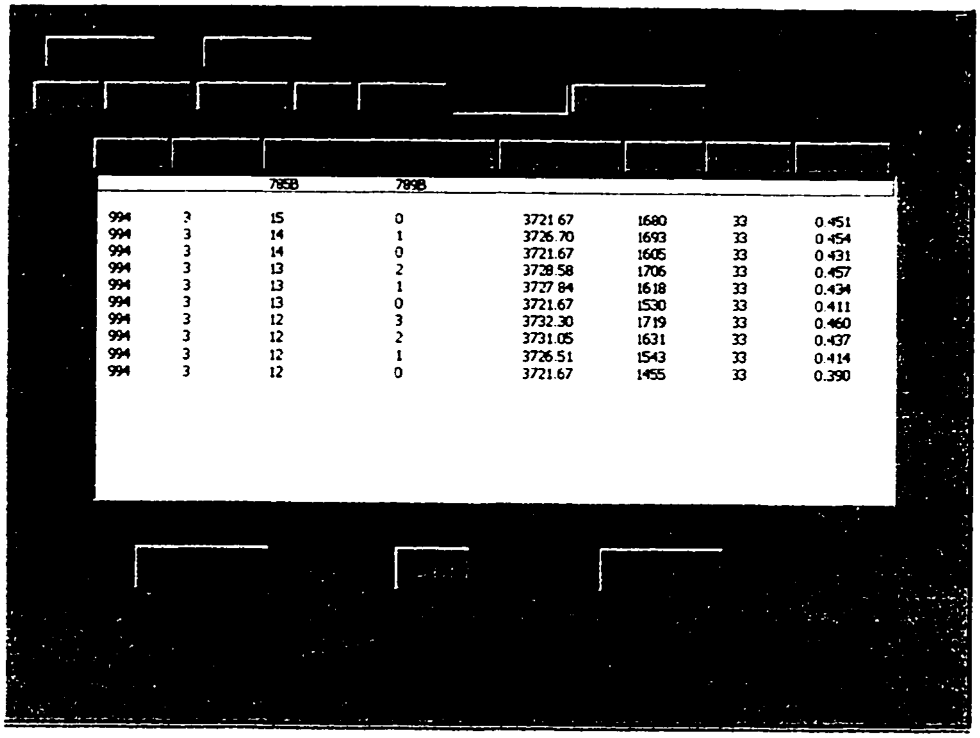


| | | 785B | 789B | | | | |
|---|---|---|---|---|---|---|---|
| 994 | 3 | 0 | 15 | 3765.76 | 1875 | 33 | 0.497 |
| 994 | 3 | 0 | 12 | 3765.76 | 1611 | 33 | 0.427 |
| 994 | 3 | 0 | 14 | 3764.50 | 1787 | 33 | 0.474 |
| 994 | 3 | 0 | 13 | 3764.50 | 1699 | 33 | 0.451 |
| 994 | 3 | 0 | 11 | 3764.50 | 1523 | 33 | 0.404 |
| 994 | 3 | 0 | 10 | 3764.50 | 1435 | 33 | 0.381 |
| 994 | 3 | 1 | 11 | 3763.51 | 1598 | 33 | 0.424 |
| 994 | 3 | 0 | 9 | 3763.25 | 1347 | 33 | 0.357 |
| 994 | 3 | 1 | 14 | 3762.64 | 1862 | 33 | 0.494 |
| 994 | 3 | 1 | 12 | 3762.63 | 1686 | 33 | 0.448 |

**Figure 4.25 Production Sorting**

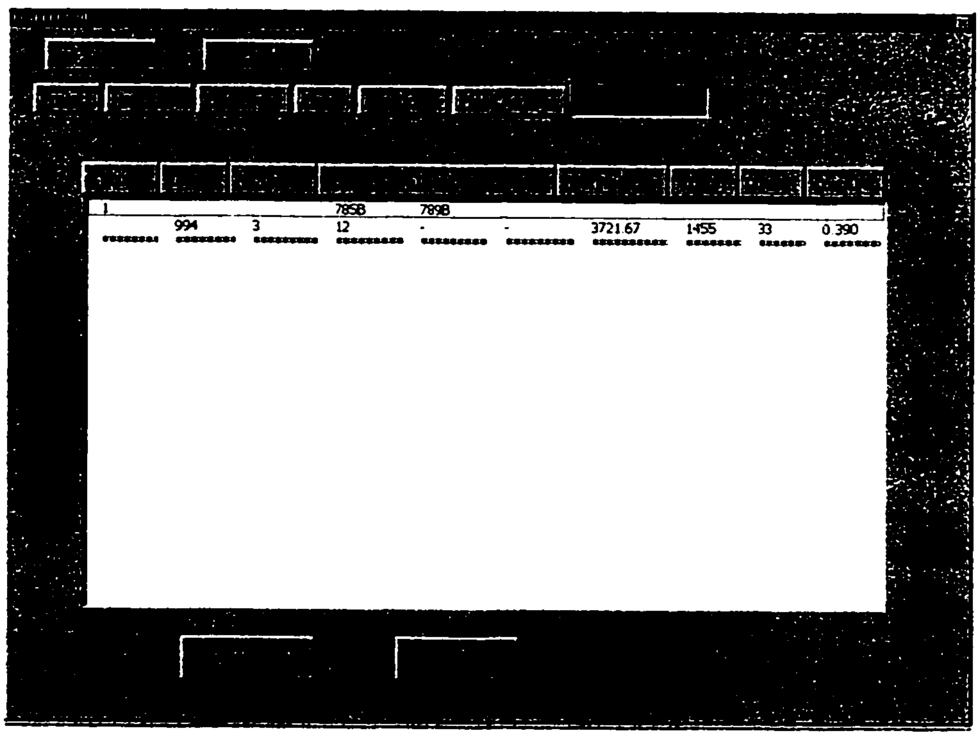
### 4.3.10 Fleet Selection

From the listed ten fleets, the user can select the best fleet for the project, this selection will be sent to the Optimization List as shown in Figure (4.27). This list enables the user to compare the productivity of fleets from different routes of the same project. The user can repeat the whole process starting from the selection of the haul road's conditions with the same project conditions (Weather, altitude) for another route.



| | | 7858 | 7898 | | | | |
|---|---|---|---|---|---|---|---|
| 994 | 3 | 15 | 0 | 3721.67 | 1680 | 33 | 0.451 |
| 994 | 3 | 14 | 1 | 3726.70 | 1693 | 33 | 0.454 |
| 994 | 3 | 14 | 0 | 3721.67 | 1605 | 33 | 0.431 |
| 994 | 3 | 13 | 2 | 3728.58 | 1706 | 33 | 0.457 |
| 994 | 3 | 13 | 1 | 3727.84 | 1618 | 33 | 0.434 |
| 994 | 3 | 13 | 0 | 3721.67 | 1530 | 33 | 0.411 |
| 994 | 3 | 12 | 3 | 3732.30 | 1719 | 33 | 0.460 |
| 994 | 3 | 12 | 2 | 3731.05 | 1631 | 33 | 0.437 |
| 994 | 3 | 12 | 1 | 3726.51 | 1543 | 33 | 0.414 |
| 994 | 3 | 12 | 0 | 3721.67 | 1455 | 33 | 0.390 |

**Figure 4.26 Duration Sorting**



| 1 | | | 7858 | 7898 | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 994 | 3 | 12 | - | - | 3721.67 | 1455 | 33 | 0.390 |

**Figure 4.27 Optimization List For The Different Routs**

### 4.3.11 Output

Charts for the different sortings can be viewed and printed out as shown in Figures 4.28, 4.29, and 4.30.A Report of the best ten fleets can also be viewed and printed out (Figure 4.31).

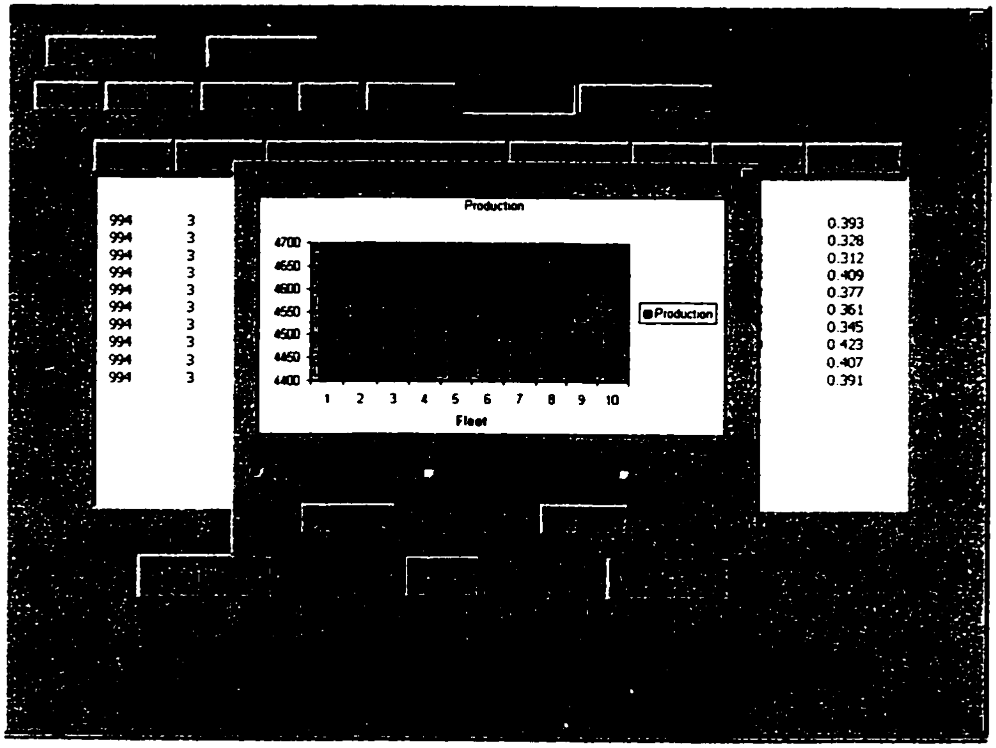



**Figure 4.28 Production Chart**

### 4.4 Assumptions and limitations

**FLSELECTOR** is developed as earthmoving fleet selection tool using queuing method; therefore the limitations of applying queuing method in earthmoving operations, apply to this work. The main limitations and assumptions of **FLSELECTOR** are:

1) The application of queuing method to earthmoving work is limited to three servers (Loaders) as for more servers calculation will be very complicated especially for large number of haulers.

2) Solving queuing method of model (M/$E_l$/c)/k with three servers and Erlang shape parameter $l$ = 20 (which best fit earthmoving field data) is analytically difficult, therefore shape parameter $l$ = 3 will be used instead.

3) Queuing methods of model ($E_l$/$E_l$/c)/k, which best represents earthmoving operations, is still difficult to solve thus it will be substituted by the closest model (M/$E_l$/c)/k.

4) **FLSELECTOR** assumes that no queues will occur at the dumping point, and that haulers have to wait only at the loading system.

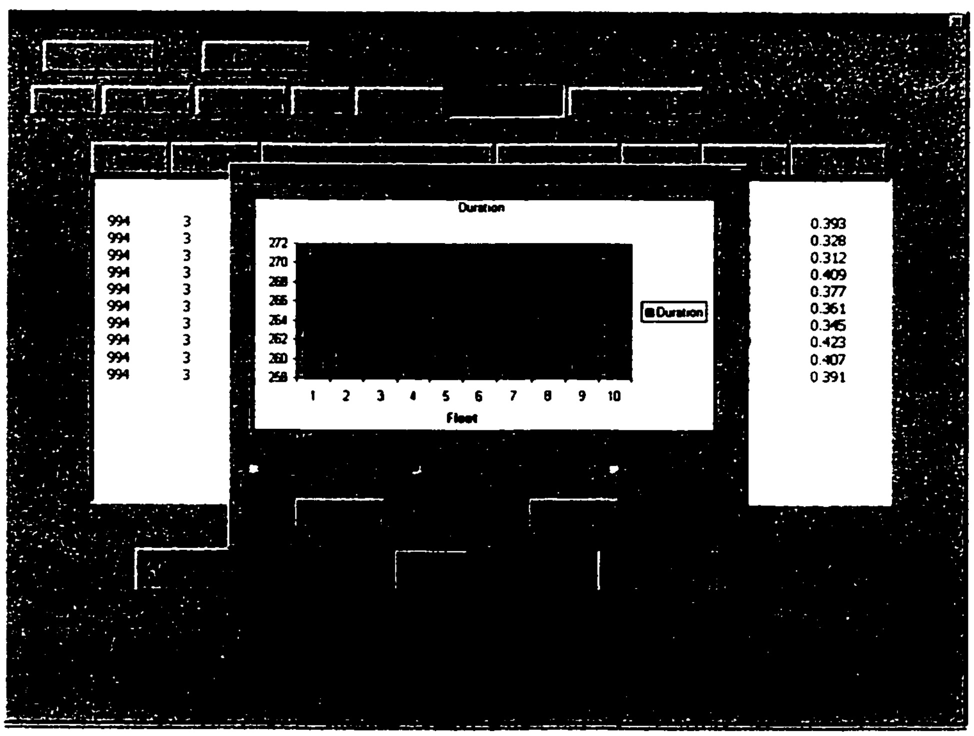



**Figure 4.29 Duration Chart**

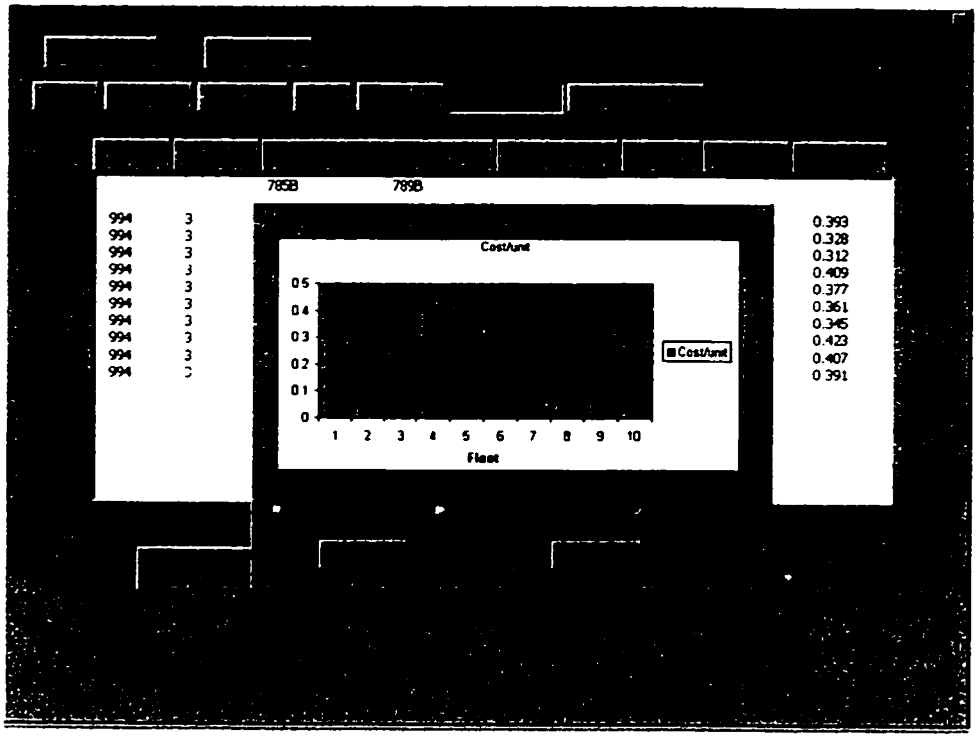



**Figure 4.30 Cost/Unit Chart**

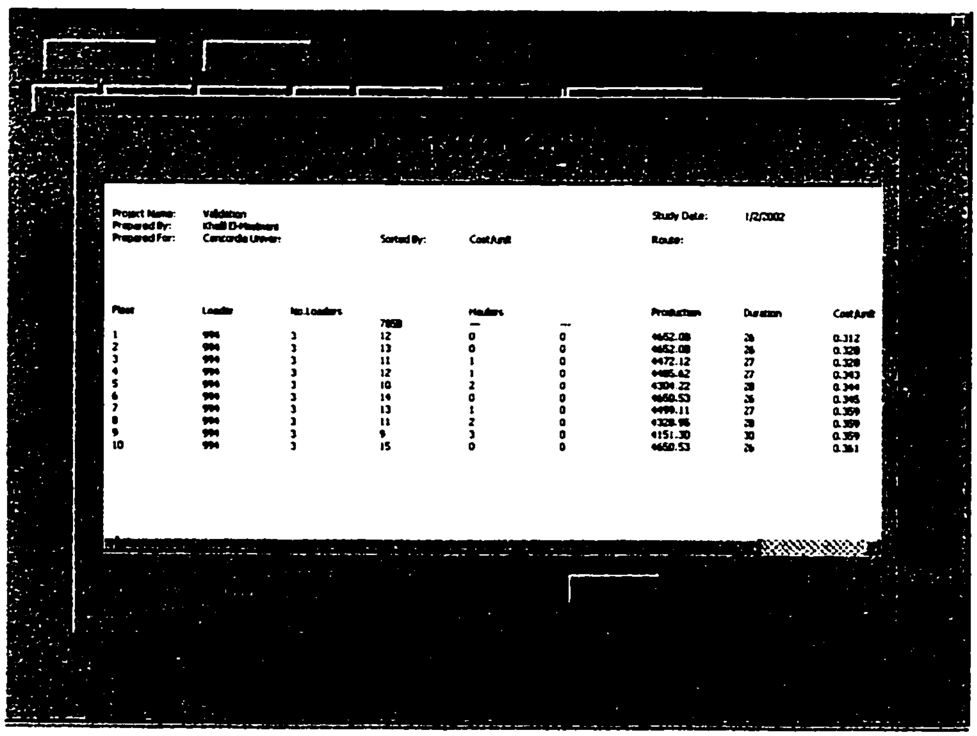


**Figure 4.31 Report of Sorted Fleets**

## 4.5 Model Validation

In order to demonstrate the capabilities of the proposed methodology, two cases have been analyzed. Two computer systems' outputs (FPC and SimEarth) were used to verify **FLSELECTOR** results.

**Case 1:**

This is a hypothetical case; it is used to verify the outputs with the deterministic method. The outputs of **FLSELECTOR** is compared with the output of Caterpillar Software (FPC).

Project Characteristics: The project requires moving 100,000 bcy of earth. The material is dry, loose sand, weighting 2700 lb per bcy. The available borrow pit requires an average haul of 5500 ft where:

-1350 ft with average grade of 3%, average rolling resistance of 10%, coefficient of traction of 0.45 and maximum allowable speed of 45 mph.

-3100 ft with average grade of 2%, average rolling resistance of 3%, coefficient of traction of 0.55 and maximum allowable speed of 50 mph.

-1050 ft with average grade of 4%, average rolling resistance of 10%, coefficient of traction of 0.36 and maximum allowable speed of 40 mph.

The earth will be excavated with a wheel loader 994. The average elevation of the project is 6300 ft above sea level.

Weather condition is of Temperature equal to +5°F, Wind speed equal to 20 miles/hour, and no precipitation.

Operator efficiency is equal to 85%

Loader availability is 78% and cost /h is 185 $

**FLSELECTOR:**

After completing all necessary data input as described earlier and shown from Figure (4.4) to Figure (4.19), calculations are done for cycle time. Fleet configurations are then listed. For each fleet, Production and Cost are calculated and this is done for one, two, and three server fleets. Finally sorting and selection for the best fleet are done. Results are shown in table 4.2.

| | | | Weather and Altitude Effect | | Minimum Weather and Altitude Effect | |
|---|---|---|---|---|---|---|
| **994** | **789B** | **785B** | **Production Ton/h** | **Cost/ton** | **Production Ton/h** | **Cost/ton** |
| 1 | 1 | 3 | 1016.75 | 0.489 | 1196.2 | 0.423 |
| 1 | 2 | 2 | 1092.46 | 0.467 | 1285.24 | 0.402 |
| 2 | 0 | 8 | 2083.63 | 0.465 | 2451.24 | 0.405 |
| 2 | 6 | 2 | 2342.12 | 0.447 | 2755.44 | 0.382 |
| 2 | 4 | 4 | 2321.31 | 0.44 | 2730.96 | 0.378 |
| 2 | 8 | 0 | 2422.5 | 0.443 | 2850 | 0.376 |
| 3 | 12 | 1 | 3762.63 | 0.448 | 4426.6 | 0.381 |
| 3 | 10 | 2 | 3760.51 | 0.421 | 4424.13 | 0.359 |
| 3 | 8 | 4 | 3755.26 | 0.415 | 4417.95 | 0.353 |

**Table 4.2 FLSELECTOR Outputs**

**FPC (Caterpillar Software).**

The outputs of the selected fleets from FPC are presented in table 4.3.

| 994 | 789B | 785B | Production ton/h | Cost/ton |
|---|---|---|---|---|
| 1 | 1 | 3 | 1397.66 | 0.394 |
| 1 | 2 | 2 | 1482.47 | 0.275 |
| 2 | 0 | 8 | 2499.09 | 0.324 |
| 2 | 6 | 2 | 3210.28 | 0.254 |
| 2 | 4 | 4 | 2964.95 | 0.275 |
| 2 | 8 | 0 | 3375.87 | 0.243 |
| 3 | 12 | 1 | 5081,81 | 0.255 |
| 3 | 10 | 2 | 5010.4 | 0.265 |
| 3 | 8 | 4 | 4698.98 | 0.261 |

**Table 4.3 FPC outputs**

**Case 2:** The second case study was presented by Marzouk and Moselhi (2001); it is an actual case study that involves the construction of a dam across Saint-Marguerite River, in the province of Quebec, Canada. Three soil materials are used in the construction of the dam: 1) moraine (clay), 2) granular (sand and gravel) and 3) rock. These materials are borrowed from different borrow pits during construction. In view of the cold weather conditions in the region, constructions was planned to performed only in the summer season over a 3-year period (from 1996 to 1998) and the project, accordingly, was phased in three stages as shown in figure 4.32.

The study presented focuses on estimating the time and cost required to borrow moraine material from MOR_1 borrow pit, shown in Figure 4.33, to fill the core of the dam. Tables 4.4, 4.5,and 4.6 summarize the scope of work, soil properties, fleet configurations and travel time distributions associated with the different activities involved (load, haul, dump and return).

Marzouk and Moselhi (2001) used a simulation system (**SimEarth**), developed to model earthmoving operations utilizing object-oriented and discrete event simulation, to estimate the time and cost required to accomplish the work in the project for each selected fleet configuration. Tables 4.7 and 4.8 list the estimated time and direct cost for the two fleets used in the three construction stages.

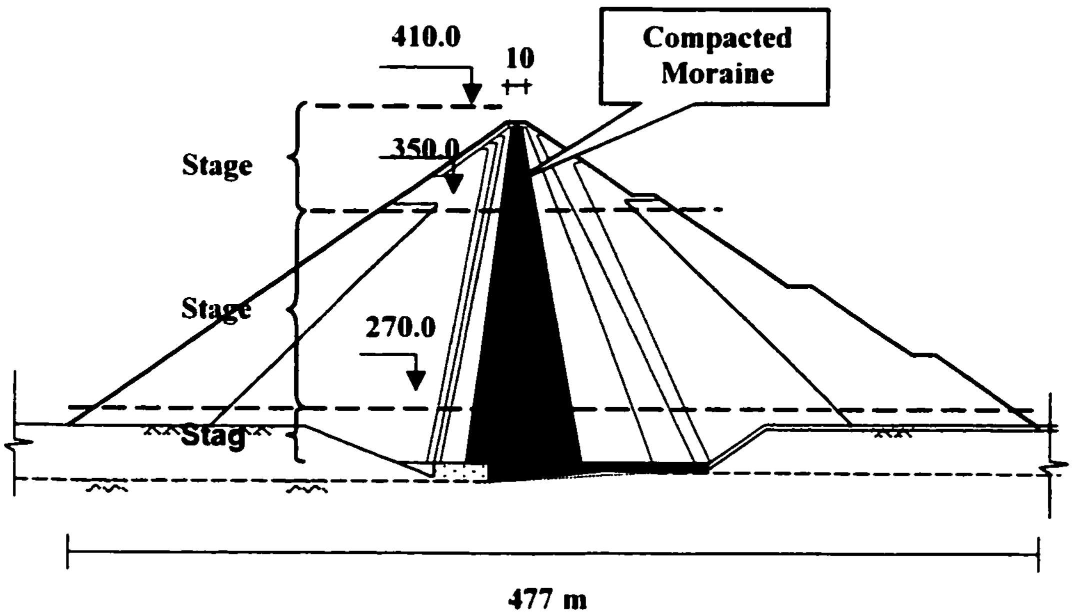



**Figure 4.32: Typical cross-section in the Dam**

**Table 4.4: HR_1 Road Segments (from Mor_1 to the dam)**

| [illegible] | [illegible] | [illegible] | [illegible] |
|---|---|---|---|
| 1 | 360 | 5 | 0.6 |
| 2 | 707 | 5 | -5.2 |
| 3 | 435 | 2 | 4.7 |
| 4 | 2,175 | 2 | -0.6 |
| 5 | 2,618 | 2 | -0.9 |
| 6 | 1,607 | 2 | 3.2 |
| 7 | 1,709 | 2 | 2.2 |
| 8 | 1,345 | 2 | -0.7 |
| 9 | 2,236 | 2 | -4.6 |
| 10 | 975 | 2 | 2.8 |
| 11 | 1,032 | 2 | 4.1 |
| 12 | 1,047 | 2 | -0.8 |
| 13 | 813 | 2 | 2.5 |
| 14 | 185 | 2 | 0 |
| | 17,262 | | |

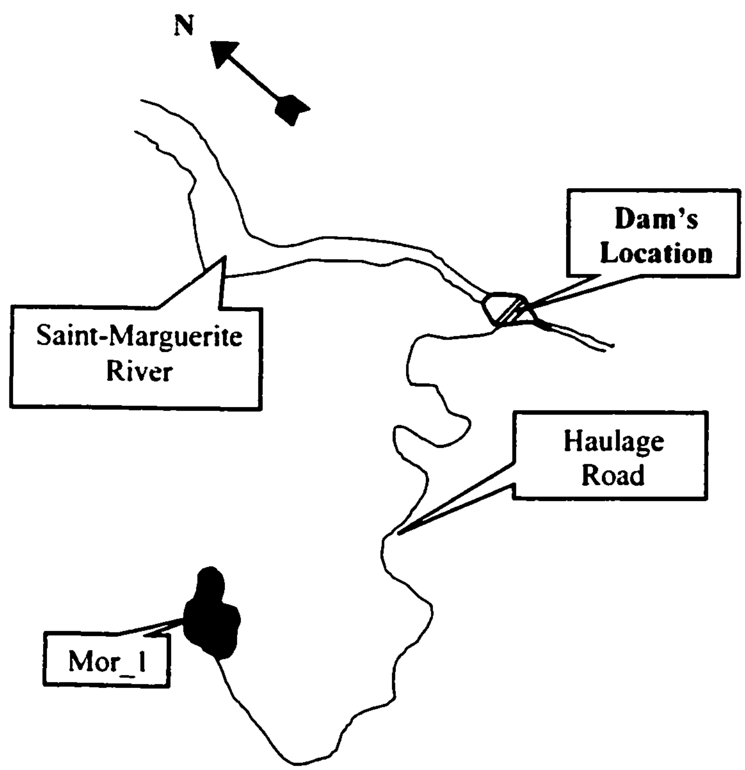



**Figure 4.33: Haulage Road profile**

**Table 4.5 : Scope of work and soil properties**

| | |
|---|---|
| Scope of work ($m^3$)(Stage 1): | 29,182 |
| Scope of work ($m^3$)(Stage 2): | 555,954 |
| Scope of work ($m^3$)(Stage 3): | 269,864 |
| Bank Density (kg/ $m^3$): | 2,080 |
| Loose Density (kg/ $m^3$): | 1,660 |
| Bucket fill factor (%): | 100 |

**Table 4.6 : Fleet Configuration**

| | |
|---|---|
| [redacted] | |
| **Loaders (Wheel Type)** | |
| Type: | CAT 990 |
| Number: | 1 |
| Buckets Capacity: | 8.41 |
| No of passes: | 3 |
| Hourly Owning and operating Cost ($/hr): | 243.35 |
| Haulers (Trucks): | |
| Type: | CAT 773D |
| Number: | 5 |
| Payload (ton): | 41.88 |
| Hourly Owning and operating Cost ($/hr): | 160.53 |
| [redacted] | |
| **Loaders (Wheel Type)** | |
| Type: | CAT 992D |
| Number: | 1 |
| Buckets Capacity: | 10.7 |
| No of passes: | 5 |
| Hourly Owning and operating Cost ($/hr): | 295.74 |
| Haulers (Trucks): | |
| Type: | CAT 77D |
| Number: | 4 |
| Payload (ton): | 88.81 |
| Hourly Owning and operating Cost ($/hr): | 212.95 |

**Table 4.7 : Scheduled Duration for the different Construction Stages (Hours)**

| | Fleet 1 | Fleet 2 |
|---|---|---|
| **Stage 1** | 221 | 139 |
| **Stage 2** | 4,204 | 2,645 |
| **Stage 3** | 2,042 | 1,284 |
| **Total** | 6,467 | 4,068 |

**Table 4.8: Estimated Direct Cost for the Different Construction Stages**

| | Fleet 1 | Fleet 2 |
|---|---|---|
| **Stage 1** | 231,166 | 159,508 |
| **Stage 2** | 4,397,384 | 3,035,243 |
| **Stage 3** | 2,135,932 | 1,473,441 |
| **Total** | 6,764,482 | 4,668,192 |

**FLSELECTOR**:

The case study is solved using **FLSELECTOR** in order it verify its results, figures 4.34 and 4.35 show respectively the travel time calculation and the output of the first loader and truck types. Table 4.9 lists the fleet outputs, and table 4.10 shows the estimated time and cost for the two fleets used in three construction stages. The analysis results indicate that fleet 2 performs the task in total duration of 3,321 hrs, and cost of $ 3,810,980.

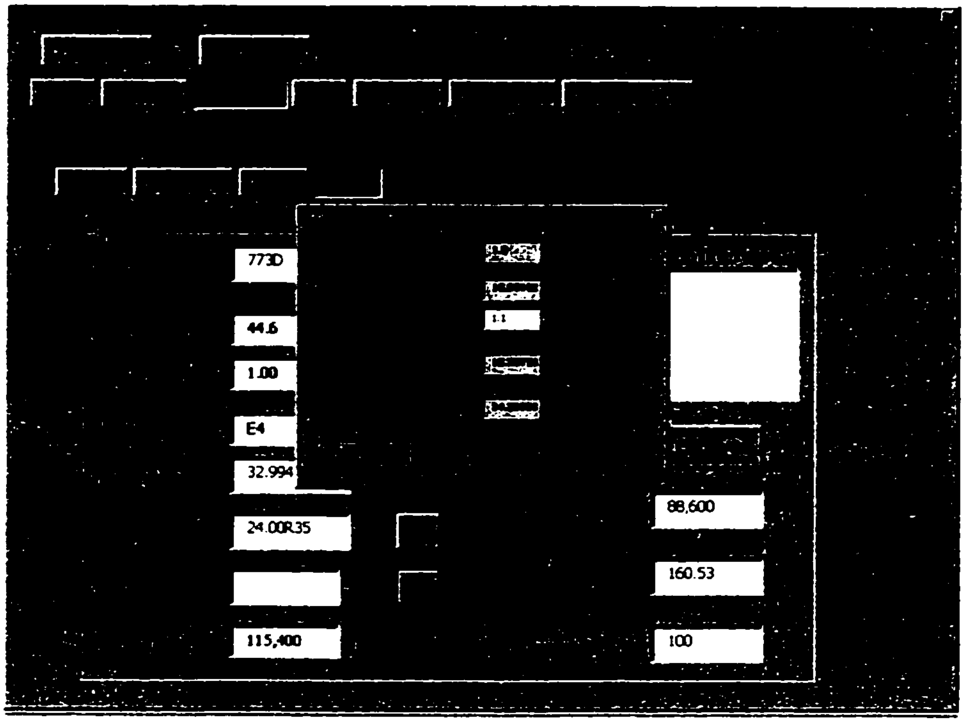



**Figure 4.34: Cycle time calculation for each hauler of the first fleet**

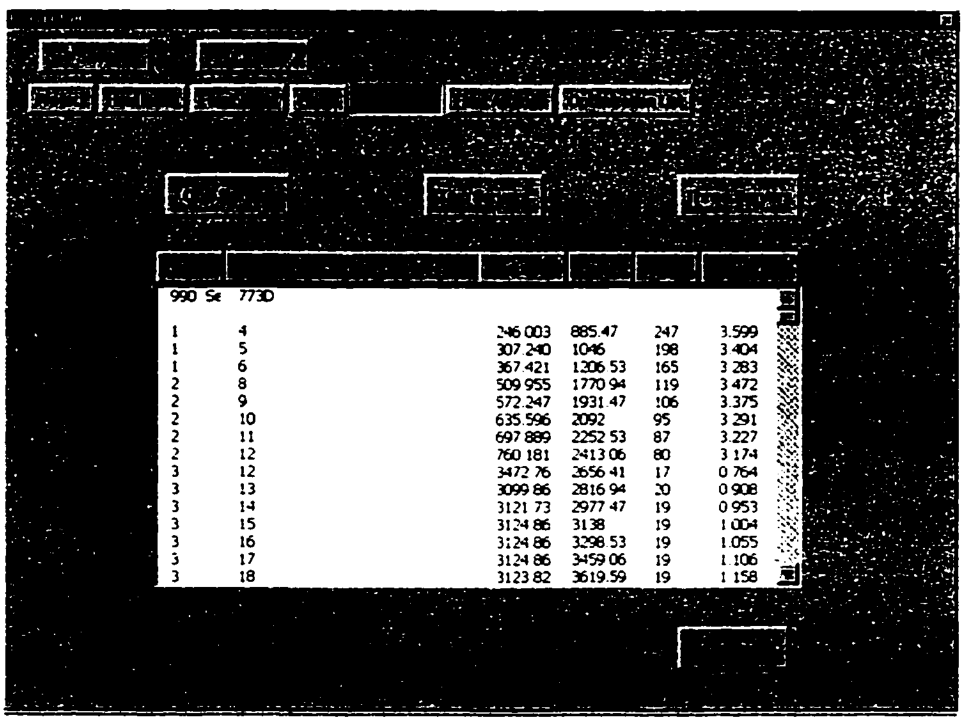



**Figure 4.35 Output of the first fleet components**

**Table 4.9:Fleet outputs**

| | Production, t | Cost $/hr | Cost/unit |
|---|---|---|---|
| Fleet 1 | 307.204 | 1046 | 3.404 |
| Fleet 2 | 535.372 | 1147.54 | 2.143 |

**Table 4.10: Estimated duration and cost for the different construction stages**

| | Fleet 1 | | Fleet 2 | |
|---|---|---|---|---|
| | Duration. Hrs | Cost. $ | Duration. Hrs | Cost. $ |
| Stage I | 198 | 207,108 | 113 | 129,672 |
| Stage II | 3764 | 3,937,144 | 2160 | 2,478,686.40 |
| Stage III | 1827 | 1,911,042 | 1048 | 1,202,621.92 |
| Total | 5789 | 6,055,294 | 3321 | 3,810,980 |

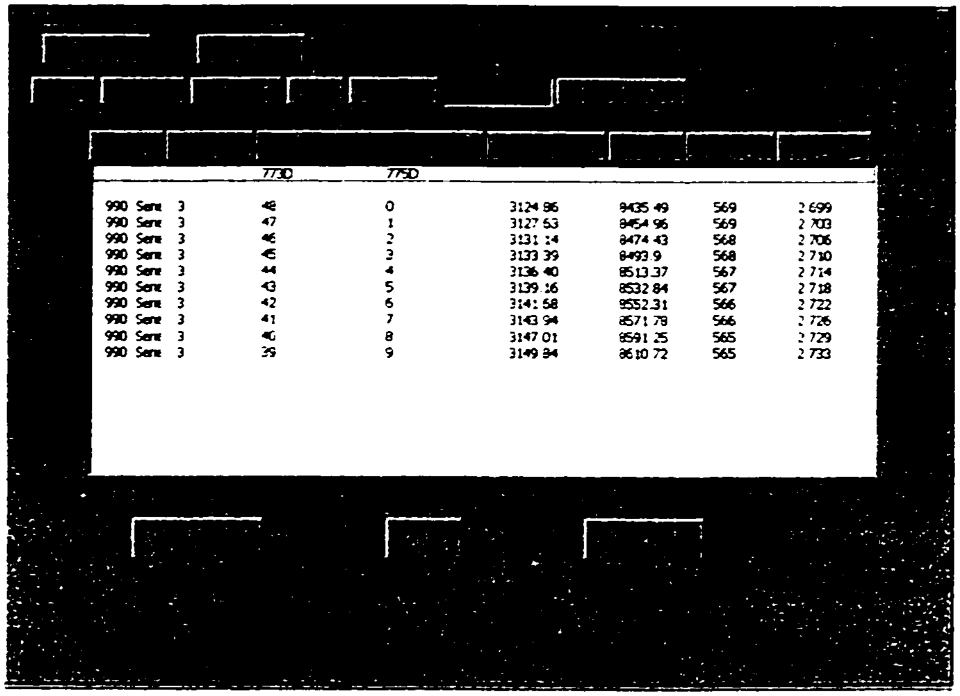
In order to validate the prototype, the same case study will be solved again but with the type and number of trucks that matches with the selected loaders: For the first fleet, the trucks that match with the loaders capacity are 773D and 775D.

Time calculations for these two trucks are:

**Table 4.11: Time calculation**

| | Loading time, Min | Trip time, Min | Matched No. loader |
|---|---|---|---|
| 773D | 1.9 | 30 | 17 |
| 775D | 2.45 | 33 | 14 |

The best ten fleets based on the cost per unit:



| | | | 773D | 775D | | | | |
|---|---|---|---|---|---|---|---|---|
| 990 | Sene | 3 | 48 | 0 | 3124 86 | 9435 49 | 569 | 2 699 |
| 990 | Sene | 3 | 47 | 1 | 3127 63 | 8454 96 | 569 | 2 703 |
| 990 | Sene | 3 | 46 | 2 | 3131 14 | 8474 43 | 568 | 2 706 |
| 990 | Sene | 3 | 45 | 3 | 3133 39 | 8493.9 | 568 | 2 710 |
| 990 | Sene | 3 | 44 | 4 | 3136 40 | 8513.37 | 567 | 2 714 |
| 990 | Sene | 3 | 43 | 5 | 3139.16 | 8532 84 | 567 | 2 718 |
| 990 | Sene | 3 | 42 | 6 | 3141 68 | 9552 31 | 566 | 2 722 |
| 990 | Sene | 3 | 41 | 7 | 3143 94 | 8571 78 | 566 | 2 726 |
| 990 | Sene | 3 | 40 | 8 | 3147 01 | 8591 25 | 565 | 2 729 |
| 990 | Sene | 3 | 39 | 9 | 3149 84 | 8610 72 | 565 | 2 733 |

**Figure 4.36 Cost / Unit Sorting for Fleet 1**

The fleet that has the maximum production is:

| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
|---|---|---|---|---|---|---|
| 990 II | 3 | 0 | 48 | 3230.99 | 550.4 | 2.9 |

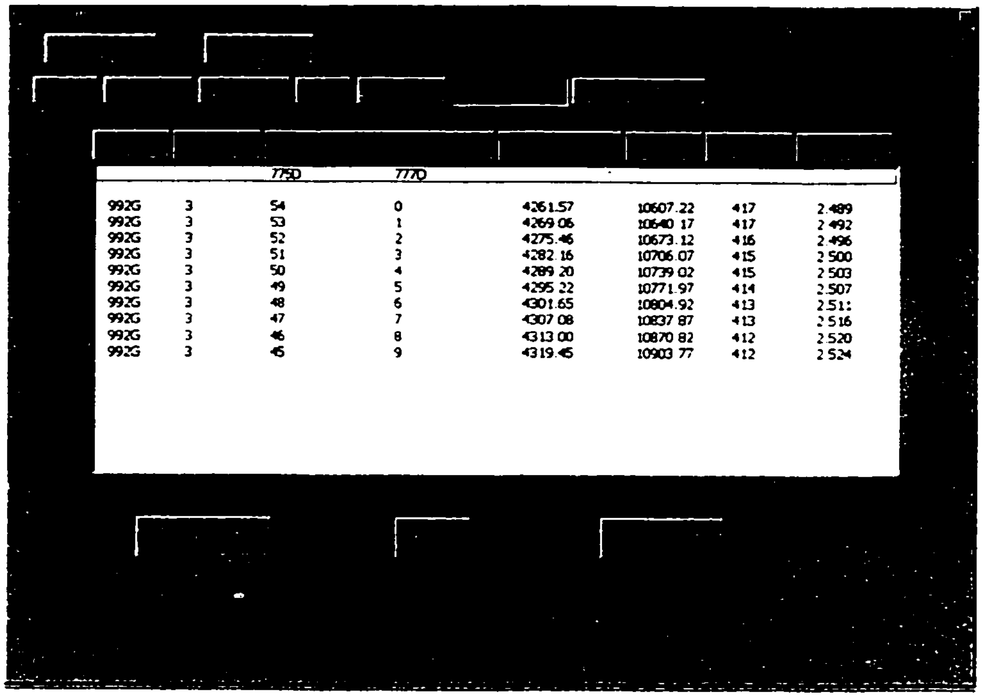
For the second fleet, the trucks that match with the loaders capacity are 775D and 777D.

Time calculations for these two trucks are:

**Table 4.12: Time calculation**

| | [illegible] | [illegible] | [illegible] |
|---|---|---|---|
| **775D** | 1.9 | 33 | 19 |
| **777D** | 3 | 30.7 | 11 |

The best ten fleets according to the cost per unit:



| | | 775D | 777D | | | | |
|---|---|---|---|---|---|---|---|
| 992G | 3 | 54 | 0 | 4261.57 | 10607.22 | 417 | 2.489 |
| 992G | 3 | 53 | 1 | 4269 06 | 10640 17 | 417 | 2 492 |
| 992G | 3 | 52 | 2 | 4275.46 | 10673.12 | 416 | 2.496 |
| 992G | 3 | 51 | 3 | 4282.16 | 10706.07 | 415 | 2 500 |
| 992G | 3 | 50 | 4 | 4289 20 | 10739 02 | 415 | 2 503 |
| 992G | 3 | 49 | 5 | 4295 22 | 10771.97 | 414 | 2.507 |
| 992G | 3 | 48 | 6 | 4301.65 | 10804.92 | 413 | 2.51: |
| 992G | 3 | 47 | 7 | 4307 08 | 10837 87 | 413 | 2 516 |
| 992G | 3 | 46 | 8 | 4313 00 | 10870 82 | 412 | 2.520 |
| 992G | 3 | 45 | 9 | 4319.45 | 10903 77 | 412 | 2 524 |

**Figure 4.37 Cost / Unit Sorting for Fleet 2**

The fleet that has the maximum production is:

| Loader | No. Loaders | 775D | 777D | Production | Duration | Cost/Unit |
|---|---|---|---|---|---|---|
| 992 G | 3 | 0 | 54 | 4498.92 | 395.3 | 2.753 |

To check out if we can get better outputs, a different Loader with its matched haulers is chosen, for example if we select loader 994, which matches with haulers 785B and 789B with the following specifications:

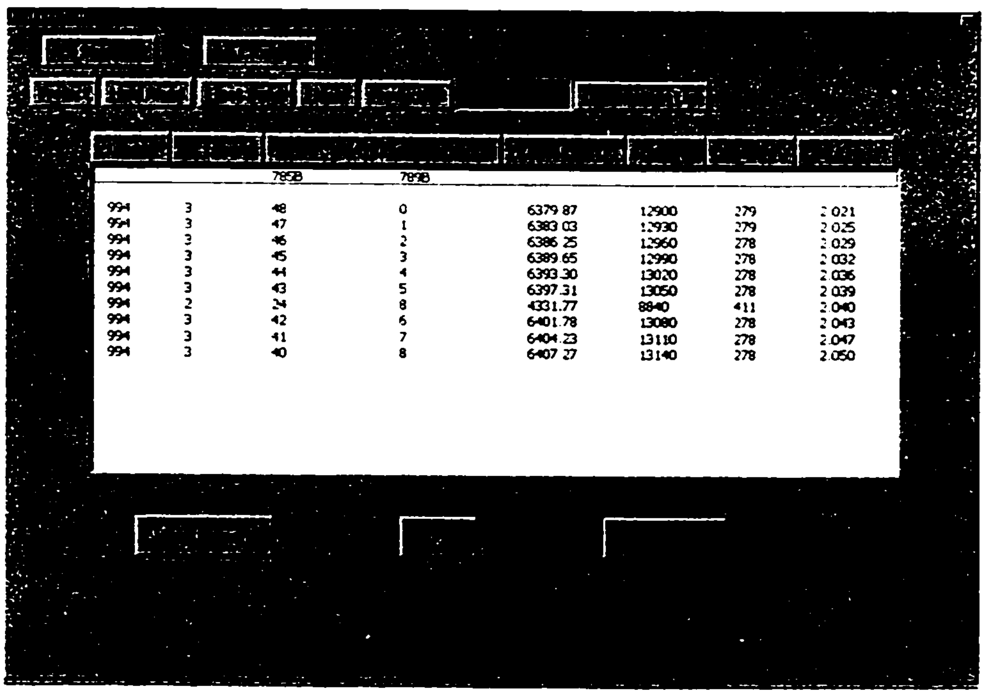
**Table 4.13: Fleet Configuration**

| | |
|---|---|
| [illegible] | |
| Type: | CAT 994 |
| Bucket Capacity ($m^3$): | 23.77 |
| Hourly Owning and Operating Cost ($/h): | 300 |
| [illegible] | |
| Type: | CAT 785B |
| Payload (ton) | 114.8 |
| Hourly Owning and Operating Cost ($/h): | 250 |
| Type: | CAT 789B |
| Payload (ton) | 197.7 |
| Hourly Owning and Operating Cost ($/h): | 280 |

The fleet with maximum production is:

| Loader | No. Loaders | 785B | 789B | Production | Duration | Cost/Unit |
|---|---|---|---|---|---|---|
| 994 | 3 | 0 | 48 | 6494.4 | 274 | 2.208 |

The best ten fleets based the cost per unit



| | | 785B | 789B | | | | |
|---|---|---|---|---|---|---|---|
| 994 | 3 | 48 | 0 | 6379.87 | 12900 | 279 | 2.021 |
| 994 | 3 | 47 | 1 | 6383.03 | 12930 | 279 | 2.025 |
| 994 | 3 | 46 | 2 | 6386.25 | 12960 | 278 | 2.029 |
| 994 | 3 | 45 | 3 | 6389.65 | 12990 | 278 | 2.032 |
| 994 | 3 | 44 | 4 | 6393.30 | 13020 | 278 | 2.036 |
| 994 | 3 | 43 | 5 | 6397.31 | 13050 | 278 | 2.039 |
| 994 | 2 | 24 | 8 | 4331.77 | 8840 | 411 | 2.040 |
| 994 | 3 | 42 | 6 | 6401.78 | 13080 | 278 | 2.043 |
| 994 | 3 | 41 | 7 | 6404.23 | 13110 | 278 | 2.047 |
| 994 | 3 | 40 | 8 | 6407.27 | 13140 | 278 | 2.050 |

**Figure 4.38 Cost / Unit Sorting for Fleet 3**

## 4.6 Summary:

This chapter presented the computer implementation stage of the proposed methodology using Microsoft Excel 2000 and Visual Basic for Applications.

The developed computer system "**FLSELECTOR**" for earthmoving equipment selection using queuing method was tested through two cases; the first case is to compare the results with the deterministic outputs of FPC, from this case we notice that the using of queuing method with Erlang distribution for the travel time in **FLSELECTOR** gives less production than the deterministic method in FPC. The result is consistent with earlier results for Carmichael (1986) who concluded that using conventional (deterministic) methods show over estimates of production of an average 12.5%. Ignoring some factors in FPC such as weather conditions, altitude, and traction coefficient attribute in increasing the difference between the two results.

The second case is an actual project presented by Marzouk and Moselhi (2001) and solved using the simulation system ***SimEarth***. A comparison of the results indicates that the outputs of the two methodologies have an average difference of 14 %.

# CHAPTER 5

# CONCLUSION AND FUTURE EXPANSION

## 5.1 Conclusion

Earthmoving operations represent a significant proportion of many large projects. These operations include excavating, hauling, and dumping of material. Selection of the appropriate fleet to work in such projects may rigorously reduce the total cost and keep the project duration within the scheduled time. Many factors affect the fleet productivity, and as a result the fleet suitability, such as the hauling road condition, project altitude, weather condition, operator efficiency, and equipment availability. Earthmoving Fleet selection may not be an easy task as construction operations are usually subject to variations and interruptions; most of these operations are classified as of stochastic type, where probability distributions are to describe the arrival and service pattern. The computer-based program **FLSELECTOR** described in this thesis is an attempt to overcome this complexity by implementing queuing theory using models of the form $(M/E_l/c)/K$ to select the best equipment fleet to work in earthmoving operations. **FLSELECTORE** has some limitations such as the number of servers (limited to three servers), and the assumption that no queues occur at the dumping point.

**FLSELECTOR** is a decision support tool to assist the users in their:

- Management decisions in earthmoving operations related to the size and number of haulers and excavators, haul road lengths and surface conditions, etc...
- Calculation of cost and duration for earthmoving operations.

In addition **FLSELECTOR** has the following features:

- It allows the user to match between the selected loader and different types of haulers.
- It incorporates a user-friendly interface to facilitate the user's input of the project.
- All the possible configurations of fleet components are obtained, so that the outputs for each fleet are calculated.
- Incorporates Graphical output charts and reports.
- Provides the user with the option to sort the best ten fleets based o n; maximum production, minimum duration or minimum cost/unit.

Two case studies were presented to test the validity of **FLSELECTORE** results. The first case results were compared with the conventional (deterministic) solution of the case. The results are consistent with earlier results of Carmichael (1986) who concluded that using conventional (deterministic) methods show over estimates of production of an average 12.5%. A similar comparison of the second case outputs was done with simulation results and it showed that the outputs of the two methodologies have an average difference of 14 %.

## 5.2 Research Contribution

The following can summarize the contributions of this research:

- A computer system for equipment fleet selection in earthmoving projects has been developed.

- Applying the queuing method of model $(M/E_l/c)/K$ in earthmoving operation for one, two, and three loaders.
- Validating the outputs of queuing method by comparing them with deterministic and simulation theories.

The developed system is designed to assist engineers, owners, and contractors of earthmoving projects in selecting the best equipment fleet that can finish the task in minimum time, total cost, or cost per unit. It presents a list of the best ten fleets to complete the work along with the production, project duration, and cost/unit for each fleet. In addition an output report for this list with the option of column charts is available. Users can compare between the productions of different routes. The stored equipment can be extended in order to use customized equipment in the fleet selection.

## 5.3 Recommendations For Future Research

- Expanding the types of equipment stored in the system.
- Solving the queuing method with Erlang shape parameter ($l$ =20) for the three-server-case, and finding a mathematical solution for the model $(E_l/E_l/c)/K$, which is the best to represent the earthmoving operations.
- Improving the system to include the case where queues are in both excavating and dumping points.
- Include more equipment types in the prototype.
- The research can be expanded to include more than one dumping pit for each project.
- Link the model with an optimization Software

# APPENDIX (A)

## HAUL-UNIT PERFORMANCE

## CALCULATION PROCEDURE

# Haul-unit performance Calculation Procedure

In the following is the explanation of the procedure used by (Hicks, 1996) to compute the coefficients of the equation that determines the haul-unit performance.

**1- Procedure**

The coefficients for a performance equation are determined for each different machine based upon the manufacturer's specifications. From a data set extracted from the individual haul-unit alignment chart, a linear (log-log) regression analysis will determine the coefficients for the performance equation. Different points selected from the alignment chart and for each point the haul-unit speed and rim pull are obtained.

**2- Beginning Data Point**

The beginning data point is located at the intersection of the torque converter drive curve (dashed line) and direct drive curve (see point A Figure A.1.). Two reasons for locating point A at this point are (1) The traction, for speeds in the vicinity of this point, and at lower speeds, may no longer be great enough to prevent wheel spin; (2) the theoretical basis for the chosen performance equation is not valid in the torque converter range.

**3- Ending Point data**

The ending point data should be the ordinate for 2.5% total resistance (grading plus rolling) and the haul unit loaded (see point B in Figure A.1.).

When speeds are near this point, and higher, the haul-unit power becomes variable and begins to decrease due to throttling. Throttling also invalidates the theoretical basis for the chosen performance equation.

**4- Intermediate data points**

Intermediate points are chosen so that there will be a data point at the intersection of the gear changes and at the breakpoint (see Figure A.1) between gear changes.

**5- Performance Equation**

The required rim pull necessary to maintain a certain speed is:

$RP_{reqd} = 0.01 c_f (W_e + U_w B) G_o$

The available rim pull at speed $V_h$ is:

$$RP_{avail} = F = \left(\frac{V_h}{K_o}\right)^{1/n}$$

Setting the available rim pull equal to the required rim pull and solving for the speed

$V_h = K_o\,[0.01\, c_f (W_e + U_w B)\, G_o]^{n'}$

Where: $V_h$ = haul-unit speed (km/hr); $K_o$ = a coefficient determined by regression analysis; $c_f$ = units conversion factor; $W_e$ = empty weight of haul unit (t or kip[mass]); $U_w$ = bank unit weight of material (t/m$^3$ or yd$^3$); $B$ = bank carrying capacity of haul unit (m$^3$ or yd$^3$); $G_o$ = effective resistance (grade plus rolling) (%); n' = an exponent determined by regression analysis; $F$ = haul unit manufacturer's rated rim pull (kN); and RP = rim pull (kN).

**6- Performance equation coefficients**

Due to the type of equation chosen it is convenient and useful to convert the raw data to $\log_{10}$. After conversion to log, the data is plotted log speed versus log rim pull (Figure A.2) is the scatter gram for the data set. The advantages of having scatter gram are: (1) Visual inspection will determine closeness of fit (correlation) for the data set: and (2) a straight line best fits the data. Measuring the $y$ intercept and slope of fitted line determines the values of log ($K_0$) and (n'), respectively. The coefficients in the performance equation can be calculated as follows:

$$n' = \frac{\sum [(\log V_h)(\log F)] - n(\text{average} \log V_h)(\text{average} \log F)}{\sum (\log F)^2 - N(\text{average} \log F)^2}$$

Log $K_o$ = (average log $V_h$)-n (average log $F$)

**7- Retarding**

The coefficients for rim push (retarding) are obtained in the same manner as described for rim pull.

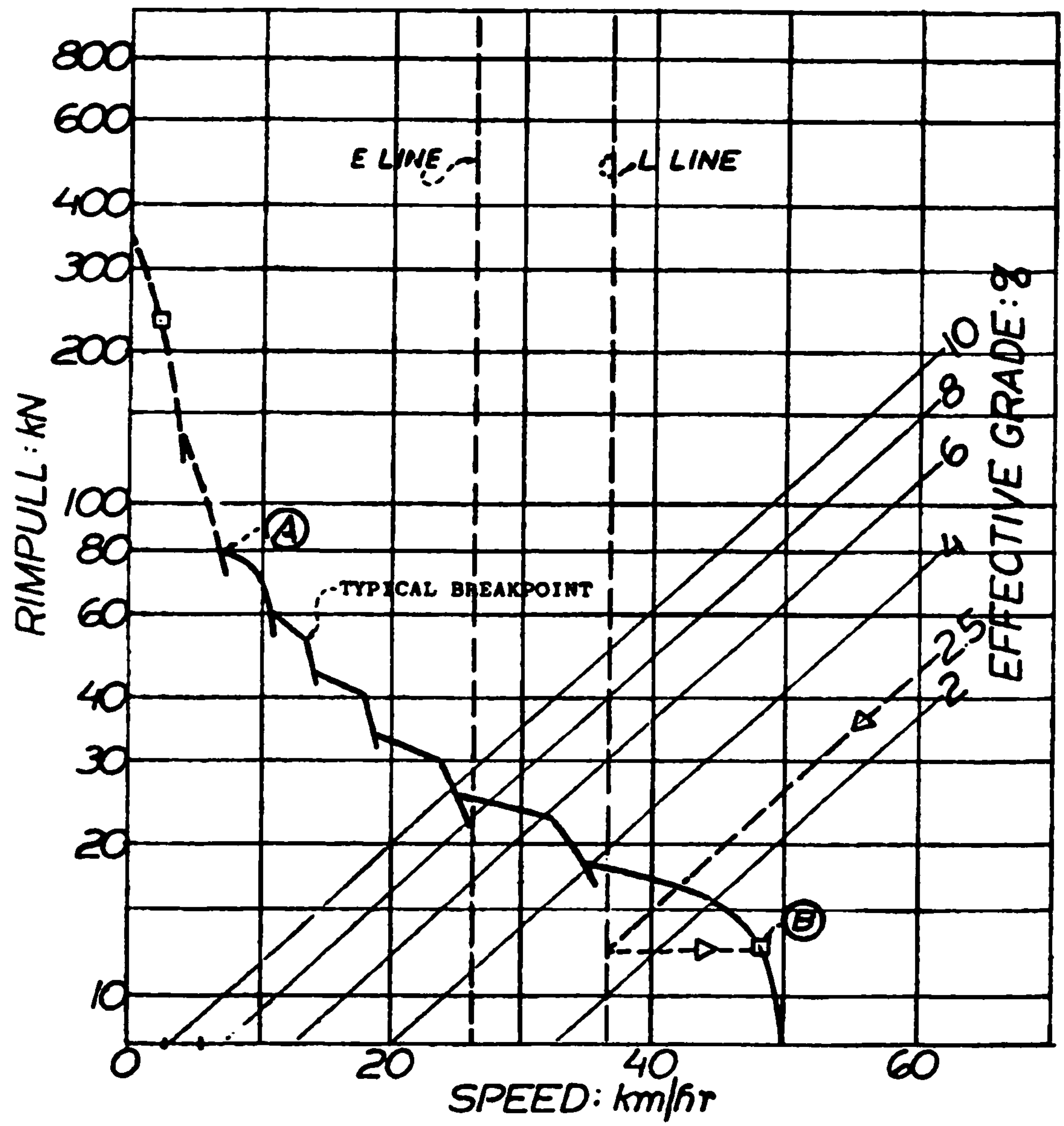



Fig A.1 Caterpillar 621E Rim Pull Speed Gradeability

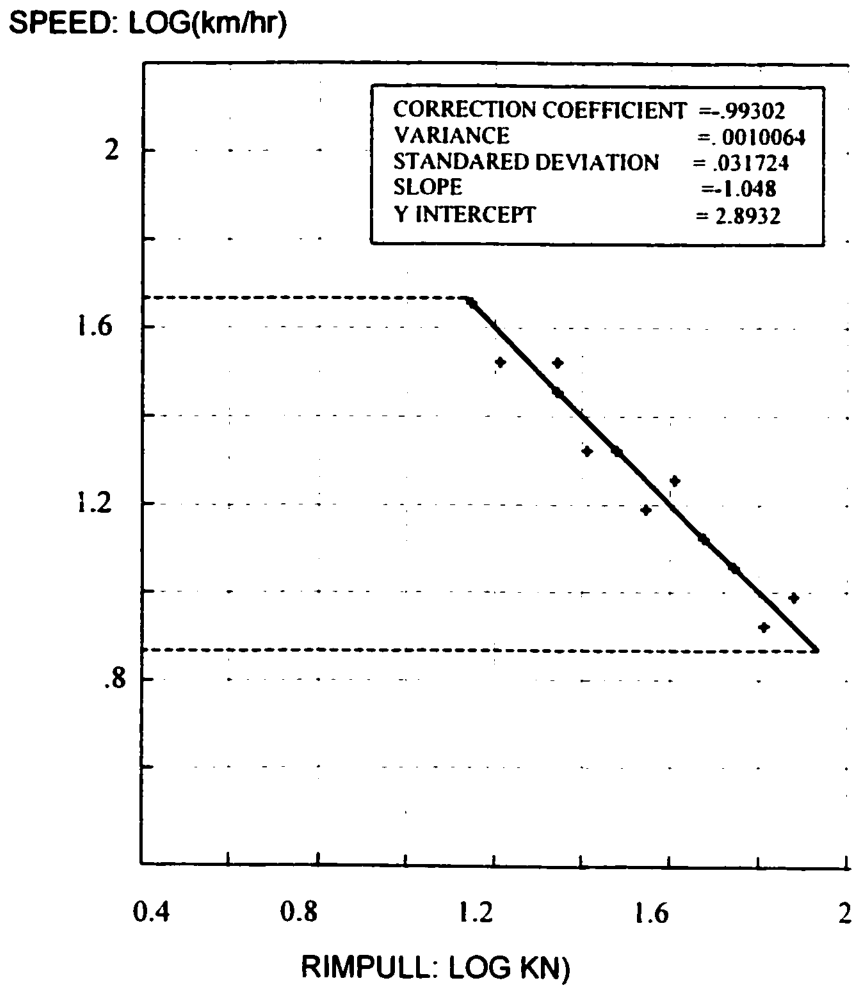



**Figure A.2 Scattergram: Caterpillar 621E Performance**

# APPENDIX (B)

## TABLES

# Tables

**Representative rolling resistance for various types of wheels and surfaces**

| Type of surface | Steel tires, plain bearing | Crawler-type track and wheel |
|---|---|---|
| Smooth concrete | 40<br>(20) | 55<br>(27) |
| Good asphalt | 50-70<br>(30-35) | 60-70<br>(30-35) |
| Earth compacted and maintained | 60-80<br>(30-40) | 60-80<br>(30-40) |
| Earth poorly maintained | 80-110<br>(40-55) | 80-110<br>(40-55) |
| Earth rutted, muddy, no maintained | 140-180<br>(70-90) | 140-180<br>(70-90) |
| Loose gravel and sand | 160-200<br>(80-100) | 160-200<br>(80-100) |
| Earth, very muddy, rutted soft | 200-240<br>(100-120) | 200-240<br>(100-120) |

In pound per 2,00 lb, -ton or (kilograms per metric ton) of gross load

**Table 3.1 Caterpillar Performance Handbook, 28th Ed.**

**Typical Coefficients of Traction**

| Type of Surface | Rubber Tires | Crawler |
|---|---|---|
| Concrete | 0.90 | 0.45 |
| Clay loam, dry | 0.55 | 0.90 |
| Clay loam, wet | 0.45 | 0.70 |
| Rutted clay loam | 0.40 | 0.70 |
| Sand, dry | 0.20 | 0.30 |
| Sand, wet | 0.40 | 0.50 |
| Quarry pit | 0.65 | 0.55 |
| Gravel road, loose | 0.36 | 0.50 |
| Firm earth | 0.55 | 0.90 |
| Loose earth | 0.45 | 0.60 |
| Packed snow | 0.20 | 0.27 |
| Ice | 0.12 | 0.12 |

**Table 3.2 Caterpillar Performance Handbook, 28th Ed.**

**Loader Bucket Fill Factors**

| Material | Fill Factor |
|---|---|
| Mixed or uniform granular | 0.95-1.00 |
| Medium, coarse stone | 0.85-0.90 |
| Well-blasted rock | 0.80-0.95 |
| Average-blasted rock | 0.75-0.90 |
| Poorly blasted rock | 0.60-0.75 |
| Rock dirt mixtures | 1.00-1.20 |
| Moist loam | 1.00-1.10 |
| Cemented materials | 0.85-0.95 |

**Table 3.3 Data for this table was extracted from Caterpillar Performance Handbook, 28$^{th}$ Ed.**

## Altitude Deration

| Model | 0-760m (0-2500') | 760-1500m (2500-5000') | 1500-2300m (5000-7500') | 2300-3000m (7500-10,000') | 3000-3800m (10,000-12500') | 3800-4600m (12,500-15,000') |
|---|---|---|---|---|---|---|
| 769D | 100 | 100 | 100 | 93 | 88 | 82 |
| 771D | 100 | 100 | 100 | 93 | 88 | 82 |
| 773D | 100 | 100 | 100 | 100 | 93 | 85 |
| 775D | 100 | 100 | 100 | 100 | 93 | 85 |
| 777D | 100 | 100 | 100 | 100 | 93 | 85 |
| 785B | 100 | 100 | 100 | 93 | 86 | 79 |
| 789B | 100 | 100 | 100 | 93 | 86 | 79 |
| 793C | 100 | 100 | 100 | 100 | 100 | 94 |
| 776C | 100 | 100 | 100 | 100 | 93 | 85 |
| 748B | 100 | 100 | 100 | 93 | 86 | 79 |

**Table 3.4 Extracted from Caterpillar Performance Handbook, 28th Ed.**

**Hauling and Excavation Efficiency Related to Temperature, Lighting and Preceipitation**

| Weather Factor | Hauling Machinery Efficiency (1.00=100%) | Excavation Machinery Efficiency (1.00=100%) |
|---|---|---|
| **Temperature (°C)** | | |
| 30 | 0.89 | 0.87 |
| 20 | 1 | 0.99 |
| 10 | 1 | 1 |
| 5 | 1 | 0.99 |
| 0 | 0.97 | 0.99 |
| -5 | 1 | 0.98 |
| -10 | 0.96 | 0.92 |
| -20 | 0.88 | 0.78 |
| -30 | 0.66 | 0.43 |
| **Light condition** | | |
| Direct sunlight | 0.96 | 0.96 |
| Indirect sunlight | 1 | 1 |
| Twilight | 0.96 | 0.88 |
| Darkness | 0.82 | 0.65 |
| **Precipitation** | | |
| Heavy rain | 0.85 | 0.81 |
| Light rain | 0.98 | 0.97 |
| Heavy snowfall | 0.76 | 0.73 |

**Table 3.5 (Roberts 1976)**

**Operator Efficiency**

| One-way Hal distance | | Average operator efficiency |
|---|---|---|
| Meters | Feet | % |
| 152 | 500 | 77 |
| 305 | 1000 | 80 |
| 610 | 2000 | 85 |
| 1067 | 3500 | 90 |
| 1524 | 5000 | 92 |
| 2439 | 8000 | 95 |

**Table 3.6 Caterpillar Software Manual**

**Material Types**

| Material | Lbs per LCY | Lbs per BCY |
|---|---|---|
| Basalt | 3,304 | 5,006 |
| Bauxite, kaolin | 2,393 | 3,203 |
| Carnotite, uranium ore | 2,747 | 3,708 |
| Caliche | 2.107 | 3,809 |
| Cinders | 944 | 1,450 |
| Clay-natural bed | 2,798 | 3,405 |
| Clay-dry | 2,495 | 3,101 |
| Clay-wet | 2,798 | 3,506 |
| Clay and gravel-dry | 2,393 | 2,798 |
| Clay and gravel-wet | 2,596 | 3,101 |
| Coal-Bituominous Ash (max) | 1,096 | 1,500 |
| Coal-Bituominous Ash (min) | 893 | 994 |
| Coal-Raw Anthracite | 2,006 | 2,697 |
| Coal-Raw Bituominous | 1,600 | 2,150 |
| Coal-Washed Anthracite | 1,854 | 1,854 |
| Coal-Washed Bituominous | 1,399 | 1,399 |
| Decomposed Rock- 25% Rock, 75% Earth | 2,646 | 3,304 |
| Decomposed Rock- 50% Rock, 50% Earth | 2,899 | 3,843 |
| Decomposed Rock- 75% Rock, 25% Earth | 3,304 | 4,703 |
| Earth-Dry packed | 2,545 | 3,203 |
| Earth-Loam | 2,107 | 2,596 |
| Earth-Wet excavated | 2,697 | 3,405 |
| Granite-Broken | 2,798 | 4,602 |
| Gravel-Dry | 2,545 | 2,849 |
| Gravel-Dry (6-50 mm) | 2,894 | 3,203 |
| Gravel-Pitrun | 3,253 | 3,658 |

| | | |
|---|---|---|
| Gravel-Wet (6-50 mm) | 3,405 | 3,809 |
| Gypsum-Broken | 3,051 | 5,343 |
| Gypsum-Crushed | 2,697 | 4,703 |
| Hematite-High Grade (max) | 5,400 | 6,400 |
| Hematite-High Grade (min) | 4,000 | 4,700 |
| Limestone-Broken | 2,596 | 4,399 |
| Limestone-Crushed | 2,596 | 2,596 |
| Magnetite | 4,703 | 5,495 |
| Pyrite | 4,349 | 5,107 |
| Sand-Damp | 2,850 | 3,200 |
| Sand-Dry, loose | 2,400 | 2,700 |
| Sand-Wet | 3,101 | 3,506 |
| Sand and Clay- compacted | 4,045 | 4,045 |
| Sand and Clay- loose | 2,700 | 3,400 |
| Sand and Gravel- Dry | 2,899 | 3,253 |
| Sand and Gravel-Wet | 3,405 | 3,759 |
| Bandstone | 2,545 | 4,248 |
| Shale | 2,107 | 2,798 |
| Slag-Broken | 2,950 | 4,956 |
| Snow-Dry | 219 | 219 |
| Snow-Wet | 876 | 876 |
| Stone-crushed | 2,697 | 4,500 |
| Taconite (max) | 4,200 | 6,100 |
| Taconite (min) | 3,600 | 5,200 |
| Tap rock-Broken | 2,950 | 4,399 |
| Top Soil | 1,601 | 2,309 |

**Table 4.1 Caterpillar Software Manual**

# APPENDIX (C)

## Sample Of The Utilization Calculation

## Samples of the Utilization Calculation

u8 = (a * b * b / 2 + b * b * c / 6 + a * c * b / 3 - a * b * b / 10 - b * b * c / 30 - a * c * b / 15 + b * c * c / 15 + 2 * a * c * c / 15)
v8 = (-a * b / 2 - c * b / 3 - b * b / 2 + a * b / 10 + b * c / 15 + b * b / 10 - 2 * c * c / 15 + a * b / 5)
k8 = N * X * b / 2 - b * b * a * c * N * X / 6 - N * X * b / 10 + b * b * a * c * N * X / 30 - b * a * c * c * N * X / 15 - b * N * X / 5 - (N - 1) * X * X * N / 5

u9 = (((-0.5 / (b / 2 + 5 * c / 6 + d / 3)) * (a * (N - 2) * X / 2 + a * b ^ 4 / 4 + b ^ 4 * c / 12 + a * c * b ^ 3 / 6 - a * b ^ 4 / 20 - b ^ 4 * c / 60 - a * c * b ^ 3 / 30 + b ^ 3 * c ^ 2 / 30 + 2 * a * b ^ 2 * c ^ 2 / 30 - (N - 1) * X * b / 2 + a * b ^ 2 * c ^ 2 / 30 + b ^ 2 * c ^ 3 / 90 + a * c ^ 3 * b / 45 - b * c ^ 4 / 45 - 2 * a * c ^ 4 / 45 - b * d * c ^ 3 / 18 - a * c ^ 3 * d / 9 - a * b ^ 2 * c * d / 15 - b ^ 2 * c ^ 2 * d / 45 - 2 * a * c ^ 2 * b * d / 45 + 2 * b * c ^ 3 * d / 45 + 4 * a * c ^ 3 * d / 45 + (N - 2) * X * d / 6 + (N - 3) * X * (b / 6 + a / 3)) + 0.5 * (a * b ^ 3 / 2 + b ^ 3 * c / 6 + a * c * b ^ 2 / 3 - a * b ^ 3 / 10 - b ^ 3 * c / 30 - a * c * b ^ 2 / 15 + b ^ 2 * c ^ 2 / 15 + 2 * a * b * c ^ 2 / 15 - (N - 1) * X)))

v9 = (((-0.5 / (b / 2 + 5 * c / 6 + d / 3)) * (-(N - 1) * X - a * b ^ 3 / 4 - c * b ^ 3 / 6 - b ^ 4 / 4 + a * b ^ 3 / 20 + b ^ 3 * c / 30 + b ^ 4 / 20 - 2 * c ^ 2 * b ^ 2 / 30 + a * b ^ 3 / 10 - a * b * c ^ 2 / 30 - b * c ^ 3 / 45 - c ^ 2 * b ^ 2 / 30 + 2 * c ^ 4 / 45 - a * b * c ^ 2 / 15 + c ^ 3 * d / 9 + a * b * c * d / 15 + 2 * b * c ^ 2 * d / 45 + b ^ 2 * c * d / 15 - 4 * c ^ 3 * d / 45 + 2 * a * b * c * d / 15 - (N - 3) * X / 3 - (N - 2) * X / 2)) + 0.5 * (-a * b ^ 2 / 2 - c * b ^ 2 / 3 - b ^ 3 / 2 + a * b ^ 2 / 10 + b ^ 2 * c / 15 + b ^ 3 / 10 - 2 * c ^ 2 * b / 15 + a * b ^ 2 / 5))

k9 = (((-0.5 / (b / 2 + 5 * c / 6 + d / 3)) * (N * X * b ^ 3 / 4 - b ^ 4 * a * c * N * X / 12 - N * X * b ^ 3 / 20 + b ^ 4 * a * c * N * X / 60 - b ^ 3 * a * c ^ 2 * N * X / 30 - b ^ 3 * N * X / 10 - (N - 1) * X ^ 2 * b ^ 2 * N / 10 + N * X * b * c ^ 2 / 30 - b ^ 2 * a * c ^ 3 * N * X / 90 + b * a * c ^ 4 * N * X / 45 + b * c ^ 2 * N * X / 15 + (N - 1) * X ^ 2 * N * c ^ 2 / 15 + b * a * c ^ 3 * d * N * X / 18 - N * X * b * c * d / 15 + b ^ 2 * a * c ^ 2 * N * X * d / 45 - 2 * b * a * c ^ 3 * N * X * d / 45 - 2 * b * c * d * N * X / 15 - 2 * (N - 1) * X ^ 2 * N * c * d / 15 - (N - 2) * X ^ 2 * N * a * d / 6 - (N - 3) * X * b * a * N * X / 6)) + 0.5 * (N * X * b ^ 2 / 2 - b ^ 3 * a * c * N * X / 6 - N * X * b ^ 2 / 10 + b ^ 3 * a * c * N * X / 30 - b ^ 2 * a * c ^ 2 * N * X / 15 - b ^ 2 * N * X / 5 - (N - 1) * X ^ 2 * b * N / 5))

u10 = (-(b / 6) - (a / 3))
v10 = (1 / 3)
k10 = b * a * N * X / 6

u11 = (-(b * c / 6) - (a * c / 3))
v11 = (c / 3)
k11 = b * a * c * N * X / 6

u12 = (-b * c * c / 6 - a * c * c / 3 - a * b * b / 5 - b * b * c / 15 - 2 * a * c * b / 15 + 2 * b * c * c / 15 + 4 * a * c * c / 15)
v12 = (c * c / 3 + a * b / 5 + 2 * b * c / 15 + b * b / 5 - 4 * c * c / 15 + 2 * a * b / 5)

```
k12 = b * a * c * c * N * X / 6 - N * X * b / 5 + b * b * a * c * N * X / 15 - 2 * b * a *
c * c * N * X / 15 - 2 * b * N * X / 5 - 2 * (N - 1) * X * X * N / 5

u13 = (a * b * b / 10 + b * b * c / 30 + a * c * b / 15 - b * c * c / 15 - 2 * a * c * c / 15)
v13 = (-a * b / 10 - b * c / 15 - b * b / 10 + 2 * c * c / 15 - a * b / 5)
k13 = N * X * b / 10 - b * b * a * c * N * X / 30 + b * a * c * c * N * X / 15 + b * N *
X / 5 + (N - 1) * X * X * N / 5

u14 = ((1 / (b / 2 + 5 * c / 6 + d / 3)) * (a * (N - 2) * X / 2 + a * b ^ 4 / 4 + b ^ 4 * c /
12 + a * c * b ^ 3 / 6 - a * b ^ 4 / 20 - b ^ 4 * c / 60 - a * c * b ^ 3 / 30 + b ^ 3 * c ^ 2 /
30 + 2 * a * b ^ 2 * c ^ 2 / 30 - (N - 1) * X * b / 2 + a * b ^ 2 * c ^ 2 / 30 + b ^ 2 * c ^
3 / 90 + a * c ^ 3 * b / 45 - b * c ^ 4 / 45 - 2 * a * c ^ 4 / 45 - b * d * c ^ 3 / 18 - a * c ^
3 * d / 9 - a * b ^ 2 * c * d / 15 - b ^ 2 * c ^ 2 * d / 45 _
- 2 * a * c ^ 2 * b * d / 45 + 2 * b * c ^ 3 * d / 45 + 4 * a * c ^ 3 * d / 45 + (N - 2) * X
* d / 6 + (N - 3) * X * (b / 6 + a / 3)))
v14 = ((1 / (b / 2 + 5 * c / 6 + d / 3)) * (-(N - 1) * X - a * b ^ 3 / 4 - c * b ^ 3 / 6 - b ^ 4
/ 4 + a * b ^ 3 / 20 + b ^ 3 * c / 30 + b ^ 4 / 20 - 2 * c ^ 2 * b ^ 2 / 30 + a * b ^ 3 / 10 -
a * b * c ^ 2 / 30 - b * c ^ 3 / 45 - c ^ 2 * b ^ 2 / 30 + 2 * c ^ 4 / 45 - a * b * c ^ 2 / 15 +
c ^ 3 * d / 9 + a * b * c * d / 15 + 2 * b * c ^ 2 * d / 45 + b ^ 2 * c * d / 15 - 4 * c ^ 3 *
d / 45 + 2 * a * b * c * d / 15 - (N - 3) * X / 3 - (N - 2) * X / 2))

k14 = (((1 / (b / 2 + 5 * c / 6 + d / 3)) * ((N * X * b ^ 3 / 4) - b ^ 4 * a * c * N * X / 12
- N * X * b ^ 3 / 20 + b ^ 4 * a * c * N * X / 60 - b ^ 3 * a * c ^ 2 * N * X / 30 - b ^ 3
* N * X / 10 - (N - 1) * X ^ 2 * b ^ 2 * N / 10 + N * X * b * c ^ 2 / 30 - b ^ 2 * a * c ^
3 * N * X / 90 + b * a * c ^ 4 * N * X / 45 + b * c ^ 2 * N * X / 15 + (N - 1) * X ^ 2 *
N * c ^ 2 / 15 + b * a * c ^ 3 * d * N * X / 18 - N * X * b * c * d / 15 + b ^ 2 * a * c ^
2 * N * X * d / 45 - 2 * b * a * c ^ 3 * N * X * d / 45 - 2 * b * c * d * N * X / 15 - 2 *
(N - 1) * X ^ 2 * N * c * d / 15 - (N - 2) * X ^ 2 * N * a * d / 6 - (N - 3) * X * b * a *
N * X / 6)))

u15 = (((-b / (2 * (b / 2 + 5 * c / 6 + d / 3))) * (a * (N - 2) * X / 2 + a * b ^ 4 / 4 + b ^ 4
* c / 12 + a * c * b ^ 3 / 6 - a * b ^ 4 / 20 - b ^ 4 * c / 60 - a * c * b ^ 3 / 30 + b ^ 3 * c
^ 2 / 30 + 2 * a * b ^ 2 * c ^ 2 / 30 - (N - 1) * X * b / 2 + a * b ^ 2 * c ^ 2 / 30 + b ^ 2 *
c ^ 3 / 90 + a * c ^ 3 * b / 45 - b * c ^ 4 / 45 - 2 * a * c ^ 4 / 45 - b * d * c ^ 3 / 18 - a *
c ^ 3 * d / 9 - a * b ^ 2 * c * d / 15 - b ^ 2 * c ^ 2 * d / 45 - 2 * a * c ^ 2 * b * d / 45 + 2
* b * c ^ 3 * d / 45 + 4 * a * c ^ 3 * d / 45 + (N - 2) * X * d / 6 + (N - 3) * X * (b / 6 +
a / 3)) + (a * b ^ 4 / 4 + b ^ 4 * c / 12 + a * c * b ^ 3 / 6 - a * b ^ 4 / 20 - b ^ 4 * c / 60 -
a * c * b ^ 3 / 30 + b ^ 3 * c ^ 2 / 30 + 2 * a * b ^ 2 * c ^ 2 / 30 - (N - 1) * X * b / 2)))

v15 = (((-b / (2 * (b / 2 + 5 * c / 6 + d / 3))) * (-(N - 1) * X - a * b ^ 3 / 4 - c * b ^ 3 / 6
- b ^ 4 / 4 + a * b ^ 3 / 20 + b ^ 3 * c / 30 + b ^ 4 / 20 - 2 * c ^ 2 * b ^ 2 / 30 + a * b ^ 3
/ 10 - a * b * c ^ 2 / 30 - b * c ^ 3 / 45 - c ^ 2 * b ^ 2 / 30 + 2 * c ^ 4 / 45 - a * b * c ^ 2
/ 15 + c ^ 3 * d / 9 + a * b * c * d / 15 + 2 * b * c ^ 2 * d / 45 + b ^ 2 * c * d / 15 - 4 *
c ^ 3 * d / 45 + 2 * a * b * c * d / 15 - (N - 3) * X / 3 - (N - 2) * X / 2)) + (-(N - 1) * X
- a * b ^ 3 / 4 - c * b ^ 3 / 6 - b ^ 4 / 4 + a * b ^ 3 / 20 + b ^ 3 * c / 30 + b ^ 4 / 20 - 2 *
c ^ 2 * b ^ 2 / 30 + a * b ^ 3 / 10))

k15 = (((-b / (2 * (b / 2 + 5 * c / 6 + d / 3))) * (N * X * b ^ 3 / 4 - b ^ 4 * a * c * N * X
/ 12 - N * X * b ^ 3 / 20 + b ^ 4 * a * c * N * X / 60 - b ^ 3 * a * c ^ 2 * N * X / 30 - b
^ 3 * N * X / 10 - (N - 1) * X ^ 2 * b ^ 2 * N / 10 + N * X * b * c ^ 2 / 30 - b ^ 2 * a *
c ^ 3 * N * X / 90 + b * a * c ^ 4 * N * X / 45 + b * c ^ 2 * N * X / 15 + (N - 1) * X ^
```

2 * N * c ^ 2 / 15 + b * a * c ^ 3 * d * N * X / 18 - N * X * b * c * d / 15 + b ^ 2 * a * c ^ 2 * N * X * d / 45 - 2 * b * a * c ^ 3 * N * X * d / 45 - 2 * b * c * d * N * X / 15 - 2 * (N - 1) * X ^ 2 * N * c * d / 15 - (N - 2) * X ^ 2 * N * a * d / 6 - (N - 3) * X * b * a * N * X / 6)) + (N * X * b ^ 3 / 4 - b ^ 4 * a * c * N * X / 12 - N * X * b ^ 3 / 20 + b ^ 4 * a * c * N * X / 60 - b ^ 3 * a * c ^ 2 * N * X / 30 - b ^ 3 * N * X / 10 - (N - 1) * X ^ 2 * b ^ 2 * N / 10))

u16 = (((-1 / (3 * (b / 2 + 5 * c / 6 + d / 3))) * (a * (N - 2) * X / 2 + a * b ^ 4 / 4 + b ^ 4 * c / 12 + a * c * b ^ 3 / 6 - a * b ^ 4 / 20 - b ^ 4 * c / 60 - a * c * b ^ 3 / 30 + b ^ 3 * c ^ 2 / 30 + 2 * a * b ^ 2 * c ^ 2 / 30 - (N - 1) * X * b / 2 + a * b ^ 2 * c ^ 2 / 30 + b ^ 2 * c ^ 3 / 90 + a * c ^ 3 * b / 45 - b * c ^ 4 / 45 - 2 * a * c ^ 4 / 45 - b * d * c ^ 3 / 18 - a * c ^ 3 * d / 9 - a * b ^ 2 * c * d / 15 - b ^ 2 * c ^ 2 * d / 45 - 2 * a * c ^ 2 * b * d / 45 + 2 * b * c ^ 3 * d / 45 + 4 * a * c ^ 3 * d / 45 + (N - 2) * X * d / 6 + (N - 3) * X * (b / 6 + a / 3)) + (1 / 3) * (a * b ^ 2 * c / 10 + b ^ 2 * c ^ 2 / 30 + a * c ^ 2 * b / 15 - b * c ^ 3 / 15 - 2 * a * c ^ 3 / 15)))

v16 = (((-1 / (3 * (b / 2 + 5 * c / 6 + d / 3))) * (-(N - 1) * X - a * b ^ 3 / 4 - c * b ^ 3 / 6 - b ^ 4 / 4 + a * b ^ 3 / 20 + b ^ 3 * c / 30 + b ^ 4 / 20 - 2 * c ^ 2 * b ^ 2 / 30 + a * b ^ 3 / 10 - a * b * c ^ 2 / 30 - b * c ^ 3 / 45 - c ^ 2 * b ^ 2 / 30 + 2 * c ^ 4 / 45 - a * b * c ^ 2 / 15 + c ^ 3 * d / 9 + a * b * c * d / 15 + 2 * b * c ^ 2 * d / 45 + b ^ 2 * c * d / 15 - 4 * c ^ 3 * d / 45 + 2 * a * b * c * d / 15 - (N - 3) * X / 3 - (N - 2) * X / 2)) + (1 / 3) * (-a * b * c / 10 - b * c ^ 2 / 15 - b ^ 2 * c / 10 + 2 * c ^ 3 / 15 - a * b * c / 5))

k16 = (((-1 / (3 * (b / 2 + 5 * c / 6 + d / 3))) * (N * X * b ^ 3 / 4 - b ^ 4 * a * c * N * X / 12 - N * X * b ^ 3 / 20 + b ^ 4 * a * c * N * X / 60 - b ^ 3 * a * c ^ 2 * N * X / 30 - b ^ 3 * N * X / 10 - (N - 1) * X ^ 2 * b ^ 2 * N / 10 + N * X * b * c ^ 2 / 30 - b ^ 2 * a * c ^ 3 * N * X / 90 + b * a * c ^ 4 * N * X / 45 + b * c ^ 2 * N * X / 15 + (N - 1) * X ^ 2 * N * c ^ 2 / 15 + b * a * c ^ 3 * d * N * X / 18 - N * X * b * c * d / 15 + b ^ 2 * a * c ^ 2 * N * X * d / 45 - 2 * b * a * c ^ 3 * N * X * d / 45 - 2 * b * c * d * N * X / 15 - 2 * (N - 1) * X ^ 2 * N * c * d / 15 - (N - 2) * X ^ 2 * N * a * d / 6 - (N - 3) * X * b * a * N * X / 6)) + (1 / 3) * (N * X * b * c / 10 - b ^ 2 * a * c ^ 2 * N * X / 30 + b * a * c ^ 3 * N * X / 15 + b * c * N * X / 5 + (N - 1) * X ^ 2 * N * c / 5))

u17 = (((-c / (3 * (b / 2 + 5 * c / 6 + d / 3))) * (a * (N - 2) * X / 2 + a * b ^ 4 / 4 + b ^ 4 * c / 12 + a * c * b ^ 3 / 6 - a * b ^ 4 / 20 - b ^ 4 * c / 60 - a * c * b ^ 3 / 30 + b ^ 3 * c ^ 2 / 30 + 2 * a * b ^ 2 * c ^ 2 / 30 - (N - 1) * X * b / 2 + a * b ^ 2 * c ^ 2 / 30 + b ^ 2 * c ^ 3 / 90 + a * c ^ 3 * b / 45 - b * c ^ 4 / 45 - 2 * a * c ^ 4 / 45 - b * d * c ^ 3 / 18 - a * c ^ 3 * d / 9 - a * b ^ 2 * c * d / 15 - b ^ 2 * c ^ 2 * d / 45 - 2 * a * c ^ 2 * b * d / 45 + 2 * b * c ^ 3 * d / 45 + 4 * a * c ^ 3 * d / 45 + (N - 2) * X * d / 6 + (N - 3) * X * (b / 6 + a / 3)) + (c / 3) * (a * b ^ 2 * c / 10 + b ^ 2 * c ^ 2 / 30 + a * c ^ 2 * b / 15 - b * c ^ 3 / 15 - 2 * a * c ^ 3 / 15)))

v17 = (((-c / (3 * (b / 2 + 5 * c / 6 + d / 3))) * (-(N - 1) * X - a * b ^ 3 / 4 - c * b ^ 3 / 6 - b ^ 4 / 4 + a * b ^ 3 / 20 + b ^ 3 * c / 30 + b ^ 4 / 20 - 2 * c ^ 2 * b ^ 2 / 30 + a * b ^ 3 / 10 - a * b * c ^ 2 / 30 - b * c ^ 3 / 45 - c ^ 2 * b ^ 2 / 30 + 2 * c ^ 4 / 45 - a * b * c ^ 2 / 15 + c ^ 3 * d / 9 + a * b * c * d / 15 + 2 * b * c ^ 2 * d / 45 + b ^ 2 * c * d / 15 - 4 * c ^ 3 * d / 45 + 2 * a * b * c * d / 15 - (N - 3) * X / 3 - (N - 2) * X / 2)) + (c / 3) * (-a * b * c / 10 - b * c ^ 2 / 15 - b ^ 2 * c / 10 + 2 * c ^ 3 / 15 - a * b * c / 5))

# APPENDIX (D)

## Table of Fleet Configurations For Case Study (1)

| Loader | Haulers | | | | | |
|---|---|---|---|---|---|---|
| 994 | 785B | 789B | Production Ton/H | Cost $/h | Duration H | Cost $/unit |
| 1 | 0 | 3 | 992.892 | 449 | 123 | 0.452 |
| 1 | 0 | 4 | 1167.5 | 537 | 105 | 0.459 |
| 1 | 0 | 5 | 1246.53 | 625 | 98 | 0.501 |
| 1 | 1 | 2 | 942.618 | 436 | 130 | 0.462 |
| 1 | 1 | 3 | 1122.87 | 524 | 109 | 0.466 |
| 1 | 1 | 4 | 1236.33 | 612 | 99 | 0.495 |
| 1 | 2 | 1 | 869.259 | 423 | 141 | 0.486 |
| 1 | 2 | 2 | 1105.31 | 511 | 111 | 0.462 |
| 1 | 2 | 3 | 1210.67 | 599 | 101 | 0.494 |
| 1 | 3 | 0 | 790.235 | 410 | 155 | 0.518 |
| 1 | 3 | 1 | 1028.71 | 498 | 119 | 0.484 |
| 1 | 3 | 2 | 1173.77 | 586 | 104 | 0.499 |
| 1 | 4 | 0 | 990.343 | 485 | 124 | 0.489 |
| 1 | 4 | 1 | 1168.29 | 573 | 105 | 0.49 |
| 1 | 5 | 0 | 1135.64 | 560 | 108 | 0.493 |
| 2 | 0 | 6 | 2120.89 | 898 | 58 | 0.423 |
| 2 | 0 | 7 | 2323.54 | 986 | 53 | 0.424 |
| 2 | 0 | 8 | 2451 | 1074 | 50 | 0.438 |
| 2 | 0 | 9 | 2514.73 | 1162 | 49 | 0.462 |
| 2 | 0 | 10 | 2538.95 | 1250 | 48 | 0.492 |
| 2 | 1 | 5 | 2073.91 | 885 | 59 | 0.426 |
| 2 | 1 | 6 | 2311.14 | 973 | 53 | 0.421 |
| 2 | 1 | 7 | 2477.39 | 1061 | 49 | 0.428 |
| 2 | 1 | 8 | 2421.59 | 1149 | 51 | 0.474 |
| 2 | 1 | 9 | 2454.31 | 1237 | 50 | 0.504 |
| 2 | 2 | 4 | 2010.83 | 872 | 61 | 0.433 |
| 2 | 2 | 5 | 2195.58 | 960 | 56 | 0.437 |
| 2 | 2 | 6 | 2369.68 | 1048 | 52 | 0.442 |
| 2 | 2 | 7 | 2475.8 | 1136 | 49 | 0.458 |
| 2 | 2 | 8 | 2532.57 | 1224 | 48 | 0.483 |
| 2 | 3 | 3 | 1934.62 | 859 | 63 | 0.444 |
| 2 | 3 | 4 | 2160.01 | 947 | 57 | 0.438 |
| 2 | 3 | 5 | 2369.43 | 1035 | 52 | 0.436 |
| 2 | 3 | 6 | 2509.33 | 1123 | 49 | 0.447 |
| 2 | 3 | 7 | 2442.12 | 1211 | 50 | 0.495 |
| 2 | 4 | 2 | 1846.85 | 846 | 66 | 0.458 |
| 2 | 4 | 3 | 2106.12 | 934 | 58 | 0.443 |
| 2 | 4 | 4 | 2348.62 | 1022 | 52 | 0.435 |

| 994 | 785B | 789B | Production Ton/H | Cost $/h | Duration H | Cost $/unit |
|---|---|---|---|---|---|---|
| 2 | 4 | 5 | 2404.77 | 1110 | 51 | 0.461 |
| 2 | 4 | 6 | 2497.09 | 1198 | 49 | 0.479 |
| 2 | 5 | 1 | 1750.24 | 833 | 70 | 0.475 |
| 2 | 5 | 2 | 2038.9 | 921 | 60 | 0.451 |
| 2 | 5 | 3 | 2310.55 | 1009 | 53 | 0.436 |
| 2 | 5 | 4 | 2413.71 | 1097 | 51 | 0.454 |
| 2 | 5 | 5 | 2535.64 | 1185 | 48 | 0.467 |
| 2 | 6 | 0 | 1670.96 | 820 | 73 | 0.49 |
| 2 | 6 | 1 | 1958.35 | 908 | 63 | 0.463 |
| 2 | 6 | 2 | 2188.94 | 996 | 56 | 0.455 |
| 2 | 6 | 3 | 2403.84 | 1084 | 51 | 0.45 |
| 2 | 6 | 4 | 2434.21 | 1172 | 50 | 0.481 |
| 2 | 7 | 0 | 1904.21 | 895 | 64 | 0.47 |
| 2 | 7 | 1 | 2187.41 | 983 | 56 | 0.449 |
| 2 | 7 | 2 | 2375.56 | 1071 | 52 | 0.45 |
| 2 | 7 | 3 | 2449.91 | 1159 | 50 | 0.473 |
| 2 | 8 | 0 | 2108.14 | 970 | 58 | 0.46 |
| 2 | 8 | 1 | 2331.99 | 1058 | 53 | 0.453 |
| 2 | 8 | 2 | 2448.21 | 1146 | 50 | 0.468 |
| 2 | 9 | 0 | 2273.83 | 1045 | 54 | 0.459 |
| 2 | 9 | 1 | 2430.61 | 1133 | 50 | 0.466 |
| 2 | 10 | 0 | 2397.47 | 1120 | 51 | 0.467 |
| 3 | 0 | 9 | 3807.52 | 1347 | 32 | 0.353 |
| 3 | 0 | 10 | 3808.79 | 1435 | 32 | 0.376 |
| 3 | 0 | 11 | 3810.06 | 1523 | 32 | 0.399 |
| 3 | 0 | 12 | 3808.79 | 1611 | 32 | 0.422 |
| 3 | 0 | 13 | 3808.79 | 1699 | 32 | 0.446 |
| 3 | 0 | 14 | 3808.79 | 1787 | 32 | 0.469 |
| 3 | 0 | 15 | 3808.79 | 1875 | 32 | 0.492 |
| 3 | 1 | 8 | 3803.17 | 1334 | 32 | 0.35 |
| 3 | 1 | 9 | 3805.88 | 1422 | 32 | 0.373 |
| 3 | 1 | 10 | 3805.84 | 1510 | 32 | 0.396 |
| 3 | 1 | 11 | 3806.51 | 1598 | 32 | 0.419 |
| 3 | 1 | 12 | 3808.17 | 1686 | 32 | 0.442 |
| 3 | 1 | 13 | 3807.33 | 1774 | 32 | 0.465 |
| 3 | 1 | 14 | 3808.18 | 1862 | 32 | 0.488 |
| 3 | 2 | 7 | 3799.68 | 1321 | 32 | 0.347 |
| 3 | 2 | 8 | 3802.06 | 1409 | 32 | 0.37 |
| 3 | 2 | 9 | 3803.66 | 1497 | 32 | 0.393 |
| 3 | 2 | 10 | 3803.48 | 1585 | 32 | 0.416 |
| 3 | 2 | 11 | 3802.56 | 1673 | 32 | 0.439 |
| 3 | 2 | 12 | 3804.24 | 1761 | 32 | 0.462 |
| 3 | 2 | 13 | 3803.88 | 1849 | 32 | 0.486 |

| 994 | 785B | 789B | Production Ton/H | Cost $/h | Duration H | Cost $/unit |
|---|---|---|---|---|---|---|
| 3 | 3 | 6 | 3794.37 | 1308 | 32 | 0.344 |
| 3 | 3 | 7 | 3798.96 | 1396 | 32 | 0.367 |
| 3 | 3 | 8 | 3800.1 | 1484 | 32 | 0.39 |
| 3 | 3 | 9 | 3799.23 | 1572 | 32 | 0.413 |
| 3 | 3 | 10 | 3800.6 | 1660 | 32 | 0.436 |
| 3 | 3 | 11 | 3802.94 | 1748 | 32 | 0.459 |
| 3 | 3 | 12 | 3803.32 | 1836 | 32 | 0.482 |
| 3 | 4 | 5 | 3788.36 | 1295 | 32 | 0.341 |
| 3 | 4 | 6 | 3795.5 | 1383 | 32 | 0.364 |
| 3 | 4 | 7 | 3797.07 | 1471 | 32 | 0.387 |
| 3 | 4 | 8 | 3798.17 | 1559 | 32 | 0.41 |
| 3 | 4 | 9 | 3797.94 | 1647 | 32 | 0.433 |
| 3 | 4 | 10 | 3800.57 | 1735 | 32 | 0.456 |
| 3 | 4 | 11 | 3802.35 | 1823 | 32 | 0.479 |
| 3 | 5 | 4 | 3782.35 | 1282 | 32 | 0.338 |
| 3 | 5 | 5 | 3789.32 | 1370 | 32 | 0.361 |
| 3 | 5 | 6 | 3793.59 | 1458 | 32 | 0.384 |
| 3 | 5 | 7 | 3794.68 | 1546 | 32 | 0.407 |
| 3 | 5 | 8 | 3796.54 | 1634 | 32 | 0.43 |
| 3 | 5 | 9 | 3795.53 | 1722 | 32 | 0.453 |
| 3 | 5 | 10 | 3799.44 | 1810 | 32 | 0.476 |
| 3 | 6 | 3 | 3775.38 | 1269 | 32 | 0.336 |
| 3 | 6 | 4 | 3786.23 | 1357 | 32 | 0.358 |
| 3 | 6 | 5 | 3788.68 | 1445 | 32 | 0.381 |
| 3 | 6 | 6 | 3791.85 | 1533 | 32 | 0.404 |
| 3 | 6 | 7 | 3793.46 | 1621 | 32 | 0.427 |
| 3 | 6 | 8 | 3793.58 | 1709 | 32 | 0.45 |
| 3 | 6 | 9 | 3796.77 | 1797 | 32 | 0.473 |
| 3 | 7 | 2 | 3765.35 | 1256 | 33 | 0.333 |
| 3 | 7 | 3 | 3781.23 | 1344 | 32 | 0.355 |
| 3 | 7 | 4 | 3786.04 | 1432 | 32 | 0.378 |
| 3 | 7 | 5 | 3787.4 | 1520 | 32 | 0.401 |
| 3 | 7 | 6 | 3789.54 | 1608 | 32 | 0.424 |
| 3 | 7 | 7 | 3791.85 | 1696 | 32 | 0.447 |
| 3 | 7 | 8 | 3792.71 | 1784 | 32 | 0.47 |
| 3 | 8 | 1 | 3752.71 | 1243 | 33 | 0.331 |
| 3 | 8 | 2 | 3773.69 | 1331 | 32 | 0.352 |
| 3 | 8 | 3 | 3782.33 | 1419 | 32 | 0.375 |
| 3 | 8 | 4 | 3784.22 | 1507 | 32 | 0.398 |
| 3 | 8 | 5 | 3786.18 | 1595 | 32 | 0.421 |
| 3 | 8 | 6 | 3789.64 | 1683 | 32 | 0.444 |
| 3 | 8 | 7 | 3790.7 | 1771 | 32 | 0.467 |
| 3 | 9 | 0 | 3740.35 | 1230 | 33 | 0.328 |

| 994 | 785B | 789B | Production Ton/H | Cost $/h | Duration H | Cost $/unit |
|---|---|---|---|---|---|---|
| 3 | 9 | 1 | 3768.32 | 1318 | 32 | 0.349 |
| 3 | 9 | 2 | 3776.77 | 1406 | 32 | 0.372 |
| 3 | 9 | 3 | 3781.38 | 1494 | 32 | 0.395 |
| 3 | 9 | 4 | 3783.8 | 1582 | 32 | 0.418 |
| 3 | 9 | 5 | 3784.22 | 1670 | 32 | 0.441 |
| 3 | 9 | 6 | 3787.49 | 1758 | 32 | 0.464 |
| 3 | 10 | 0 | 3755.41 | 1305 | 33 | 0.347 |
| 3 | 10 | 1 | 3769.74 | 1393 | 32 | 0.369 |
| 3 | 10 | 2 | 3775.46 | 1481 | 32 | 0.392 |
| 3 | 10 | 3 | 3779.53 | 1569 | 32 | 0.415 |
| 3 | 10 | 4 | 3783.14 | 1657 | 32 | 0.437 |
| 3 | 10 | 5 | 3784.22 | 1745 | 32 | 0.461 |
| 3 | 11 | 0 | 3765.45 | 1380 | 33 | 0.366 |
| 3 | 11 | 1 | 3769.35 | 1468 | 32 | 0.389 |
| 3 | 11 | 2 | 3774.69 | 1556 | 32 | 0.412 |
| 3 | 11 | 3 | 3778.56 | 1644 | 32 | 0.435 |
| 3 | 11 | 4 | 3779.24 | 1732 | 32 | 0.458 |
| 3 | 12 | 0 | 3764.19 | 1455 | 33 | 0.386 |
| 3 | 12 | 1 | 3770.35 | 1543 | 32 | 0.409 |
| 3 | 12 | 2 | 3773.69 | 1631 | 32 | 0.432 |
| 3 | 12 | 3 | 3776.21 | 1719 | 32 | 0.455 |
| 3 | 13 | 0 | 3765.45 | 1530 | 33 | 0.406 |
| 3 | 13 | 1 | 3770.44 | 1618 | 32 | 0.429 |
| 3 | 13 | 2 | 3773.7 | 1706 | 32 | 0.452 |
| 3 | 14 | 0 | 3764.19 | 1605 | 33 | 0.426 |
| 3 | 14 | 1 | 3769.29 | 1693 | 32 | 0.449 |
| 3 | 15 | 0 | 3765.45 | 1680 | 33 | 0.446 |

**Table 4.1**