PRODUCTIVITY IMPROVEMENT METHODS IN EARTHMOVING PROJECTS

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by

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ABSTRACT

Improving construction productivity is essential today due to stringent financial resources. Micro-computer based decision support systems and operational research models can be used as tools at different phases of construction projects to improve the productivity and to minimize the cost.

Among the wide variety of operations on many construction projects, the earthmoving operation plays an important role. Selection of the most appropriate type, size, and number of machines, and the optimal distribution of the cut and the fill quantities of soil are therefore significant in reducing the overall cost of a construction project.

In this thesis, a micro-computer based decision support system is developed for selecting the most economical group of machines for an earthmoving project. An operational research model based on the transportation algorithm is also introduced to find the optimal cut and fill distribution of an earthmoving operation.

The developed micro-computer based decision support system consists of a computer program, which simulates a consultation between an expert in equipment selection and a user. It presents a series of questions and a series of answers for which the user has to respond according to the requirements and the conditions of the earthmoving operation. For convenience, the system is developed in three phases.

In the first phase of the system, the selection of the suitable types of equipment for the earthmoving operation is made from eleven different types of earthmoving machines. In the second phase of the system, after checking the height and weight constraints that may be applicable to the site and to the haul roads, the production rates of all the models and sizes of the usable machines are determined. By comparing the cost per unit volume of material handled by each group of machines, the most economical group is determined in the final phase, to suit the scheduled duration and the total quantity of material to be handled of the earthworks project. Also, the cost per unit volume of material to be handled, the expected production rates, and the durations of the employable groups of machines are presented to the user.

Once the most economical group of machines is decided, using the introduced operational research model, the optimal distribution of cut and fill quantities of an earthworks operation can be deduced.

The application of the proposed micro-computer based decision support system and the operational research model are simple and can be used as effective tools in improving the earthmoving productivity of construction projects.

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CHAPTER 1

INTRODUCTION

1.1 Productivity of earthmoving in construction

Construction is an extremely important industry for a country from an economic point of view. The annual money value involved in construction work represents a substantial portion of a nation's gross national product. Moreover, the construction industry utilizes up to about 10% of a nations labour force, and significantly influences the commitments of national resources [6,12,20].

The rapid pace of changing technology in recent years has made construction projects large and complex. The size and the complexity of construction projects along with the problems of inflation, energy conservation, safety and environmental requirements, and stringent financial resources, have contributed to make construction project management challenging. Nevertheless, construction productivity has been on the decline in the past decade [1]. This has made productivity one of the most overriding concerns in construction organizations.

Accordingly, one of the critical management tasks faced by construction managers today, is to improve construction productivity and thereby reduce the construction costs without sacrificing the quality, the aesthetics or the maintainability. In recent years, the methods and techniques to improve construction productivity have been the subject of extensive research. However, due to the highly competitive nature of this industry, the results of some of the research and development activities are kept proprietary. Consequently, the amount of current research data available in construction is very small compared with other industries [34]. Most of this research and development, however, is in response to solving immediate and pressing problems in the industry. Long-term programmatic research generally plays a minor role, yet could be vital in improving and sustaining the growth in productivity.

In developing and implementing any form of productivity improving tools and procedures for a construction project, it is first necessary to identify the functions having the greatest potential for construction productivity improvement. Choromokos and McKee conducted a survey of the top four hundred Engineering-News-Record contractors in 1979 to identify these functions perceived by construction executives of the respective organizations [5]. The same survey was duplicated in 1983 to identify the new trends. In these two surveys, it was recommended that effort should primarily be concentrated in the functions of planning and scheduling, site supervision, and engineering design, besides the marketing practices of a construction organization [1,5].

This reveals that the degree to which a constructor predicts and foresees the planning demands of a project, schedules the limited and critical resources to fit those demands, and implements that schedule by effectively directing and supervising the labour, promotes construction productivity [18,27]. It has also been increasingly recognized that the level of influence over the construction costs is great during the design phase of a project [37].

The next necessary aspect of construction productivity improvement is the understanding of the resources or the areas which contribute to construction productivity, such as labour, equipment, material, management, and engineering [5]. This understanding is important, as construction productivity is increased or enhanced when these items are combined synergistically in such a way as to multiply their effects greater than each would do independently.

However, the overall productivity of a construction project is influenced directly or indirectly by a host of factors. The degree of influence of each of these factors on each function, resource, or area is different for each type of operation of construction. Some of the dominant influencing factors are area layout, economy, management and engineering expertise, leadership, experience, skill, motivation, weather, working conditions, crew absenteeism, overtime, organizational structure, regulations, and resource utilization related to the project [2,3,16,18,21,24,40].

Considering these factors, various methods and techniques have been introduced in the literature to improve construction productivity at different phases of a construction project [28]. Among them, the use of micro-computer based decision support systems, knowledge based expert systems, and operational research models are well known methods to improve productivity, and to minimize the cost of construction [11,42,43].

The decrease in cost, and the increase in capability of computer systems have made computer based techniques accessible to the construction industry [22,35]. Therefore, computer based techniques are largely used in various areas and functions in the construction industry. Micro-computer based spread sheets, data bases, critical path scheduling programs, modeling/simulation/optimization programs, office information and reporting systems, and expert systems are enabling engineers to greatly enhance the construction productivity nowadays [19]. It is also interesting to note that some of the recently developed computer based simulators can be integrated with video methods of data acquisition such as time lapse photography, and linked with computers for data extraction and statistical analysis [29].

The use of graphical and analytical operational research models to improve productivity, has also been a common practice in the construction industry. One early gain of the use of operational research models is that the planner is forced to think through the problem before the operation is executed. Too often, a construction operation is thoroughly analyzed and thought out only after its execution is imminent or even already begun [34]. Therefore, the use of operational research models may assist to prevent cost overruns and productivity problems which typically appear to the management's attention only when the project is in its advanced stages, leaving little time for preventive or corrective measures. Linear programming, network analysis, queuing theory, probability concepts, statistical analysis techniques, and learning curve models are extensively utilized in developing operational research models to improve construction productivity [10,13,14,23,25,38,39].

Though various methods and techniques introduced in the past have been used in various functions of improving construction productivity, those methods and techniques have their own limitations in different situations due to the custom-oriented nature of the industry. Yet, the recognition of the need for construction productivity improvement is vital, owing to the size of its share of the gross national product of a country.

Among the wide variety of operations on many construction projects, the earthmoving operation is very significant in terms of cost and productivity. Therefore, the productivity improvements in earthmoving operations can make substantial cost reductions in many construction projects. To improve the productivity of an earthmoving operation, various methods and techniques can be incorporated at different phases of a construction project.

The development of feasible methods and the selection of appropriate equipment to accomplish various activities at the planning and scheduling stage of an earthmoving project therefore, could be among the most important ingredients for successful competitiveness and profitability in a construction project.

The selection of the most appropriate type, size, and number of machines for a particular earthmoving activity is therefore very significant in reducing the overall cost of a project. The development of a micro-computer based decision support system would enable the selection of the most appropriate and economical type of equipment to be made, on the basis of suitability and availability for an earthworks operation. Thus, a micro-computer based decision support system to select the proper type, size, and the number of machines for a particular earthmoving operation is introduced in this research. The system is developed for an IBM (or compatible) personal computer with 256 kilo-bytes of RAM.

When there are several excavation and fill areas present in the earthmoving operation, the overall cost can also be minimized by optimizing the distribution of the cut and fill quantities along the various haul routes. Often, the allocation of earthworks volumes between cut and fill areas are carried out on an 'ad hoc' basis. If this allocation and the cost factors involved in such operations are scrutinized, it will often be found that the optimal solution has not been obtained. However, an operational research model can be easily used as a tool to determine the optimal solution. Therefore, an operational research model which optimizes the earthmoving cost is also introduced in this thesis.

1.2 Organization of the thesis

This thesis is primarily concerned with the development of a micro-computer based decision support system which enables the selection of the most economical group of equipment to be made on the basis of suitability and availability for a particular earthmoving operation. An operational research model is also developed to minimize the total earthmoving cost by optimizing the distribution of the cut and fill quantities along the various haul routes.

In Chapter 2, the general description, and the structure of the developed micro-computer based decision support system (EQUIPSELECT) to select earthmoving equipment are outlined.

The types of equipment used in the system and their possible applications are first discussed in Chapter 3. The selection process to find the suitable equipment for a particular earthworks operation is then explained.

Once the suitable types of equipment for a particular earthworks operation are selected, the next step in the developed system is to obtain the production rates of all the models and sizes of the selected types of machines. The methods used in the system to obtain these production rates are discussed in Chapter 4.

Chapter 5 focuses on the selection of the most economical group of machines, which has the minimum cost per unit volume of material handled, from the available fleet of machines to suit the required schedule and the quantity of the earthworks operation.

If the user is unaware of the hourly costs involved in any of the machines, the method of determining the probable costs of those machines is presented in Chapter 6.

Development of the operational research model which minimizes the earthmoving cost of an earthworks operation having several cut and fill areas, is introduced in Chapter 7.

Finally, in Chapter 8, the applications and qualities of the developed microcomputer based decision support system and the operational research model are discussed. The thesis is concluded after a brief discussion of possible further improvements pertaining to this research.

A descriptive instruction sheet on 'How to to use EQUIPSELECT', an example problem on a fictitious earthmoving operation using EQUIPSELECT, the information stored in the data base, and the derivation of some of the equations used in finding the cost factors are given in the Appendices.

CHAPTER 2

MICRO-COMPUTER BASED DECISION SUPPORT SYSTEM TO SELECT EARTHMOVING EQUIPMENT

2.1 Introduction

The selection of appropriate machines, and the estimation of cost per unit volume of material handled, are common tasks encountered in the planning stage of any earthmoving project. However, the time available for finding the solutions to such problems is often very short. Furthermore, errors and miscalculations in the selection and estimation process, in the earthworks operations, can have costly effects. The use of micro-computer based decision support systems not only reduces the time involved in such processes, but also improves the accuracy considerably. Also, one of the many advantages of using a micro-computer based decision support system is, its ability to perform sensitivity analyses which create a simple diagnostic capability. The development of a micro-computer based decision support system can therefore greatly facilitate the selection of the most economical group of earthmoving machines from the available fleet of equipment for an earthworks operation.

2.2 General description of the system

The micro-computer based system described in this thesis (EQUIPSELECT) consists of a computer program, which simulates a consultation between an expert in equipment selection and a user. This system has a logically structured knowledge base and a data base. The knowledge base consists of self-contained segments of knowledge in the form of 'if...and...then...else' rules and algorithmic or closed-form solutions. The data base constitutes of information about the equipment being considered and the properties of different types of materials.

The operation of the decision support system is similar to the operation of many computer programs. The system presents a series of questions, and for some questions a series of answers, for which the user has to respond according to the requirements and the conditions of the earthworks operation under consideration. In the process of asking the questions, the system gives the user a brief idea about the current analysis and the relevance of the questions to the hypothesis pursued. The types of answers expected from the user are also indicated in the text of the questions to facilitate the answering process. Should extra information be necessary, the system then presents further questions.

A descriptive information sheet on 'How to use EQUIPSELECT', as shown in Appendix A, is also provided to the user. This sheet may be used as a guideline in preparing the user for prompt answering of the questions in the system. The system provides the facility to incorporate changes according to the user's responses to some of the questions in the program, by going back to the previous questions. The user can also observe the intermediate outputs within the system at different stages of the program as it proceeds.

A brief description of the developed system is discussed in the following section.

2.3 Structure of the system

The micro-computer based decision support system for the selection of earthmoving equipment is developed using three main phases, as illustrated in Figure 2.1. Eleven different types of earthmoving equipment are considered in the main menu. Selection of the suitable types of equipment for the earthworks operation under consideration is made from the main menu in the first phase of the system. In deciding the types of equipment suitable for an earthworks operation the following factors are considered :

(a) average intended haul distance,

(b) requirement of transporting material on or across a highway,

(c) type of the operation,

(d) power potential limitations of machines due to traction ability, and gradability at the altitude of the working area,

and (e) constraints and options applicable to the working area.

In the second phase of the system, the production rates of all the models and sizes of the selected types of machines are obtained. The menu of the second phase contains information on the models and sizes of eighty items of equipment from five different manufacturers. These models are given in Table A.1 of Appendix A. However, the program contains a provision to include more types and models within reason, depending on the memory capacity of the micro-computer. Should this be required, relevant technical information would then have to be inserted.

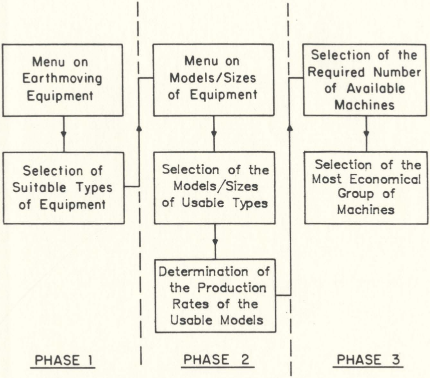

Fig. 2.1 Block diagram of the system

The usable models of machines are ascertained by comparing the height and weight constraints that may be applicable to the site and to the haul road. The production rates of the usable machines are then deduced. In this process, the system takes into account the following factors which influence the production rate of a machine :

(a) properties of the material to be handled,

(b) haul and return route distances, grades, and soil types,

(c) overall job efficiency,

and (d) type and capacity of the loading machines.

Using the production rates obtained in the second phase of the system, the optimum combination of machines to suit the total quantity of material to be handled, and the time allotted for the earthworks activity are then determined in the final phase of the system. In deciding the most economical group of machines, first, the availability of machines, and the physical feasibility to operate the number of each model of machine within the working area, are considered. The concept of effective equipment matching is also considered for machines which require a separate loading machine. The system next decides the number of machines that should contain in a group, to achieve the required rate of production. The expected production rate and the expected duration to complete the earthworks activity by each group of machines are then determined.

To find the total cost of the operation, the owning and operating cost or the total rental cost of each machine, and the construction and maintenance cost of the haul and return routes or the access roads are then considered in the system.

Knowing the total quantity of material to be handled and the total cost outlaid by each group of machines, the system then finds the cost per unit volume of material of all the selected groups of machines.

The system presents the cost per unit volume of material handled, the expected production rate, and the expected duration to complete the earthworks operation, of each employable group of machines as an intermediate output. By comparing the unit cost figures, the system then selects and presents the most economical group of machines disregarding the scheduled duration of the operation. Finally, the most economical group of machines that could complete the operation within the scheduled duration is chosen and presented to the user.

A detailed explanation of the three phases of the system is given in Chapters 3, 4, and 5.

CHAPTER 3

SELECTION OF SUITABLE TYPES OF EQUIPMENT

3.1 Introduction

The types of equipment used in an earthworks project can differ enormously depending on a number of basic engineering fundamentals, such as job and material characteristics. If the work requirements of an earthworks operation are analyzed, it can often be found that, each job, to greater or lesser degree, is associated with a unique set of job and material characteristics. Also, in general, the types of equipment that have been designed for each category of earthmoving job, and their operating costs considerably vary under different operating conditions. Selection of the proper type of equipment for a particular job is therefore, difficult and vital in reducing the overall cost of a project.

The types of equipment used in the decision support system and their possible applications are first discussed in this chapter. The selection process to find the suitable types of equipment for a particular earthworks operation, is then explained.

3.2 Types of equipment considered in the system

There are various types of equipment used in earthmoving operations. However, in choosing the types of equipment for the developed system, the number of types of machines was limited to eleven, considering the memory capacities of commonly available micro-computers. Also, in selecting these eleven types, more priority was given to versatile machines, than to highly specialized ones.

The eleven types of machines considered in the system are :

(a) Track type tractors (TTT), (b) Wheel type tractors (WTT),

(c) Track type loaders (TTL), (d) Wheel type loaders (WTL),

(e) Standard scrapers (SS), (f) Tandem powered scrapers (TPS),

(g) Elevating scrapers (ES), (h) Push-pull scrapers (PPS),

(i) Standard trucks (ST), (j) Four-wheel-drive trucks (4WDT),

and (k) Belt conveyers (BC).

Eventhough motor graders are widely used in earthmoving operations, they are not considered in the system due to the fact that these machines are categorized as utility machines. Therefore, the production figures are not available by the manufacturers. The important features, which are taken into account in choosing the above types of machines for the system, are briefly discussed in the following sections.

Track type tractors and wheel type tractors are the first two types of equipment considered in the system. They are widely used in earthmoving operations and probably the most versatile of any of the earthmoving machines. By fixing different types of blades and attachments, these machines can be used to perform difficult jobs, such as ripping of solid or highly consolidated material, or clearing of land of timber and stumps, to fairly easy jobs like spreading of earthfill and so forth [6]. However, track type tractors and wheel type tractors are considerably productive only when the average haul length is 100 meters or less. Also, due to the nature of these machines, tractors are unable to operate on highways.

The next two types of machines used in the system are track type loaders and wheel type loaders. A track type loader or a wheel type loader can be satisfactorily and economically used as an excavating machine, a loading machine, or a transporting machine, up to an average haul distance of 200 meters. Because of their mobility, maneuverability, and versatility, these two machines are ideal for any earthmoving operation that involves picking up material, hauling, and dumping. However, loaders are not usually allowed to transport material on highways.

Standard scrapers, tandem powered scrapers, elevating scrapers, and push-pull scrapers, which are the most commonly used four types of scrapers, are then considered in developing the decision support system. Some of the advantages of scrapers over the other types of earthmoving machines are the ability of self-loading and the ability of handling large quantities of material per cycle. When working with materials which are difficult to load or when poor traction conditions exist at the cuts, the use of tandem powered scrapers or push-pull scrapers is warranted [15]. Scrapers are the most economical excavating and hauling equipment for large earthmoving operations, except where the route is sited on or across a public highway, or when the nature of the job prevents their use. However, scrapers are generally employed on earthmoving operations for medium haul distances of up to about 2 kilo-meters [6].

When large amounts of material are to be hauled over public roads to long distances, trucks are generally suitable for most kinds of materials [30]. Since there has to be a separate loading machine to load a truck, the hourly production of a truck partly depends on the hourly production of the loading unit. In developing the system, standard trucks and four-wheel-drive trucks, which are the most commonly used types of trucks, are considered.

Finally, belt conveyers, which are sometimes used in the field of construction, are considered in the menu on types of equipment of the system. The significant advantages of belt conveyers over other means of haulage are their ability to cross adverse terrains, ability to deliver material continuously, and low maintenance and labour requirements. Environmental advantages and safe working conditions of belt conveyers are also particularly attractive compared to the other types of machines. Though the initial cost of a belt conveyer is higher, if large quantities of material are to be transported, the belt conveyer becomes a feasible choice [6,15,30].

The factors to be considered in selecting the suitable types of equipment from the above eleven types of equipment for a particular earthworks operation are discussed in the following sections.

3.3 Factors considered in selecting the suitable types of equipment

The concept of the selection of the most appropriate types of equipment for a particular type of earthmoving operation under consideration is diagrammatically shown in Figure 3.1. As stated earlier in this chapter, there are eleven types of equipment listed in the menu on types of earthmoving equipment. The relevant technical information of each type of machine required in the knowledge base of the first phase of the system is stored in the data base. The corresponding

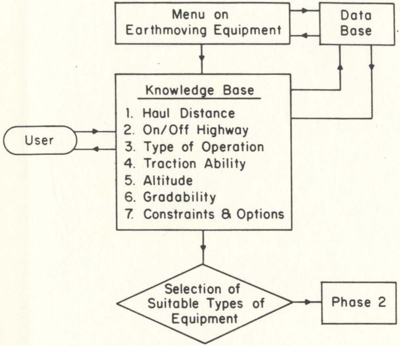

Fig. 3.1 Phase 1 of the system

properties of various types of soils required in phase 1, are also stored in the data base. The system can retrieve these information from the data base as and when required.

The choice of types of equipment for an earthworks operation depends on many parameters. Among those parameters, only the following important ones are considered in the system in selecting the suitable types of equipment :

(a) haul distance,

(b) on-off highway requirement,

(c) type of operation,

(d) power potential limiting factors,

and (e) constraints and options that may be applicable to the working conditions.

These influencing factors which are logically structured in the knowledge base are discussed below.

The production rate of an earthmoving machine considerably varies with the average haul distance. This variation is graphically represented in Figure 3.2. As shown in Figure 3.2, some types of equipment cannot be economically used to haul material outside a certain range. Since this is an inherent feature of the type of machine, it is required to consider the average intended haul distance of the operation in selecting the appropriate types of equipment for an earthworks operation.

Most of the equipment considered in the menu on types of equipment of the

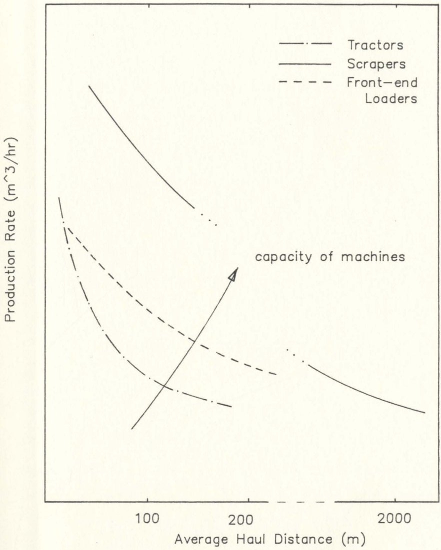

Fig. 3.2 The variation of production rate with haul distance of earthmoving machines

system are not allowed to travel on public highways. Therefore, the requirement of transporting material on or across a highway is also important when selecting the appropriate types of equipment. The choice of earthmoving equipment depends upon the type of operation as well. Hence, it is necessary to take the type of operation such as, clearing land of timber, or spreading of earthfill, also into account when selecting the types of equipment for a particular earthworks operation.

The other factor which influences the selection of types of equipment for an earthworks operation is the power potential of the machine. It is required to assess the power potential of the machine in working against all the resistance forces to maintain its movement through-out the haul and return routes. The power potential of a machine is limited either by the maximum power output delivered by the power unit to the driving wheels, or by the maximum force which could be exerted without slipping the tires or tracks of the equipment on the supporting surface. As such, in assessing the power potential of a machine the two limiting factors, the gradability and the traction ability, are needed to be considered. Furthermore, when a machine is operated in high altitudes, the power output decreases as a result of the decreased density of air. This decrease in the power output is reflected in the machines gradability. However, this power loss is apparent only in naturally aspirated machines, and it is negligible for turbo-charged machines. Therefore, the power loss due to altitude, or the altitude dera-tion is also needed to be incorporated in the gradability calculation, if a naturally aspirated machine is to operate in high altitudes.

Finally, if there are any constraints applicable to operate any type of machine within the construction area, those constraints have to be taken into account in the selection process. Similarly, if there are any options or any special preferences to use a particular type of machine, those options should also be considered in selecting the appropriate types of machines.

By considering all the above factors, it is possible to select the suitable types of equipment for an earthmoving operation. The development of phase 1 of the system, which considers all the above influencing factors on the selection of the appropriate types of machines, is described in the next section. However, for the sake of clarity in understanding and being able to apply the various factors in a selection, these factors are considered one at a time in the system. That is, while considering one influencing factor, it is assumed that the other factors remain subordinate in their effect.

3.4 Development of Phase 1

In the developed system, the selection of the appropriate earthmoving equipment begins by requesting an answer to a question (Question 1 of Appendix B) on the haul distance requirement. The following ranges of average haul distances in meters are presented to the user as an aid, so that the anticipated average haul distance of the earthworks operation can be selected :

(a) average haul distance $\leq$ 100,

(b) 100 $<$ average haul distance $\leq$ 200,

(c) 200 $<$ average haul distance $\leq$ 2000,

and (d) average haul distance $>$ 2000.

As shown in Figure 3.2, some types of equipment cannot be economically used to haul material outside a certain range. Therefore, from the economical haul distance ranges given in Figure 3.2, the following logic as depicted in Table 3.1 is developed.

Table 3.1 Types of equipment unsuitable for different ranges of haul distance. (The symbols represent the machines given in page 15)

Average intended haul distance (m)	Unsuitable types of equipment
haul disance $\leq$ 100	none
100<haul distance $\leq$ 200	TTT, WTT
200<haul distance $\leq$2000	TTT, WTT, TTL, WTL
2000 < haul distance	TTT, WTT, TTL, WTL
	SS, TPS, ES, PPS

Table 3.1 is used in the system, in selecting the types of machines to suit the average intended haul distance. After deciding the types of equipment which can be economically employed to suit the average haul distance of the earthworks operation under consideration, the system proceeds by asking a question regarding the on-off highway need (Question 2 of Appendix B).

Since, most of the types of machines considered in the system are not allowed to operate on highways, the system eliminates certain types of equipment to suit the user's requirement to transport material on or across a public highway. Eventhough, trucks are usually allowed to operate on highways, there may be certain limitations on weight and height. Since these limitations are separately considered at the beginning of phase 2 of the system, all the trucks are considered as operable on highways at this stage. Therefore, in the logic relevant to on-off highway requirement, if the user needs to transport material on or across a highway, only the standard trucks, the four-wheel-drive trucks and the belt conveyers are taken as suitable. Otherwise, all the types of machines are taken as suitable for the earthworks operation. Once the types of equipment suitable for the earthworks operation are selected considering the haul distance and the on-off highway requirement, the selected types of machines are then considered for further requirements.

For the purpose of considering the type of operation intended to perform, the following most common types of earthmoving operations are presented to the user :

(a) clearing land of timber and/or stumps,

(b) clearing construction sites and debris, or clearing the floors of borrow or quarry pits,

(c) excavating from slope or excavating from wide cutting, and hauling,

(d) clearing stock pile or handling of bulk material,

(e) clearing snow,

(f) opening up pilot roads through mountains and rocky terrains,

(g) maintaining haul roads,

(h) back filling of trenches,

(i) spreading of earth fill,

(j) final spreading,

(k) excavating from vertical face or cutting with wide slopes (Vee shaped ditches), and hauling,

(l) scraping and spreading or dumping,

and (m) shallow cutting or cutting trenches, and hauling.

The user is asked to choose the most apposite operation or operations (Question 3 of Appendix B) related to the job under consideration from the above set. Considering the capabilities of each type of machine used in the system, the suitable types of equipment to perform the above types of operations can be summerized as given in Table 3.2. According to the user's choice, the suitable types of equipment are assigned for possible utilization using Table 3.2.

In addition to the above factors, the power potential of a machine, limited either by the traction ability or by the gradability, is then considered in selecting the types of suitable earthmoving machines. The maximum gradient that a belt conveyer can operate is limited by a number of factors such as the type of material handled and the construction of the belt. Due to the complexity of incorporating these factors in developing the system, the belt conveyers are exempted from the traction ability and the gradability checks.

Table 3.2 Types of equipment unsuitable for different earthmoving operations.

(The symbols represent the machines given in page 15)

Type of operation	Unsuitable types of equipment
(a) clearing land of timber and/or stumps	TTL, WTL, SS, TPS, ES, PPS, ST, 4WDT, BC
(b) clearing construction sites and debris, or clearing the floors of borrow or quarry pits	BC
(c) excavating from slope or excavating from wide cutting, and hauling	none
(d) clearing stock pile or handling of bulk material	none
(e) clearing snow	BC
(f) opening up pilot roads through mountains and rocky terrains	WTT, TTL, WTL, SS, TPS, ES, PPS, ST, 4WDT, BC
(g) maintaining haul roads	ST, 4WDT, BC
(h) back filling of trenches	BC
(i) spreading earthfill	TTL, WTL, BC
(j) final spreading	TTT, WTT, TTL, WTL, ST, 4WDT, BC
(k) excavating from vertical face or cutting with wide slopes (Vee shaped ditches), and hauling	SS, TPS, ES, PPS
(l) scraping, and spreading or dumping	TTL, WTL, ST, 4WDT, BC
(m) shallow cutting or cutting trenches, and hauling	TTT, WTT, TTL, WTL, SS, TPS, ES, PPS

In the questions related to the traction ability and the gradability considerations (Questions 4a, 4b, 5a, and 5b of Appendix B), the user is requested to choose the appropriate soil types of the haul and return routes from a set of seven soil types. The types of soils considered in the system are very hard or concrete, hard or well compacted gravel, dry clay or gravel, wet clay or loose earth, dry sand, wet sand or loose gravel, and snow. These seven kinds of soils are chosen as they represent most of the commonly available haul surfaces. However, the traction ability and gradability checks are performed only on those sectors of the haul and return routes, which the user suspects as slippery or difficult to climb. To perform these checks, the grade resistance factors (GRF) of the specified sections are required and this information is requested from the user.

In the gradability check, the user has the option to consider the altitude derating as well, if he intends to perform the earthworks operation at a high altitude (Questions 4a and 4b of Appendix B). The derating factors of different types of machines with altitudes were collected from the relevant manufacturers handbooks [4,9,17,36,41], and stored in the data base of the system (Table C.1 of Appendix C). In developing mathematical models for the above two checks, the traction ability and the gradability are separately considered.

3.4.1 Traction ability check

Although both the traction ability and the gradability influence the power potential of machines, in developing the theory for the traction ability check, it is considered as if traction ability governs the selection.

The maximum power of an engine of a machine which is designed to travel on a road, can be utilized only if sufficient traction exists between the driving wheels or the tracks, and the travel surface. If the traction between the wheels or the tracks, and the surface is not sufficient, the wheels or the tracks will slip on the haul surface limiting the power transmission. In the event of limiting the power transmission due to traction, the usable pull for a given machine can be given as [6] :

Usable pull = (coefficient of traction) . (weight on the driving wheels) . (3.1)

Clearly, the usable pull increases when the weight on the driving wheels increases. Therefore, the worst situation which occurs when the machine is in the unloaded condition, is considered in checking the traction ability. The weight on driving wheels can be represented as a percentage of the tare weight of the given machine. Therefore, (3.1) can be re-arranged as

Usable pull = (coefficient of traction) . (α) . (tare weight of machine) (3.2)

where α is the percentage weight on the driving wheels of the tare weight of the machine.

It may be assumed that for a given type of machine used in the system, the value of α of all the models and sizes of different manufacturers, remains reasonably unchanged. Hence the average value of α for all the models of the given type of machine is taken for the traction ability check. Also, for both track type machines and for all-wheel-drive machines, the value of α is 100%. The α values of different types of machines used in the system [4,9,17,36,41] are shown in

Table C.2 of Appendix C. These α values are stored in the data base in order to be retrieved when required.

In general, to move a machine on a haul surface, the usable pull has to be greater than the total resistance forces acting on the machine. This can be expressed as :

$$\text{usable pull} > \text{total resistance} . \tag{3.3}$$

Neglecting all the internal resistance forces such as the wheel bearing friction force, and the drag force due to wind, the total resistance can be taken as the sum of the rolling resistance and the grade resistance. The rolling resistance is the resistance to the movement of a machine over level ground. This may be expressed as a percentage of the total weight of the machine and load [6]. This percentage is called the rolling resistance factor (RRF). The grade resistance is the resistance due to the gravity effect of the weight of the machine acting against the movement of the machine. The grade resistance can also be expressed as a percentage of the total weight of the machine and load. This percentage is called the grade resistance factor (GRF). Therefore, the total resistance to the movement of the machine can be expressed as

$$\text{total resistance} = \Big[(\text{GRF}) + (\text{RRF})\Big] . (\text{ tare weight of machine }) , \tag{3.4}$$

where GRF = grade resistance factor,

and RRF = rolling resistance factor.

Substituting (3.2) and (3.4) in (3.3)

$$\text{(coefficient of traction)}.(\alpha).\text{(tare weight of machine)} > \Big[\text{(GRF)} + \text{(RRF)}\Big].\text{(tare weight of machine)},$$

$$\text{(coefficient of traction)}.(\alpha) > \Big[\text{(GRF)} + \text{(RRF)}\Big]. \quad (3.5)$$

Hence the power limitation due to traction in a machine can be checked using (3.5). The variables in (3.5) can be found as explained in the following subsections.

3.4.1.1 Coefficient of traction

The coefficient of traction is a function of the surface in contact. The coefficient of traction between rubber wheel tires and road surfaces varies with the type of road, the tread on the tires, and with the nature of the road surface. For crawler tracks, it varies with the design of the grouser and the road surface. For both the rubber wheel and the crawler type tracks, it is difficult to find the exact coefficient of traction. However, for estimating purposes like equipment selection the values [4,6,30,33] given in Table C.3 of Appendix C are accurate enough.

The coefficients of traction for different ground surfaces are stored in the data base. According to the user's choice on the type of soil, the corresponding coefficient of traction values are retrieved from the data base.

3.4.1.2 Rolling resistance factor

The rolling resistance factor depends upon a number of factors such as ground condition and soil type, tire pattern, tire pressure, speed of the machine, and wheel bearing friction. For track type equipment, the rolling resistance is essentially a constant value independent of ground conditions, because the machine lays its own traveling surface as it advances. Generally, the values of drawbar pull which are supplied by the manufacturers, have already accounted for the rolling resistance for track type machines. Therefore, for simplicity of calculating the total resistance, the RRF of all track type machines are assumed as negligible.

Neglecting the effects of tire pattern, tire pressure, air friction, and wheel bearing friction, the RRF of wheel type machines for different ground surfaces are approximated as given in Table C.3 of Appendix C [4,6,30,33]. These RRF values are stored in the data base along with the coefficients of traction. Depending on the user's choice to the type of soil in the question related to the traction ability, the relevant RRF is retrieved from the data base.

3.4.1.3 Grade resistance factor

In the questions pertaining to the traction ability and gradability checks, the user is supposed to give the GRF values of the required sectors of the haul and return routes which are slippery or difficult to climb.

Once all the factors in (3.5) are obtained as explained in the above sections, it is possible to check the traction ability of all the types of machines for these critical sectors of the haul and return routes.

3.4.2 Gradability check

The power required to move and to work earthmoving equipment is provided by an engine or by a prime mover. When a machine is loaded, the available power at the wheels or at the tracks should be sufficient to move the machine against all the resistive forces. As far as the economy of an earthmoving operation is concerned, all the machines used should be powerful enough to haul a sufficient amount of material along the worst and the difficult portions of the haul road. If the power available is not sufficient to carry its rated load, the load can be reduced or a machine with more power can be used. Therefore, in the gradability calculations of the system, for a given machine to provide a reasonable load per cycle the minimum economical pay load is assumed as 75% of the rated load or recommended operating load. However, due to the nature of track type tractors and wheel type tractors neither the rated load nor the recommended operating load is given in the manufacturers' specifications. Therefore, to obtain the maximum gradability of tractors, an alternate method is used and explained in Section 3.4.2.1.

As explained in Section 3.4.1, the total resistance to the movement of a machine is equal to the sum of the rolling resistance and the grade resistance. To move a machine against the total resistive forces, the available power at the wheels or tracks should be greater than the total resistance at the wheels or tracks. This can be expressed as

$$(\text{available power at wheels or tracks}) > (\text{total machine weight}) \cdot \Big[(\text{GRF}) + (\text{RRF})\Big], \tag{3.6a}$$

where GRF = grade resistance factor,

and RRF = rolling resistance factor.

As explained earlier in this section, the total machine weight is equal to the sum of the tare weight of the machine and 75% of the rated or the recommended load. Therefore, (3.6a) can now be rewritten as

$$(\text{available power at wheels or tracks}) > \Big[(\text{EW}) + 0.75(\text{RW})\Big] \cdot \Big[(\text{GRF}) + (\text{RRF})\Big], \tag{3.6b}$$

where EW = tare weight of the machine in kg,

and RW = rated load of the machine in kg.

The maximum available power at the wheels or tracks of a machine is the maximum drawbar pull of the machine in the first gear, when operating at its rated horse power. The maximum drawbar pull values can be obtained from the rimpull charts of each machine given in the manufacturers' hand books. The rimpull chart is a graphical representation of the variation of maximum drawbar pull values at different gears with different speeds. The power loss due to operating a machine at a higher altitude is reflected in the gradability of the machine and this must be considered in job estimations. Manufacturers give these altitude deration factors as a percentage of the flywheel power. By incorporating the power loss due to altitude in (3.6b), it can be written as

$$(DR) . (AP) > \left[(EW) + 0.75(RW)\right] . \left[(GRF) + (RRF)\right] , \tag{3.7}$$

where DR = derating factor due to altitude (%),

and AP = maximum drawbar pull in the first gear.

Therefore, from (3.7), the GRF of the road should satisfy the following relationship in order to move a machine :

$$(GRF) < (DR) . \left[\frac{(AP)}{(EW) + 0.75(RW)}\right] - (RRF) . \tag{3.8}$$

3.4.2.1 Gradability check for tractors

As mentioned before, the rated loads or the recommended operating loads of track type tractors and wheel type tractors are not given in the manufacturers literature due to the nature of these machines. In order to perform the gradability check for track type tractors and wheel type tractors, the following alternate method is developed.

Instead of the rated load, the manufacturers provide the maximum drawbar pull values of these two types of machines in different gears and at the rated rpm (revolutions per minute). These drawbar pull values are used to obtain the gradability as explained below.

It is assumed that a soil load is being pushed by a tractor in an up-hill as shown in Figure 3.3. When the soil load is equal to the rated load of the tractor, and when the machine is operated at a high altitude, considering the equilibrium of the load at the limiting conditions

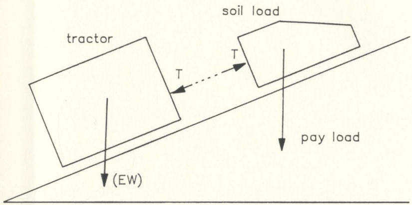

Fig. 3.3 Force configuration of tractors

$$(T_m) \,.\, (DR) = (RW) \,.\, \Big[(GRF) + (RRF_l) \Big] \,, \tag{3.9a}$$

where T_m = maximum forward drawbar pull at the blade in the first gear at the standard altitude,

DR = derating factor due to altitude,

RW = rated load of the machine,

GRF = GRF of the load and machine,

and RRF_l = RRF of the load.

When the machine is pushing a load equivalent to 75% of its rated load, at the limiting conditions

$$T = 0.75\,(RW) \,.\, \Big[(GRF) + (RRF_l) \Big] \,, \tag{3.9b}$$

where T = drawbar pull required to push 75% of the rated load.

From (3.9a) and (3.9b)

$$T = 0.75\,(DR)\,T_m \,. \tag{3.10}$$

Therefore, for these two types of machines, (3.7) can be re-arranged as

$$\begin{aligned}(DR)\,.\,(AP) \;&> (EW)\,.\,\Big[(GRF) + (RRF) \Big] \\ &\quad + 0.75\,(RW)\,.\,\Big[(GRF) + (RRF_l) \Big] \,.\end{aligned} \tag{3.11a}$$

Using (3.9b) and (3.11a)

$$(DR)\,.\,(AP) \;> (EW)\,.\,\Big[(GRF) + (RRF) \Big] + T \,. \tag{3.11b}$$

Substituting (3.10) in (3.11b), to move the machine and the load against all resistive forces

$$(DR)\,.\,(AP) > (EW)\,.\,\Big[(GRF) + (RRF) \Big] + 0.75\,(DR)\,.\,T_m \,. \tag{3.11c}$$

Therefore to push the load, the GRF of the machine should satisfy the following condition :

$$(GRF) < (DR) \,.\, \left\{ \frac{(AP) - 0.75T_m}{(EW)} \right\} - (RRF) \,. \tag{3.12}$$

where GRF = grade resistance factor,

DR = derating factor due to altitude,

AP = maximum drawbar pull in the first gear,

T_m = maximum forward drawbar pull at the blade in the first gear at the standard altitude,

EW = tare weight of the machine in kg,

and RRF = rolling resistance factor.

Hence from (3.8) and (3.12), in order to move a machine, the GRF of the road should satisfy the following condition :

$$(GRF) < (DR) \,.\, (k) - (RRF) \,. \tag{3.13}$$

where

$$k = \frac{(AP) - 0.75\ T_m}{(EW)} \quad \text{for TTT and WTT} \tag{3.14a}$$

$$k = \frac{(AP)}{(EW) + 0.75\,(RW)} \quad \text{for TTL, WTL, SS, TPS, ES, PPS, ST, and 4WDT.} \tag{3.14b}$$

(The symbols have the same meaning as given in (3.12) and page 15).

In (3.13) the values of grade resistance factor (GRF) and rolling resistance factor (RRF) can be obtained as outlined in Sections 3.4.1.2 and 3.4.1.2. According to the user's answers to the questions related to the altitude of the working area, it is possible to find the corresponding altitude derating values (DR).

The k values of all the models and sizes of track type tractors and wheel type tractors are evaluated using (3.14a). For all the other types of machines except belt conveyers, the corresponding k values are evaluated using (3.14b). Although the value of k significantly varies with the type of machine, the variation with the capacity of a machine is very small. Therefore, it is justifiable to use a constant k value for a given type of machine irrespective of its capacity. However, to obtain a reasonable value for k, the smallest value of k which gives the lowest gradability is considered. The k values of all the types of machines except belt conveyers are given in Table C.2 of Appendix C. These values are stored in the data base to use in the gradability calculation. Thus utilizing (3.13) and the user's input parameters in response to the relevant questions, the system checks the gradability of different types of machines.

After checking the traction ability and the gradability of the selected types of machines for the suspected sectors of the haul and return routes which are slippery or difficult to climb, the remaining machines are finally considered for the constraints and options applicable to the working conditions.

According to the user's past experience, the user may find that some of the selected types of machines are not suitable for the earthworks operation. The system provides the user an opportunity to incorporate such constraints by asking a question related to it (Question 6a of Appendix B). In response to this question, the user can delete the unsuitable types of machines from the selected set of machines. However, some or all of the unsuitable types of machines could be utilized, by fixing special attachments or by changing the operating conditions of the earthworks operation. The user may accommodate such variations by responding appropriately to the relevant questions (Question 6b of Appendix B).

Finally, by considering all the above factors separately, the system decides the suitable types of machines for the earthworks operation. These suitable types of machines are then presented to the user as an intermediate output.

In the second phase of the system, the production rates of all the models and sizes of these selected types of machines are determined. The factors considered and the development of phase 2 of the system are discussed in the next chapter.

CHAPTER 4

PRODUCTION RATES OF EARTHMOVING EQUIPMENT

4.1 Introduction

The estimation of probable production rates of various machines involved in different operations is important in any construction project, as this is a prerequisite for many vital functions such as costing, scheduling, and so forth. Production rates of earthmoving equipment which can be estimated by various methods, are affected by a host of factors. Some of these factors can be easily viewed before the execution of work, but many of them can not be. Also, some of the factors influencing the production rates of machines are subtle and difficult to assess. In this study, only the most influential factors on production rates are considered.

In this chapter, the most significant factors which influence the production rates are first briefly discussed. Then, the development of phase 2 of the system, along with the methods used to obtain the production rates of all the models and sizes of the selected machines from phase 1 of the system, is explained.

4.2 Factors influencing production rate

The production rate of a machine is basically the amount of material the machine can handle in a given period of time. This amount of material depends on several factors. Among them, the design features and the capabilities of the machine are the most dominant. Also, the production rate depends upon the properties of the excavated material, the loading and hauling activities, the haul and return route conditions, the output of the loading machine, and the overall job efficiency. These factors influence the production rates of machines differently. Therefore, the system calculates the production rates of machines using different methods.

4.3 Development of Phase 2

Suitable types of equipment for a particular earthworks operation have been selected in phase 1. The next step in the selection process is to obtain the production rates of all the models and sizes of the selected types of machines. These rates are obtained as outlined in Figure 4.1.

First, the system displays the models and sizes of the types of machines selected. Then the user is requested to assign the limiting values on weight and height that may be applicable to the construction site and to the haul and return routes (Questions 7, 8, and 9 of Appendix B). The consideration of weight and height limitations is essential to ensure that each machine can travel and be operated without any restriction within the required area. The operating and traveling heights, and the operating weight of each hauling machine are stored in the data base for these comparisons. Once the usable models are ascertained by comparing the limiting values with the operating and traveling heights, and the operating weights of the models given in the data base, the production rates of the remaining machines are determined.

As mentioned in Section 4.2, the production rates of earthmoving equipment

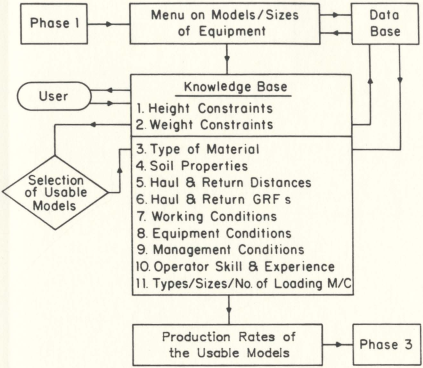

Fig. 4.1 Phase 2 of the system

depend on several factors. For the calculation of production rates, the eleven types of machines considered in the system are grouped into four different categories according to the nature of the machine. These categories are

(a) track type tractors and wheel type tractors,

(b) track type loaders, wheel type loaders, standard scrapers, tandem powered scrapers, elevating scrapers, and push-pull scrapers,

(c) standard trucks and four-wheel-drive trucks,

and (d) belt conveyers.

4.3.1 Theoretical production rates of track type tractors and wheel type tractors

Production rates of track type tractors and wheel type tractors vary depending on

(a) type and size of the machine,

(b) shape and size of the blade,

(c) average haul distance,

(d) density of the material,

(e) hardness of the cut or the stockpile,

(f) total resistance on the machine,

and (g) overall job efficiency.

Ideal production rates of track type tractors and wheel type tractors for different types of blades, with average haul distances are usually given in manufacturers' handbooks. However, in the developed system, the production estimates are carried out only for the standard straight blade, which is the most versatile. These ideal production rates, which have been estimated under the following operating conditions, are stored in the data base [4,17,36] :

(a) density of material 1370 kg/m^3 (loose),

(b) moderate hardness of material at the cut,

(c) 0% of total resistance factor,

and (d) 100% overall job efficiency.

To obtain the theoretical production rates of track type tractors and wheel type tractors, the ideal production rates given in the manufacturers' hand books have to be corrected according to the anticipated working conditions [4,36]. The theoretical production rate of these two types of machines can be expressed as

$$(TP) = (IP) . (CD) . (CH) . (CR), \tag{4.1}$$

where TP = theoretical production rate [m^3 (loose)/min],

IP = ideal production rate [m^3 (loose)/min],

CD = correction factor due to density,

CH = correction factor due to hardness of stockpile or ground,

and CR = correction factor due to total resistance.

The ideal production rates, and the correction factors due to density, hardness, and total resistance are found as explained below.

In the question related to the distances and the conditions of the haul and return routes (Question 12 of Appendix B), the user is first requested to assign various sectors to the haul and return routes. The difference in the sectors being dependent on the soil type and the grade. The system then provides a table showing these sectors, so that the relevant GRF values, and the soil types can be inserted. In deciding the soil types, the user is given a set of seven soil types, similar to those provided in Question 5a of phase 1. As explained in Sections 3.4.1.2 and 3.4.1.3, the system then determines the total resistance factors of individual sectors of the haul and return routes. By adding the individual distances given to the sectors of the haul route, the system finds the total haul distance of the earthworks operation as well. Then, using the production rates stored in the data base, the ideal production rates corresponding to the total haul distance of the machines are deduced.

The nature of the material to be handled is basically represented by the soil properties and the degree of hardness of the stock-pile or the ground. In the questions related to the nature of the material (Questions 10a, 10b, and 11 of Appendix B), a set of nine material types and a set of four stock-pile types are presented to the user to select the suitable combination. The densities, the bucket fill factors (BFF), and the coefficients of bulking of these nine types of material considered in the system are stored in the data base [4,15,33,36] as shown in Table C.4 of Appendix C. Also, the user may opt to insert any type of material in addition to the provided nine types. Should this be needed the density, the bucket fill factor, and the coefficient of bulking of the new type of material have to be provided. Eventhough the BFF and the coefficient of bulking are not required in calculating the production rates of track type tractors and wheel type tractors, they are required in obtaining the production rates of the other machines considered in the system.

As the ideal production rate of (4.1) is given for materials of density 1370 kg/m^3(loose), the correction factor due to density (CD) is always given in the manufacturers' literature as

$$(CD) = \frac{1370}{\text{density of the material}}. \tag{4.2}$$

The correction factors due to hardness of the stock-pile or the ground, and the correction factors due to total resistances can be found in the manufacturers' hand books [4]. These values are stored in the data base of the system (Tables C.5 and C.6 of Appendix C). Therefore, according to the user's response to the question on hardness of the stock-pile or the ground, the correction factor on hardness (CH) is retrieved from the data base. In finding the correction factor due to the total resistance (CR), the system first obtains the maximum total resistance of the haul road. The total resistance of the haul road is determined in the system as explained in Section 3.4.1. Then the corresponding correction factor on the total resistance is obtained from the data base.

By the use of these correction factors, and the ideal production rates of track type tractors and wheel type tractors, the theoretical production rates can be found using (4.1).

4.3.2 Theoretical production rates of track type loaders, wheel type loaders, and scrapers

Theoretical production rates of loaders and scrapers are related to the amount of material handled per cycle, and to the cycle time of the machine.

$$(TP) = \frac{L_c}{t_c}, \tag{4.3}$$

where TP = theoretical production rate [m^3(loose)/min],

L_c = material handled per cycle [m^3(loose)],

and t_c = cycle time [min].

The maximum amount of material handled per cycle of track type loaders, wheel type loaders, scrapers, and trucks, is limited either by the capacity of their buckets or bowls, or by their rated pay loads [4,15,36]. If the equivalent weight of the heaped capacity of the bucket or the bowl is greater than the rated pay load, the maximum amount of material handled per cycle is governed by the rated pay load. Whichever situation governs the maximum load per cycle, the amount of material the bucket or the bowl can load also depends on the type of material. Therefore, to obtain the actual amount of material which can be scooped or loaded per cycle, the heaped capacity of the bucket has to be multiplied by the bucket fill factor (BFF).

The BFF depends on the type of material and the shape of the bucket. However, the variation of BFF with the shape of the bucket is negligible. Therefore, the effect due to the shape of the bucket is ignored in the system.

To obtain the amount of material handled per cycle, the heaped capacities and the rated pay loads of different models and sizes of loaders, scrapers, and trucks are stored in the data base.

The BFF and the density of the material to be handled are obtained from the questions related to the nature of the material (Questions 10a and 10b of Appendix B). Since the heaped capacities and the rated capacities of all the models and sizes of loaders and scrapers are stored in the data base, it is possible to find the load per cycle of each machine using the following equation.

$$L_c = \begin{cases} (H_v)\,.\,(BFF) & \text{if } (H_v)\,.\,(BFF) < \dfrac{R_c}{D_l} \\ \dfrac{R_c}{D_l} & \text{if } \dfrac{R_c}{D_l} < (H_v)\,.\,(BFF) \end{cases} \tag{4.4}$$

where L_c = material handled per cycle [m^3(loose)],

H_v = heaped bucket capacity [m^3],

BFF = bucket fill factor of the material handled,

R_c = rated load of the machine [kg],

D_l = density of the material handled [kg/m^3(loose)].

The cycle time of a machine is the sum of the load and maneuver time, the haul and return time, the dump and maneuver time, and the delay time. The sum of the load, maneuver, and dump times is called the fixed time as it is fairly constant over any given equipment regardless of the travel time. The fixed times of loaders and scrapers obtainable from the manufacturers' catalogs are also stored in the data base along with the heaped capacities.

The time taken for the haul and return journeys is known as the variable time. It depends on the distances, conditions, and grades of the haul and return routes. The variable time also depends on the type, the model, and the possible average speed of the machine. Depending on the soil types and the grades, if there are n_1 sectors in the haul route and n_2 sectors in the return route, the total variable time of a machine is given by

$$t_v = \sum_{i=1}^{i=n_1} (t_i)_h + \sum_{j=1}^{j=n_2} (t_j)_r \tag{4.5}$$

where t_v = total variable time [min],

$(t_i)_h$ = time taken to travel the i^{th} sector of the haul route [min],

and $(t_j)_r$ = time taken to travel the j^{th} sector of the return route [min].

To find the time taken to travel any sector of the road, it is required to know the average travel speed of the machine along that sector. The maximum speed of a machine over a particular section of the haul or return route under a specific total resistance value can be obtained from performance charts given by the manufacturers. However, since the machine may not operate at its maximum speed over the whole length of the road, the maximum speed must be changed to a practical average value to compensate for the acceleration and deceleration of the machine [30,33]. This average speed is determined by multiplying the maximum possible speed of the machine on a given section of a road by a speed factor. Then the average travel speed within the k^{th} sector of the haul or return route can be expressed as

$$(S_a)_k = (S_m)_k \cdot (SF)_k, \tag{4.6}$$

where $(S_a)_k =$ average speed of the machine in the k^{th} sector [m/min],

$(S_m)_k =$ maximum speed of the machine in the k^{th} sector [m/min],

and $(SF)_k =$ speed factor of the machine within the k^{th} sector.

Among the several variables which determine the speed factor of a machine, the more dominant ones are the mass-to-power ratio, and the length and grade of the road [33]. To find the speed factors, all the machines are first categorized into three groups according to their mass-to-power ratios. Then for these three categories, the speed factors for different grade resistance factors (GRF) and for different haul distances are obtained [33] and stored in the data base as shown in Tables C.7a, C.7b, and C.7c of Appendix C.

The total resistance to the movement of a machine on each sector can be found by similar arguments to those of Section 3.4.1. The variation of maximum speeds of machines with the total resistance of the haul and return routes are stored in the data base using the performance charts of machines. Therefore, the maximum speed that a machine can attain over a certain sector of the route can now be found using the speed versus total resistance values.

Once the distance, the maximum speed, and the speed factor are known, it is possible to find the travel time for a particular sector. Hence the total variable time of each machine can be obtained from (4.5). Using the fixed times of each machine stored in the data base and the corresponding variable times, the system can find the cycle time. In doing so, the delay time is assumed to be zero, as it will be taken into account in finding the overall job efficiency. Equation (4.3) can now be used to find the theoretical production rates of loaders, and scrapers.

4.3.3 Theoretical production rates of standard trucks and four-wheel-drive trucks with loading machines

The theoretical production rate of a truck always depends on the production rate of the loading machine. Therefore, the theoretical production rate of a truck should necessarily be the combined production rate with the loading machine used.

The method of determining the production rates of trucks with loading machines is almost similar to the method of determining the production rates of track type loaders, wheel type loaders, and scrapers. However, with trucks, the production rates are determined as a combined output with different loading machines. When determining the combined production rates, the physical compatibility of loading machines with trucks has to be first considered. This ensures that the horizontal and vertical reaches are adequate to perform the loading operation efficiently, and that the load per cycle of the loading machine is compatible with the load per cycle of the truck.

The fixed time for trucks can be written as

$$t_f = t_l + t_m + t_d, \tag{4.7}$$

where $t_f =$ fixed time [min],

$t_l =$ loading time [min],

$t_m =$ maneuvering time [min],

and $t_d =$ dumping time [min].

In the above equation, the value of $(t_m + t_d)$ for trucks usually varies between 1.8 minutes to 2.0 minutes [4,6,41]. In the developed system the average value of $(t_m + t_d)$ is taken as 1.9 minutes. The loading time, t_l , depends on the production rate of the loading machine.

In finding the loading times, the following four types of loading machines are considered:

(a) front end loaders,

(b) hydraulic backhoes or face shovels,

(c) cable operated power shovels,

and (d) draglines.

The average cycle times of these four types of loading machines [4,6,8,15] are stored in the data base (Table C.8 of Appendix C). In the questions related to the loading machines (Question 14 of Appendix B), the user is prompted to input the availability and the available number of models of each of the loading machine. The heaped capacities of all the available models are then requested. With the knowledge of the BFF of the material to be handled and the average cycle times of the four types of loading machines, the system determines the production rates of the loading machines using the following formula :

$$(TP)_l = \frac{(H_v)_l \,.\, (BFF)}{(t_c)_l}, \tag{4.8}$$

where $(TP)_l$ = theoretical production rate of the loading machine [m^3(loose)/min],

$(H_v)_l$ = heaped capacity of the loading machine [m^3], BFF= bucket fill factor of the material handled,

and $(t_c)_l$= average cycle time of the loading machine [min].

The user has the option to input other types of loading machines in addition to front end loaders, hydraulic backhoes or face shovels, cable operated power shovels, and draglines. Should this be required, the type and the models of those machines, and the corresponding production rates would then need to be inserted.

Once the production rates of all the models of loading machines are known, it is possible to find the approximate loading time for each combination of truck and loading machine using (4.9). Assuming that the loading activity is carried out using only one loading machine, the approximate loading time, t_l, can be written as

$$t_l = \frac{(H_v) \, . \, (BFF)}{(TP)_l}, \tag{4.9}$$

where H_v = heaped bucket capacity of the truck [m^3],

BFF = bucket fill factor of the material handled,

and $(TP)_l$ = theoretical production rate of the loading machine [m^3(loose)/min].

Once t_l for a given set of truck and loading machine is known, using (4.7), the system finds the fixed time of that set of machines. The variable time corresponding to the truck can be found using (4.5) and (4.6) as explained in Section 4.3.2. Therefore, with the knowledge of the cycle time and the material handled per cycle, (4.3) can be used to calculate the combined production rates of trucks with loading machines.

4.3.4 Theoretical production rates of belt conveyers

In order to use a belt conveyer as a hauling machine, a separate loading machine is needed to feed the belt at a uniform rate. Therefore, the production rate of a belt conveyer, invariably is affected by the production rate of the loading machine. However, as the possible combinations of belt conveyers and loading machines are not known at this stage, the maximum production rates of belt conveyers are determined neglecting the effect of loading machines. The evaluation of combined production rates of belt conveyers with the available loading machines, which required to find the most economical group, is discussed in the next chapter.

The amount of material that can be transported by a belt conveyer in a given time is equal to the product of the cross sectional area of the material and the distance of travel during that time. The cross sectional area of the material moving on the belt depends on the width of the belt, density of the material being transported, the angle of the troughing idlers, and surcharge angles of the material. However, based on commonly used values of the surcharge angle for bulk material and a 35^0 angle of troughing idlers, the area of cross section of material varies from $0.075w^2$ to $0.123w^2$, where w is the width of the belt in meters, depending on the density of the material being handled [8]. In this cross sectional area of material, it is assumed that the belt is loaded from the feeder to 90% of its full width. The estimated theoretical production rate can be given as [8,30]

$$(TP) = k\, w^2\, S, \tag{4.10}$$

where (TP) = theoretical production rate [m^3(loose)/min],

$$k = \begin{cases} 0.123 & \text{if material density} \geq 1780\text{kg}/\ \text{m}^3\text{(loose)}, \\ 0.075 & \text{otherwise,} \end{cases}$$

w = width of the belt [m],

and S = speed of travel of belt [m/min].

In the questions related to belt conveyers, the user has the option either to give theoretical production rates, or to give design features of the belts, such as the widths and the speeds of travel of belts. As the density of the material handled is known, if the user is not aware of the production rate of any belt conveyer model in the fleet, the theoretical production rate is determined using (4.10).

In addition to this, if the belt conveyers are available in the fleet of loading machines, the same facility is provided to find the production rates.

Once the theoretical production rates of all the models of selected types of hauling machines and all the loading machines are obtained, the actual production rates are determined by considering the overall job efficiency as a common factor for all the machines in the system.

4.3.5 Overall job efficiency

The actual production rate that can be expected from a machine can considerably differ from the theoretical production rate, depending on the overall job efficiency. In determining the overall job efficiency, the user has the option either to suggest a value or to use the facility in the system.

Among the many factors that influence the overall job efficiency of an earthmoving activity, the working conditions, condition of the equipment, efficiency of the management, and workers' experience, skill, and attitude are the most important. If the user fails to suggest a value for the overall job efficiency, the system determines the overall job efficiency by considering the above four influencing factors. These four factors, however, influence each type of machine in different magnitudes. Various authors and manufacturers of earthmoving equipment, have given different ratings for the above four factors depending on the relevant degree of contribution. After scrutinizing the values given in the literature [4,8,36], the ratings given in Tables C.9 and C.10 of Appendix C are used in the system. As the overall job efficiency can be represented by the number of minutes actually worked in an hours time, it may be written as

$$\eta_0 = 60\,(\eta_w)\,(\eta_e)\,(\eta_m)\,(\eta_d), \tag{4.11}$$

where η_0 = overall job efficiency in actual working minutes per hour,

η_w = efficiency rating due to weather, visibility, and working time of the day,

η_e = efficiency rating due to equipment condition and working space,

η_m = efficiency rating due to management condition,

and η_d = efficiency rating due to operator's skill, experience, and attitude.

Depending on the user's response to the relevant questions (Questions 15a, 15b, and 15c of Appendix B), the system assigns different ratings to the efficiency factors using Tables C.9 and C.10 of Appendix C.

Once the overall job efficiency (η_0) is obtained either by using (4.11) or from the value given by the user, the system finally calculates the actual production rates of all the machines as follows:

$$(AP) = (TP) \, . \, \eta_0, \tag{4.12}$$

where AP = actual production rate [m^3(loose)/hr],

and TP = theoretical production rate [m^3(loose)/min].

At the end of phase 2, the estimated production rates of all the selected models and sizes of hauling and loading machines are displayed on the screen. In the final phase of the system, the most economical fleet of machines is deduced using the actual production rates estimated in phase 2. This is elaborated in the next chapter.

CHAPTER 5

SELECTION OF THE MOST ECONOMICAL GROUP OF MACHINES

5.1 Introduction

The main objective of construction management is, to accomplish all the operations related to a project according to the required specifications and standards within the scheduled time at the least possible cost. For example, in an earthmoving project, it is paramount that the selection of earthmoving equipment be done carefully, so that it meets the required standards and production rates, at the minimum cost per unit volume of material to be handled. Apart from the cost and production rate considerations, it is also important to consider the impact on the effective utilization of other related equipment.

Selection of the most economical group of machines from the available equipment for the earthworks operation is carried out in the final phase of the system. In developing the final phase, the production rates, the physical feasibilities, and the cost per unit volume of material handled are considered. This chapter is focused on the development of the final phase of the system.

5.2 Factors considered in selecting the most economical group of machines

The most economical group from a fleet of machines is determined on the basis of the least cost per unit volume of material handled. In doing so, it is necessary to find the cost per unit volume of material handled by each group of machines. The cost per unit volume of material handled depends on the total cost incurred by the group, and the total volume of material handled. To find the total cost, the number of machines in the group and their individual costs have to be known. The cost of an individual machine may include various cost components such as owning and operating cost, mobilization and installation cost, and road construction and maintenance cost.

The number of machines required from a particular model for an earthworks operation depends upon the required rate of production of the earthmoving activity and the anticipated rate of production of the machine. The required rate of production is a function of the total quantity of material to be handled and the time allotted for the earthmoving activity. Once the required rate of production and the anticipated rates of production of all the models and sizes of machines are known, it is possible to find the number of machines required from each model to meet the required rate of production. Moreover, it is important to keep at least one extra machine to compensate for any breakdowns, delays, or for unfavorable, unforeseen circumstances [28]. However, it may not be possible to employ the required number of machines of a particular model for the earthworks operation, either due to a limitation on availability of the model, or due to the physical feasibility of operating the required number of machines within the confines of the construction site. It is therefore necessary to consider these two constraints, before deciding on the number of machines required.

When the required number of machines for the earthworks operation is less than the available number of machines, it is possible to form a group of machines by combining with other models of the same type of machine. The number of such combinations which can be formed is very large. Therefore, to limit the memory requirement to 256 kilo-bytes, it was decided to use only two combinations. These two combinations are formed by combining the model with the available next large and the next small capacity models of the same type of machine.

Once the total cost incurred by each group of machine is known, it is possible to find the cost per unit volume of material using the total quantity of material to be handled. The development of phase 3, and the mathematical and logical approach used in the system to find the most economical group of machines are discussed in the next section.

5.3 Development of Phase 3

Once the actual production rates of all the models and sizes of hauling and loading machines are known, the next step is to decide the most economical group of machines in the fleet. This is achieved in the system as shown in Figure 5.1.

At the beginning of the third phase, the final phase of the system, the user is requested to provide the total quantity of material to be handled, the time allotted for the earthworks operation, and the intended working hours per day during the period of construction. However, the number of working hours per day during

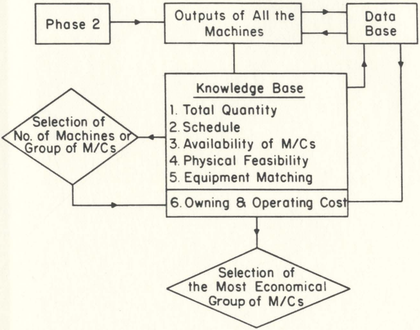

Fig. 5.1 Phase 3 of the system

the time span of the earthworks operation may vary to allow for the maximum usage of daylight. To take this situation into account, the user has to provide the number of such time intervals of the earthworks operation, the number of working hours per day during each time interval, and the corresponding durations, in the appropriate questions (Questions 16, 17, and 18 of Appendix B). Once these are known, it is possible to calculate the required rate of production to meet the schedule of the earthworks operation, using the following equation :

$$(RP) = \frac{Q_t}{\sum_{i=1}^{i=(p-1)} h_{wi} D_{ti} + \left[D_s - \sum_{i=1}^{i=(p-1)} D_{ti} \right] h_{wp}} , \tag{5.1}$$

where (RP) = required rate of production to meet the schedule [m^3 (loose)/hr],

Q_t = total quantity of material to be handled [m^3(loose)],

p = number of time intervals having different number of working hours per day during the earthworks operation,

h_{wi} = number of working hours per day during the i^{th} time interval of the earthworks operation,

D_s = scheduled duration of the operation in working days,

and D_{ti} = duration of the i^{th} time interval in working days.

The system then requests the user to input the number of machines available of each model and size in the entire fleet, and to suggest the number of machines that could be operated within the working area (Question 19 of Appendix B). However, due to the memory capacities of the available micro-computers on most construction sites, the maximum number of machines of each model and size that is available or feasible is limited to ten. The available number of machines from each model and size is the lesser of the two values given by the user in response to the question on the availability and the physical feasibility.

In selecting the most economical group of machines, the next major objective is to obtain the cost incurred by each group of machines. To obtain the total cost, it is first required to know the owning and operating cost or in the event of renting the total rental cost, and the transportation and mobilization cost. As a substantial amount of money is required to construct and maintain the haul and return routes necessary for the earthworks operation, this cost component is also to be known in evaluating the total cost. Accordingly, the system enables the user either to suggest a value for the cost per hour of each machine, or to utilize the facility in the system to find the individual costs. Nevertheless, for both these situations, the user has to provide the miscellaneous cost consisting of the transportation and mobilization cost, and the road construction and maintenance cost. A detailed explanation of the method used in the system to find the rates of expense and the miscellaneous cost is given in Chapter 6.

To find the total cost involved in each group, it is necessary to find the number of machines needed to achieve the required rate of production. However, the method of deciding this number is different for each type of machine. Depending on the method used to determine the number of machines required to suit the required rate of earthmoving, the eleven types of machines considered in the system are categorized as follows :

(a) track type tractors, wheel type tractors, track type loaders, wheel type loaders, and scrapers,

(b) standard trucks, four-wheel-drive trucks, and loading machines, and (c) belt conveyers and loading machines.

5.3.1 Cost per unit volume of material handled of track type and wheel type tractors, track type and wheel type loaders, and scrapers.

The individual production rates of all the models and sizes of the above types of machines were determined in phase 2 of the system. If the individual actual production rate of a model is known, the number of machines required from that particular model to meet the required rate of earthmoving can be written as

$$n_r = \frac{(RP)}{(AP)} \tag{5.2}$$

where n_r= required number of machines,

RP = required rate of production [m^3(loose)/hr],

and AP = actual rate of production [m^3(loose)/hr].

However, as mentioned in Section 5.2, it is always desirable to keep at least one extra machine to compensate for possible delays and unfavorable circumstances. Therefore, the actual number of machines required for the earthworks operation is decided by adding one to the integer value of n_r obtained from (5.2).

The available number of machines of a particular model, n_a, under consideration may or may not be adequate to furnish the full requirement n_r. Therefore, the following five possible cases are considered in the system, in finding the machines suitable for a group. The number of cases are limited to five, due to the memory limitations of generally available micro-computers.

case i - $n_a = n_r$,

case ii - $n_a > n_r$,

case iii - $n_a = n_r - 1$,

case iv - $n_a = n_r - 2$,

case v - otherwise.

The methods used to obtain the expected production rates, the total cost incurred in handling a unit volume of material, and the expected duration of the above five cases are explained separately in the following sections.

5.3.1.1 Case i - Number of machines available is equal to the number of machines required ($n_a = n_r$)

In this case, the number of machines available of the model is equal to the number required for the earthworks activity. Assuming that the production rates of all the machines of the model under consideration are equal, the total production rate of the group can be given as

$$(EP) = n_r \cdot (AP) \tag{5.3}$$

where EP = expected production rate of the group [m^3(loose)/hr],

n_r = required number of machines for the earthworks activity,

and AP = actual production rate of a machine [m^3(loose)/hr].

Therefore, the rate of expense of the group can be written as $\sum_{i=1}^{i=n_r} (E)_i$, where $(E)_i$ is the rate of expense of the i^{th} machine excluding the miscellaneous cost of the model under consideration. However, the miscellaneous cost due to the road construction and maintenance cost can be treated as a common cost to the group of machines. Therefore,

$$\text{total expense of the group} = \frac{\sum_{i=1}^{i=n_r} (E)_i \cdot Q_t}{(EP)} + (HC) + \sum_{i=1}^{i=n_r} (MC)_i\,, \quad (5.4)$$

where Q_t = total quantity of material to be handled [m^3(loose)],

HC = cost due to road construction and maintenance of the type of the i^{th} machine [dollars],

and $(MC)_i$ = transportation, and mobilization and demobilization cost of the i^{th} machine (dollars).

Therefore, the cost to haul a unit volume of material, C_t, in dollars/ m^3 (loose), is given by

$$C_t = \left[\frac{\sum_{i=1}^{i=n_r} (E)_i \cdot Q_t}{(EP)} + (HC) + \sum_{i=1}^{i=n_r} (MC)_i \right] \cdot \frac{1}{Q_t}\,. \quad (5.5)$$

The expected duration, D_e, in working days, of the earthworks operation is obtained using the following method :

There are a number of time intervals having different working hours per day, within the time span of the earthworks operation. Therefore, in finding the expected duration, D_e, for a given group of machines, it is first required to find the time interval number, m, at which the earthworks operation is completed. In this situation, at the end of the $(m-1)^{th}$ time interval

$$(EP) \sum_{i=1}^{i=(m-1)} h_{wi} D_{ti} < Q_t , \qquad m=1,2,\ldots,p. \tag{5.6a}$$

where EP = expected production rate of the group $[m^3(\text{loose})/hr]$,

h_{wi} = number of working hours per day during the i^{th} time interval of the earthworks operation,

D_{ti} = duration of the i^{th} time interval in working days,

Q_t = total quantity of material to be handled $[m^3(\text{loose})]$,

and p = total number of time intervals having different number of working hours per day during the time span of the earthworks operation.

Similarly, at the end of the m^{th} time interval

$$(EP) \sum_{i=1}^{i=m} h_{wi} D_{ti} \geq Q_t , \qquad m=1,2,\ldots,p \tag{5.6b}$$

Therefore, it is possible to find the time interval number, m, which satisfies (5.6a) and (5.6b). However, there may exist a 'm' which satisfies (5.6a) and dissatisfies (5.6b). In this situation, 'm' is assumed as equal to 'p', and the number of working hours per day during the p^{th} time interval, h_{wp}, is assumed to remain unchanged until the completion of the operation.

Using the m value obtained, the expected duration, D_e, can be evaluated from the following expression :

$$D_e = \sum_{i=1}^{i=(m-1)} D_{ti} + \frac{\left[Q_t - (EP) \sum_{i=1}^{i=(m-1)} h_{wi} D_{ti} \right]}{(EP) \cdot h_{wm}} . \tag{5.6c}$$

5.3.1.2 Case ii - Number of machines available is greater than the number of machines required ($n_a > n_r$)

When the available number of machines, n_a, is greater than the required number of machines, n_r, the latter has to be selected from n_a machines. To obtain the group which gives the minimum cost, it is first required to select the n_r number of machines having the lowest rate of expense of the model under consideration. Once these machines are identified, using (5.3), (5.5), and (5.6), it is possible to find (EP), C_t, and D_e of each group as explained under Case i.

5.3.1.3 Case iii - Number of machines available is equal to the number of machines required less one ($n_a = n_r - 1$)

When the available number of machines is equal to the required number of machines less one, a group is formed with the available number of machines. Then (EP), C_t , and D_e can be obtained as explained under Case i.

5.3.1.4 Case iv - Number of machines available is equal to the number of machines required less two ($n_a = n_r - 2$)

When the available number of machines is equal to the required number of machines less two, the following two combinations are considered in the system.

(a) a group consisting of n_a machines of the model being considered, and one machine of the same type having the next large capacity.

(b) a group consisting of n_a machines of the model being considered, and one machine of the same type having the next small capacity.

In this situation, to find the expected production rate, and the rate of expense of the group, it is necessary to consider the actual production rate and the rate of expense of the next small or the next large capacity machine which is added to the group, as well. Then as explained under Case i, the expected production rates, the cost incurred to handle a unit volume of material, and the expected duration of the group can be found.

5.3.1.5 Case v - Any other combination

If the number of machines available does not belong to any of the above four cases, the model being considered is treated as unsuitable for the earthworks operation. This provision is made primarily to avoid the possibility of having very large combinations in the computer program.

5.3.2 Cost per unit volume of material handled for trucks with loading machines

The combined actual production rates of trucks and loading machines, the production rates of loading machines, the cycle times, and the loading times of trucks, which were evaluated in phase 2 of the system, are used in finding the number of machines required.

To decide on an efficient and an economical group of trucks and loading machines, it is first necessary to find the number of loading machines needed to meet the required rate of production. This is found using (5.2) as explained in Section 5.3.1. However, in comparing the required number of machines with the available numbers, out of the five cases explained in Section 5.3.1, the Case iv is not considered. This is avoided, because combining of models would be difficult and complicated when matching different sizes of loading machines with hauling units.

Once the number of loading machines required for the earthworks operation is decided, the expected production rates of the individual groups of loading machines are determined using the following equation :

$$(EP)_l = (n_r)_l \cdot (AP)_l \,, \tag{5.7}$$

where $(EP)_l$ = expected production rate of the group of loading machines [m^3(loose)/hour],

$(n_r)_l$ = number of loading machines in the group,

and $(AP)_l$ = actual production rate of a loading machine [m^3(loose)/hour].

When selecting the hauling machines, they have to be matched with the loading machines, as their production rates depend on each other. If there are '*a*' number of groups of loading machines which can be formed with the available types and numbers of loading machines, and there are '*b*' number of models of trucks available with a contractor, then the total number of possible types of combinations becomes '*ab*'. All of these '*ab*' combinations are considered in the system in obtaining the most economical group. Though there are various schools of thought applied in matching or balancing the trucks with the loading machines, the most simple and common method which is explained below, is used for all the possible loader-truck combinations [6,30]. The number of trucks of a particular model required, n_r, to match with the loading machines being considered, can thus be written as

$$n_r = \frac{t_c}{t_l} \cdot (n_r)_l + 1 , \tag{5.8}$$

where t_c = cycle time of the truck with the loading machine,

t_l = loading time of the truck with the loading machine,

and $(n_r)_l$ = required number of loading machines.

In the above equation, always one additional hauling unit is included in order to compensate for any possible delays due to breakdowns, personnel delays and so forth. In forming the possible groups of trucks, the checks for the available number of machines, and for the physical feasibility to operate the machines are then considered in the system as explained in Section 5.3.1. In deciding the number of trucks in a group, Case iv in Section 5.3.1.4 is neglected to avoid the combinations of different models of trucks as explained earlier.

Once the group of machines which consists of loading machines and trucks is decided, the next step is to find the possible production rate of the group. The possible production rate of the group $[(EP)_g]$ is governed by the lowest value of the total independent production rate of the group of loading machines, and the total combined expected production rate of the loader-truck combination. Here, the total combined expected production rate of the loader-truck combination can be found using (5.3). However, for the loader -truck combination, the values of (AP) are the combined actual production rates instead of the actual production rates. Knowing the expected production rate of the loader-truck group, the total expenses incurred can be found as

$$\text{total expense of the group} = \left[\frac{\sum_{i=1}^{i=n_r} (E)_i + \sum_{j=1}^{j=(n_r)_l} (E_l)_j}{(EP)_g} \right] . Q_t + (HC) +$$

$$\sum_{i=1}^{i=n_r} (MC)_i + \sum_{j=1}^{j=(n_r)_l} [(MC)_l]_j \qquad (5.9)$$

where $(E)_i$ = rate of expense of the i^{th} truck in the group [dollars/hour],

$(E_l)_j$ = rate of expense of the j^{th} loading machine in the group [dollars/hour],

n_r = number of trucks in the group,

$(n_r)_l$ = number of loading machines in the group,

Q_t = total volume of material to be handled [m^3 (loose)],

$(EP)_g$ = expected production rate of the group [m^3(loose) / hour],

HC = road construction and maintenance cost [dollars],

$(MC)_i$ = transportation, and mobilization and demobilization cost of the i^{th} hauling machine [dollars],

and $[(MC)_l]_j$ = transportation, and mobilization and demobilization cost of the j^{th} loading machine [dollars].

Therefore, the cost to haul a unit volume of material to be handled, C_t, is given by

$$C_t = \left[\frac{\sum_{i=1}^{i=n_r} (E)_i + \sum_{j=1}^{j=(n_r)_l} (E_l)_j}{(EP)_g} . Q_t + (HC) + \sum_{i=1}^{i=n_r} (MC)_i + \sum_{j=1}^{j=(n_r)_l} [(MC)_l]_j \right] . \frac{1}{Q_t} \qquad (5.10)$$

The expected duration to complete the earthworks operation, D_e, is found using (5.6) as explained in Section 5.3.1.1. However, for the truck-loader combination, the value of $(EP)_g$ has to be used for (EP) in (5.6).

5.3.3 Cost per unit volume of material handled of belt conveyers with loading machines

As explained in Section 4.3.4, the production rate of a belt conveyer always depends on the production rate of the loading machine. Therefore, in finding the most economical group of machines, it is required to find the combined production rates of belt conveyers with the available loading machines.

The number of loading machines needed to achieve the required rate of production can be found using (5.2) and as explained in Section 5.3.1. By comparing the required number of loading machines with the available number, the loading machine groups are found as explained in Section 5.3.2. As the individual production rates of loading machines are known, the production rates of each group of loading machines can be evaluated using (5.7). The same method is employed in finding the number of belt conveyers needed to meet with the required production rate, the number of machines in a group, and the group production rates of belt conveyers.

Once the groups are decided for all the belt conveyers and the loading machines independently, the expected combined production rate of each group of belt conveyers with each group of loading machines is then obtained. Since the group production rates of belt conveyers and loading machines are also interdependent, the expected combined group production rate is always the lowest of the group production rate of belt conveyers and the group production rate of loading machines. The cost per unit volume of material to be handled and the expected durations are evaluated using a method similar to that of Section 5.3.2.

By comparing the cost per unit volume of material to be handled of all the groups of machines, the system then determines the most economical group of machines for the earthmoving operation. Moreover, the most economical group of machines which meets the scheduled duration is also found in the system. Furthermore, the cost per unit volume of material handled, the expected duration and the expected production rates of all the employable groups of machines in the entire fleet are also given as outputs in the system.

An example problem of a fictitious earthmoving operation to select the most economical groups of machines is presented in Appendix B.

CHAPTER 6

COST FACTORS INVOLVED IN EARTHMOVING

6.1 Introduction

The methods of determining the probable cost involved in a group of machines to perform an earthworks operation are complex. Among the available methods, none will give an exact cost value under all operating conditions. This is because, the operating costs of earthmoving machines are influenced by many factors which may alter fairly rapidly not only with the time but also with the location. However, as the selection of the most economical group of machines from the available fleet of machines for an earthworks operation is based upon the total cost and the hourly production rates, the accurate estimation of the total cost for a group is of vital importance.

In this chapter, the cost factors involved in earthmoving and the development of the cost model used in the system are explained.

6.2 Cost factors involved in earthmoving equipment

Generally, a contractor may either use his own equipment or lease the equipment to employ on an earthworks operation. If cost is the only factor to be considered, the method of selection of the equipment should be the one which provides the lowest cost to operate equipment under the given operating conditions. Depending on the method of acquiring the equipment for employment in the earthworks operation, the cost factors involved would differ. As such, the costs involved in owned equipment and the costs involved in rented equipment are separately considered in this chapter.

Irrespective of how the equipment is acquired, it is important to know the specific cost categories involved in the earthworks operation, to properly perform an operating cost estimate. However, the indirect costs such as overhead expenses are disregarded in the cost model, as they affect all the equipment equally, regardless of the nature and the size of the group of equipment.

6.3 Costs involved in owning equipment

When employing the owned equipment for an earthworks operation, there are two categories of costs which should be recognized for cost estimation purposes. They are the ownership cost and the operating cost.

The ownership cost represents the cost that would be incurred whether the equipment is actually working or not. It is usually related to the calendar time. The operating cost is the cost incurred in actually operating the equipment and it is related to the actual production time of the operation.

6.3.1 Ownership cost

The ownership cost is the expense that the owner of an item of equipment contemplate to protect the investment and to evaluate its value. The following main cost factors which contribute to the ownership cost, are considered in the system in developing the cost model. They are the costs due to :

(a) depreciation,

(b) interest,

(c) property taxes and licenses,

(d) insurance,

and (e) storage and security [6].

These cost factors are separately explained in the following sub-sections. However, the interest, property taxes and licenses, insurance, and storage and security costs are usually incurred annually and are based on the equipments' average book value during the year. Therefore, all those costs are explained in one section.

6.3.1.1 Depreciation

Depreciation is the loss of value of a piece of equipment over time due to deterioration and obsolescence. There are several methods of calculating equipment's depreciation. However, the three methods that frequently used and approved by the tax authorities are the straight line method, the declining balance method, and the sum of the year digits method [6,30]. Out of the above three methods the sum of the year digits method, which provides an intermediate depreciation compared to the other two methods, is used in developing the cost model in the system. The amount to be depreciated is based on the total initial cost of the equipment. Therefore, the extra accessories, delivery charges, and so on are subsumed into the initial equipment cost. As tires are not expected to last as long as the machine, the tire costs are deducted from the initial machine cost and regarded as an operating cost. The grouser of track type machines is, however, considered as part of the initial machine cost [6].

Using the sum of the year digits method, the depreciation cost during the x^{th} year, $(DC)_x$, in dollars can be given by [(D.1) of Appendix D]

$$(DC)_x = \frac{\left(P_o + P_d - P_t - P_s\right)\ \left(N - (x-1)\right)}{\sum_{z=1}^{z=N} z}, \tag{6.1}$$

where P_o = Free On Board (F.O.B) price of the equipment including the accessories (dollars),

P_d = total delivery cost (dollars),

P_t = cost of a new set of tires, if applicable (dollars),

P_s = salvage value or resale value of the machine after N years (dollars),

N = estimated useful life of the machine (years),

x = the year being considered $(1 \leq x \leq N)$,

and z = any integer number between 1 and N $(1 \leq z \leq N)$.

6.3.1.2 Investment cost due to interest, taxes, insurance, and storage

There are many other costs, besides depreciation, in the ownership of equipment. Among them, the interest on the money invested, the property taxes and license fees, the insurance charges, and the costs incurred due to storage and security are the most dominant. These cost components can be figured based on an average yearly book value of the equipment over its useful life. Therefore, the total investment cost, due to interest, taxes, insurance, and storage during the x^{th}

year, $(IC)_x$, in dollars, can be found using the following equation [(D.7) of Appendix D] :

$$(IC)_x = \left(\frac{(p_x+t_x+j_x+s_x)}{100} \right) \left[(P_o+P_d-P_t) - \frac{1}{2}(DC)_x - \sum_{z=1}^{z=(x-1)} (DC)_z \right], \tag{6.2}$$

where p_x % = interest charges per annum,

t_x % = property taxes and license charges per annum,

j_x % = insurance per annum,

s_x % = storage and security charges per annum,

$(DC)_x$ = depreciation during the x^{th} year (dollars),

x = the year being considered $(1 \leq x \leq N)$,

and z = any integer between 1 and x $(1 \leq z \leq x)$.

Since the annual ownership cost is equal to the sum of the costs due to depreciation, interest, property taxes and licenses, insurance, and storage and security, the rate of total ownership cost per operating hour during the x^{th} year, $(E_{own})_x$, in dollars per hour, can be written as

$$(E_{own})_x = \frac{\left[(DC)_x + (IC)_x\right]}{y}, \tag{6.3}$$

where $(DC)_x$ = depreciation cost during the x^{th} year (dollars),

$(IC)_x$ = investment cost during the x^{th} year (dollars),

and y = the number of hours the machine is anticipated to operate during the x^{th} year, and $(1 \leq x \leq N)$.

6.3.2 Operating cost when owning equipment

Equipment operating costs are the expenses that are affiliated with the utilization of the equipment. Generally, operating costs are the outlay due to

(a) fuel or power consumption,

(b) service of the machine,

(c) major maintenance and repairs of the machine,

(d) tire replacement and repairs (if applicable),

and (e) operator's wages including fringe benefits [4,6].

The above five items are considered in the system in finding the total operating cost. The mathematical approach to obtain each of those cost factors is explained below.

6.3.2.1 Fuel or power consumption cost

The hourly fuel consumption cost is obtained by multiplying the fuel consumption rate of the prime mover of the equipment, by the cost of each liter of fuel being used. But, for belt conveyers, the prime mover can be an internal combustion engine or an electric motor. If a belt conveyer is powered by an electric motor, the power consumption cost can be obtained by multiplying the power of the motor in kW, by the electric tariff charge of the area, in dollars/kilo-Watt-hour. Whichever the power source is, the fuel or the power consumption rate varies with the load and operating conditions of the equipment, and also on the operator. However, owing to its complexity, the variation of fuel consumption due to the operator is not considered in the system. To obtain the fuel consumption rate under the expected operating conditions, the average fuel consumption rate of the equipment has to be multiplied by a load factor, K_l, to compensate for it. The average fuel consumption rates of all the machines except belt conveyers and loading machines are stored in the data base [4,9,17,36,41].

The load factor is different for internal combustion engines and electric motors. Also, the load factor of an internal combustion engine varies with the type of equipment. However, in the developed system these variations have been disregarded as their effect on the overall cost is insignificant. The load factors for different operating conditions, listed in Table D.2 of Appendix D represent the average K_l values, were obtained by scrutinizing the fuel consumption tables and load factor guides of various manufacturers [4,17,33,36, 41].

Although, the most accurate method of determining the power or fuel consumption rate is the actual measurement under similar job conditions, the following method is used in the system, for estimation purposes.

$$(FC) = K_l\, F_c\, C_f\,, \tag{6.4}$$

where FC = fuel or power consumption cost (dollars/hr),

K_l = load factor,

F_c = average fuel consumption (liters/hr), or power consumption (kW),

and C_f = cost of fuel (dollars/liter) or electricity tariff charge (dollars/kWh).

6.3.2.2 Service cost

Labour and material required for routine maintenance, hydraulic fluid, lubricants, and filters are commonly treated as equipment service cost. This cost depends on the operating conditions and the operator. However, as the fuel consumption cost is also dependent upon the operating conditions and the operator, it is possible to relate the service cost as a percentage of the fuel consumption cost [32]. Therefore, assuming average conditions, the hourly service cost (SC) can be obtained using the following expression [26,30] :

$$(\mathrm{SC}) = \frac{1}{3}\,(\mathrm{FC})\,. \tag{6.5}$$

6.3.2.3 Major maintenance and repairs cost

The major maintenance and repairs cost is normally the largest single item of the operating cost which includes all the direct costs related to the activity. Minor repairs cost normally follows an upward stair-step pattern since major outlays for repairs usually come in spurts [4]. Although, these maintenance and repairs costs may occur years apart, they should be charged by hours of operation.

The major repairs cost component of the operating cost of equipment tends to rise over the life of the machine. In estimating the major repairs cost, actual cost experience on similar work provides the best basis for establishing the hourly repairs cost. However, when local records are inadequate or not available, the following method may be used as an alternative [26,32,36]. The cost of tires (if applicable), is deducted from the total expenses, and the tire repairs cost is separately assessed. However, like in the depreciation calculations, the cost of tracks of track type machines is included in the calculations [32].

$$(RC)_x = \frac{1}{y} \cdot \left\{ \frac{x \left[K_2 (P_o + P_d - P_t - P_s) \right]}{\sum_{z=1}^{z=N} z} \right\} , \tag{6.6}$$

where $(RC)_x$ = repairs cost per hour during the x^{th} year,

and K_2 = repair factor which depends upon the type of machine and the operating conditions.

All the other variables have the same meaning as given in Section 6.3.1.1.

The average K_2 values for different operating conditions obtained from manufacturers' handbooks and various publications [4,8,30,32,33,36] are given in Table D.2 of Appendix D.

6.3.2.4 Tire replacement and repairs cost

Estimation of the tire replacement and repairs cost is difficult owing to the inability to accurately estimate the tire life. The tire replacement cost can be found using the following formula [30] :

$$\text{hourly tire replacement cost} = \frac{\text{cost of a new set of tires}}{\text{estimated tire life in hours}} . \tag{6.7}$$

In the above formula the useful life span of a set of rubber tires is affected by many factors. The tire industry has made numerous surveys on tire performance and has arrived at a system which gives rough estimates of tire life. By scrutinizing a number of tire life estimation methods, the following simple method is used in the cost model of the system [4].

$$\text{tire life (hrs)} = 3000\, K_3 , \tag{6.8}$$

where K_3 is the tire life factor which depends on the operating conditions of tires.

Though the value of K_3 depends on the type of machine as well, for simplicity this has been neglected. The values of K_3 for various operating conditions [4] are given in Table D.3 of Appendix D.

Tire repairs cost may be estimated as a percentage of the tire replacement cost. In the cost model, the tire repairs cost is taken as 15% of the tire replacement cost [26,30,32]. Therefore, the tire replacement and repairs cost, (TC), in dollars per operating hour, of the machines having rubber tires, can be written as

$$(\mathrm{TC}) = \frac{1.15\,\mathrm{P_t}}{3000\,\mathrm{K_3}}, \qquad (6.9)$$

where P_t = cost of a new set of tires, if applicable [dollars].

6.3.2.5 Operators' wages

The operators' wages have both a direct and an indirect bearing on the total operaing cost. The direct effect depends on the amount the operator is paid per hour which varies according to the prevailing local wage rates. Though there is an indirect cost involved by the manner in which the operator treats the equipment, it is not considered in the cost model as it is very subjective. In finding the direct expense, the number of operators involved in the operation is important. The operators' wages should include, the costs such as the fringe benefits, workers' compensation insurance, and taxes on wages. Operators' hourly wages including all those cost components is represented by (OC) in the cost model.

By adding all the above cost components, the total operating cost during the

x^{th} year when owning the earthmoving equipment, $[(E_{ope})_o\,]_x$, in dollars per hour, can be written as

$$[(E_{ope})_o]_x = (FC) + (SC) + (RC)_x + (TC) + (OC)\,, \qquad (6.10)$$

where FC = fuel or power consumption cost [dollars/hr],

SC = hourly service cost [dollars/hr],

$(RC)_x$ = repairs cost per hour during the x^{th} year [dollars/hr],

TC = tire replacement and repairs cost [dollars/hr],

and OC = operators' hourly wage including fringe benefits [dollars/hr].

Therefore, from (6.3) and (6.10), the total hourly ownership and operating cost during the x^{th} year is $\{[(E_{own})]_x + [(E_{ope})_o\,]_x\}$

6.4 Costs involved in renting equipment

In the event of renting equipment to employ in an earthworks operation, there are two main categories of costs involved. These two are the rental cost and the operating cost.

6.4.1 Rental cost

The hourly rental rate charge for a given item of equipment can vary from location to location considerably. It also may differ substantially with the time duration for which the equipment is rented. However, it is fairly easy to find the hourly rental charges for various types and sizes of equipment for an earthworks operation in a certain area. In developing the cost model, $(LC)_x$ is taken as the lease or rental charge per hour of an earthmoving equipment during the x^{th} year.

6.4.2 Operating costs when renting equipment

As explained in Section 6.3.2, the operating costs are the expenses that are associated with the utilization of equipment. Though there are a number of cost factors contributing to the operating cost, only a few expenses need to be borne by the contractor when renting earthmoving equipment. Those cost factors are the costs due to

(a) fuel or power consumption,

(b) service of the machine,

(c) major maintenance and repairs of the machine,

(d) tire repairs,

and (e) operators' wages [30].

All the cost factors above, except the cost due to major maintenance and repairs are similar to when owning equipment as explained in Section 6.3.2. Generally, a portion of the major maintenance and repairs costs must be borne by the user who rents the equipment. However, when renting a machine, the user may not be aware of the purchase price, delivery charges, and so forth, which are required to make an estimate of the repairs cost. Therefore, the user is required to suggest a value for the portion of the major maintenance and repairs cost to be borne. When renting equipment, the tire replacement cost is not included in the operating cost, as usually the person who rents the equipment is not responsible for it. Nevertheless, the user is responsible for the tire repairs cost. Therefore, the total hourly operating cost when renting an equipment during the x^{th} year,

$[(E_{ope})_r]_x$, can be expressed as

$$[(E_{ope})_r]_x = \frac{4}{3} F_c C_f + [(RC)_r]_x + \frac{0.15 P_t}{3000 K_3} + (OC), \tag{6.11}$$

where F_c = average fuel consumption [liters/hr], or power consumption [kW],

C_f = cost of fuel [dollars/liter], or electricity tariff charge [dollars/kWh],

$[(RC)_r]_x$ = major repairs cost per hour, to be borne by the user of the equipment during the x^{th} year [dollars/hr],

P_t = cost of a new set of tires, if applicable [dollars],

K_3 = tire life factor,

and OC = operators' hourly wages including fringe benefits [dollars/hr].

Therefore, the total hourly renting and operating cost during the x^{th} year is $\{(LC)_x + [(E_{ope})_r]_x\}$.

6.5 Miscellaneous costs

Besides the ownership and operating, or the rental and operating costs discussed in the previous sections there may be numerous miscellaneous cost factors associated when employing a group of machines for an earthworks operation. Among these miscellaneous costs, the most dominant are

(a) transportation, and mobilization and demobilization cost,

and (b) construction and maintenance costs of haul or access roads.

These two costs are separately discussed below.

6.5.1 Transportation, and mobilization and demobilization costs

It is necessary to transport equipment and the associated appurtenances to the construction site before the execution of an earthworks operation. Once the equipment is transported to the site, there may be some prerequisites necessary to mobilize it such as fixing the necessary attachments and performing the necessary checks. Similarly, once the earthmoving operation is over, money, labour, time, and material have to be spent to demobilize and transport the equipment back to the required location. To carry out all these activities, usually a significant amount of money is required. This expense can be accounted for individual machines as this cost varies with the type and the size of the equipment. In developing the cost model of the system, the transportation, and mobilizing and demobilizing cost of the i^{th} machine in dollars is taken as $(MC)_i$.

6.5.2 Road construction and maintenance cost

The other significant miscellaneous cost considered in the system is the road construction and maintenance cost. To perform an earthworks operation efficiently, it is very important to have a well planned, properly constructed, and adequately maintained haul or access road system. However, the required nature, and condition of a haul or access road can vary depending on the types and sizes of the earthworks machines, and the operation itself. For the usable groups of machines for the earthworks operation, it is possible to prepare estimates for the road construction and maintenance cost. In the cost model, it is assumed that the road construction and maintenance cost for a selected group of machines as (HC), in dollars.

6.6 Development of the cost model

In finding the costs involved with each usable group of machines, initially in Question 20 of Appendix B of the system, the user is asked to provide the ownership and operating cost or the rental and operating cost, and the cost due to transportation, mobilization, and demobilization, $(MC)_i$ of each machine in the group. For the machines which the user has no idea about the ownership and operating or the rental and operating cost, further questions are presented to evaluate those two costs. Also, the anticipated cost due to the haul or access road construction and maintenance cost for the type of machine in the selected group of machines, (HC), of individual machines in the group is obtained from the user (Question 21 of Appendix B). To determine the operating costs of individual machines, Questions 22a to 22f of Appendix B are then presented to the user. These questions are related to the following input parameters :

(a) cost of a new set of tires (P_t), (if applicable),

(b) operating conditions on tires to find the tire life factor (K_3), (if applicable),

(c) operating conditions on fuel or power consumption to find the load factor (K_1),

(d) fuel consumption or power consumption rate (F_c), (only for loading machines and belt conveyers),

(e) cost per liter of fuel or the electrical tariff charge of the construction area (C_f),

and (f) operators' hourly wages including fringe benefits (OC).

In the above factors the values for K_1 and K_3 are retrieved from the data base according to the user's response to the appropriate questions.

Once the required parameters to find the operating costs are known, it is necessary to divide the machines in the group into two sub groups depending on whether they are owned by the user or they are to be rented. In order to gather that information, Question 22g of Appendix B is presented to the user. Depending on the response to this question, the system presents Questions 22h(own) to 22l(own) of Appendix B for those machines the user owns; whereas, for the machines which the user intends to rent, Questions 22h(rent) and 22i(rent) of Appendix B are presented.

In Questions 22h(own) to 22l(own), the following information about the equipment is gathered in the system :

(a) Free On Board (F.O.B) price of the machine at the time of purchase (P_o),

(b) total delivery cost including freight charges and tax at the time of purchase (P_d),

(c) estimated useful lifetime of the equipment at the time of purchase (N),

(d) estimated salvage or resale value after N years, at the time of purchase (P_s),

(e) age of the machine at the time of the earthmoving operation (x),

(f) number of hours the machine is intended to operate during the year of the earthmoving operation (y),

(g) interest, property taxes and licenses, insurance, and storage and security charges as a percentage of the book value of the equipment during the year of execution of the earthmoving operation (p_x, t_x, j_x, s_x),

and (h) operating condition to find the repair factor of the machine (K_2).

The values for K_2 are retrieved from the data base according to the user's answers to the corresponding questions. Questions 22h(rent) and 22i(rent) extract the following information related to the machines, which are intended to be rented :

(a) lease or rental cost of the machine, (LC),

and (b) estimated rate of maintenance cost during the year of the execution of the earthworks operation, $[(RC)_r]_x$.

After all the above information about the individual machines in a group is gathered, it is possible to find the ownership and operating cost or the rental and operating cost of machines using Equations (6.1) to (6.11). Hence, $(E_e)_i$, the rate of expense of the i^{th} machine excluding the miscellaneous costs, is the rate of ownership and operating cost, or the rental and operating cost.

With the use of this cost model, it is possible to find the rates of expense of all the usable machines, required in the final phase of the micro-computer based decision support system where the most economical group of machines is deduced. Once the most economical group is selected, the earthmoving cost of the earthworks operation having several cut and fill areas can be minimized by the use of an operational research model. The development of this operational research model is explained in the next chapter.

CHAPTER 7

OPERATIONAL RESEARCH MODEL TO OPTIMIZE EARTHMOVING COST

7.1 Introduction

Development of feasible methods, and selection of appropriate equipment to accomplish various activities are common tasks at the planning stage of a construction project.

When soil is to be cut from various areas and hauled to numerous destinations for fill and compaction, the earthmoving cost involved in these operations can be minimized by distributing the cut and fill quantities of soil in the most economical combination.

In all earthmoving operations, the required quantities of cut and fill at various locations, the transportation distances between these locations, the properties of soil at the excavation areas, and also the component unit costs for excavation, haul, and fill and compaction are estimated before the execution of work. It is therefore possible to formulate an earthmoving cost optimization problem as an operational research model using the standard transportation algorithm which is generally concerned with the distribution of a certain product from several sources to numerous localities at the minimum cost [31].

In this chapter, the existing practice in allocating the cut and fill quantities, and the formulation of a new operational research model are discussed.

7.2 General practice in allocating cut and fill quantities in earthmoving

Often, the allocation of earthwork volumes between cut and fill areas are carried out on the basis of largest quantity to the nearest place. If these allocations and the cost factors involved in such operations are carefully analyzed, it will often be found that an optimal solution has not been obtained.

Also, when large volumes of soil are to be excavated, transported comparatively long distances to the fill areas, and compacted, the unit costs involved for each activity of all the locations and all the haul and return routes are generally estimated prior to the execution of work. If these unit excavation, haul, and fill and compaction costs are accurate, the overall cost of the earthworks operation can be determined fairly accurately, although imponderable factors, such as the weather, can always influence the significant part in actual cost fluctuations. However, in a fairly typical situation, if a large area of excavation is adjacent to a large area of fill, the haul route distance and the grade can vary quite considerably as time progresses. A change in the values of the unit costs is associated with these variations in haul and return distances and grades. Normally, in this case, overall average values for distance, grade, and unit costs are used in the estimates and this can result in inaccurate cost and production estimates. Thus, the resultant cost of transportation is an accomplished fact today.

An operational research model can be used as a tool to optimize the earthmoving cost by distributing the cut and fill quantities economically. This model can easily and simply accommodate the case when the haul road distance and the slope change significantly with time.

7.3 Formulation of the operational research model

Any earthmoving operation, which has 'm' locations to be excavated and 'n' areas to be filled and compacted can be diagrammatically represented as shown in Figure 7.1. The other values given in the figure are

X_{ij} = the quantity of soil to be excavated from location 'i' in order to fill and compact at destination 'j' [m^3 (in-situ)].

H_{ij} = the quantity of soil hauled from location 'i' to destination 'j' [m^3(loose)].

F_{ij} = the quantity of soil compacted at destination 'j', excavated from location 'i' [m^3(compacted)].

d_{ij} = the distance between location 'i' and destination 'j' (km).

where $i = 1, 2, 3, \ldots, m$ and $j = 1, 2, 3, \ldots, n$.

The volume of loose soil is related to the in-situ volume as [6]

$$V_l = (1 + C_b) V_b \,, \tag{7.1a}$$

where V_l = loose volume [m^3(loose)],

V_b = in-situ volume [m^3(in-situ)],

and C_b = coefficient of bulking.

For simplicity, let

$$(1 + C_b) = K_b \,. \tag{7.1b}$$

Then, for all the types of soil, (7.1b) can be generalized as

$$(1 + C_{bi}) = K_{bi} \,, \quad \text{where } i = 1, 2, 3, \ldots, m. \tag{7.1c}$$

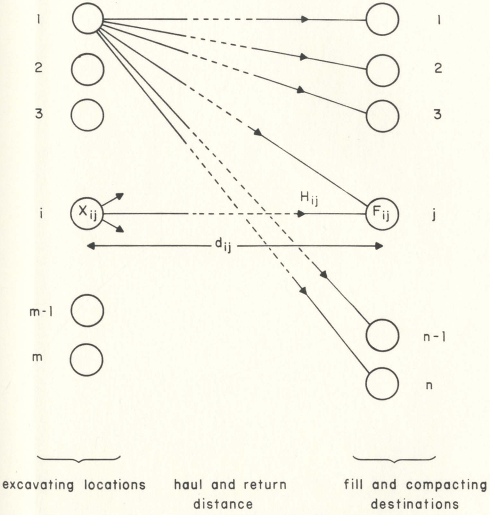

Fig. 7.1 The earthmoving model

Similarly, the volume of compacted soil is related to the in-situ volume as [6]

$$V_c = (1 - C_c) V_b , \tag{7.2a}$$

where V_c = compacted volume [m^3(compacted)],

V_b = in-situ volume [m^3(in-situ)],

and C_c = coefficient of compaction.

For simplicity, let

$$(1 - C_c) = K_c . \tag{7.2b}$$

Then, for all the types of soil, (7.2b) can be generalized as

$$(1 - C_{ci}) = K_{ci} , \quad \text{where } i = 1, 2, 3,....., m. \tag{7.2c}$$

Therefore, using (7.1a) and (7.1c), the quantity of soil hauled from location 'i' to destination 'j' in m^3(loose), H_{ij}, is given by

$$H_{ij} = K_{bi} X_{ij} . \tag{7.3a}$$

Similarly, using (7.2a) and (7.2c), the quantity of soil compacted at location 'j' from location 'i' in m^3(compacted), F_{ij}, is given by

$$F_{ij} = K_{ci} X_{ij} . \tag{7.3b}$$

Since the cost of the earthmoving operation depends upon the excavation cost, the hauling cost, and the fill and compaction cost, these three costs are considered separately.

If the component unit cost for excavation at location 'i' is C_{ei} in dollars/m^3(in-situ), where i = 1, 2, 3,....., m, then the total excavation cost (EC) can be expressed as

$$EC = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ei} X_{ij} \,. \tag{7.4}$$

If the component unit cost per unit distance hauled from location 'i' to destination 'j' is C_{tij} in dollars/km m^3(loose), where $i = 1, 2, 3,\ldots\ldots, m$, the total transportation cost (TC) can be written as

$$TC = \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} K_{bi} d_{ij} C_{tij} \,. \tag{7.5}$$

If the component unit cost for filling and compaction at destination 'j' is C_{fj} in dollars/m^3(compacted), where $j = 1, 2, 3,\ldots\ldots, n$, the total filling and compaction cost (FC) is

$$FC = \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} K_{ci} C_{fj} \,. \tag{7.6}$$

Therefore, from (7.4), (7.5), and (7.6), the total earthmoving cost (TEC) is given by

$$(TEC) = (EC) + (TC) + (FC) \tag{7.7a}$$

$$= \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} \left[C_{ei} + K_{bi} d_{ij} C_{tij} + K_{ci} C_{fj} \right] \tag{7.7b}$$

$$= \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} C_{ij} \tag{7.7c}$$

where the total component unit cost C_{ij} is

$$C_{ij} = C_{ei} + K_{bi} d_{ij} C_{tij} + K_{ci} C_{fj} \,, \tag{7.7d}$$

where $i = 1, 2, 3, \ldots, m$ and $j = 1, 2, 3, \ldots, n$.

If a_i is the maximum quantity that can be excavated at location 'i' in m^3(in-situ), and b_j is the maximum quantity that can be compacted at destination 'j' in m^3(compacted), a_i and b_j can be expressed as

$$a_i \geq \sum_{j=1}^{n} X_{ij} \tag{7.8a}$$

(excavation restriction at location 'i') for $i = 1, 2, 3, \ldots, m$

$$\text{and} \quad b_j \leq \sum_{i=1}^{m} X_{ij} K_{ci} \tag{7.8b}$$

(compaction requirement at destination 'j') for $j = 1, 2, 3, \ldots, n$

$$\text{and also} \quad X_{ij} \geq 0 \tag{7.8c}$$

(non-negative restriction) for $i = 1, 2, 3, \ldots, m$ and $j = 1, 2, 3, \ldots, n$.

The total compacted volume requirement can be met only if the total excavated quantities are at least equal to the total required at the fill areas. That is if

$$\sum_{i=1}^{m} a_i \geq \sum_{j=1}^{n} b'_j, \tag{7.9}$$

where b'_j is the equivalent quantity of b_j in m^3(in -situ). In this case, (7.7c), (7.8a), (7.8b), and (7.8c) form a typical transportation model and the X_{ij} values which minimize the total earthmoving cost (TEC) given by the objective function shown in (7.7c) can be evaluated using the standard transportation algorithm.

There is generally, however, an imbalance between the cut and fill quantities; either when the total fill requirement exceeds the total excavated volume, or when the total excavated volume exceeds the total requirement at the fill areas.

The problem then becomes non-standard. Any non-standard problem, where the supplies and the demands do not balance, must be converted to a standard transportation problem before it is solved [31]. In this conversion, a dummy excavation location or a dummy fill and compacting destination is created to absorb the excess fill or excavated quantities. In practical problems these dummy excavating locations or dummy fill destinations would be either a borrow pit to import the deficient suitable fill volumes or a disposal area to cart away the surplus quantities. Excavated material transported to a stock-pile for temporary storage, such as top soil, can be considered separately.

At a particular excavation site, one type of machine may be suitable for excavation to one destination, whereas at the same excavation site, another type of machine may be required for soil destined to another fill site. For example, part of the excavation may require teams of loaders and trucks but another part may require a group of scrapers. This would create different unit excavation cost at the same excavation site. This situation can be overcome by multiplying the unit transportation cost by a factor which would subsume the difference in the unit excavation costs. The same simple process can also be applied to the unit fill and compaction costs.

Furthermore, if the transportation of soil between any two locations is not physically feasible, the situation can be accounted for in the transportation algorithm by assigning an unreasonably high unit transportation cost C_{tij} between the two locations.

When large volumes are present in the cut and fill areas, as shown in Figure 7.2, it may be necessary to divide the total cut area and the total fill area into a number of volumes, X'_{i1}, X'_{i2}, X'_{i3}, F'_{j1}, F'_{j2}, F'_{j3}, and F'_{j4}, in order to improve the accuracy. These volumes can then be considered as separate cut areas and separate fill areas in the transportation model but the transportation of any one cut area to a particular fill area may not be feasible. For the physically possible cut and fill combinations, the cut volumes and the fill volumes are equivalent in the same units of measurements. The distances between these cut and fill areas are represented by d'_{11}, d'_{22}, and d'_{33}. The large cut and fill areas which are close to each other, shown in Figure 7.2 are considered as i^{th} cut and j^{th} fill areas in the earthmoving model represented in Figure 7.1. Let X'_i be the total quantity of material to be excavated at location 'i' in m^3(in-situ), and F'_j be the total quantity of material to be filled and compacted at destination 'j' in m^3(compacted). If X'_i and F'_j volumes are divided into 'p' excavating volumes and 'q' fill volumes. When $p > q$, the remaining (p-q) excavating locations can be considered as a single excavating location in the transportation model. Similarly, when $p < q$, the remaining (q-p) fill and compacting locations can be considered as a single fill and compacting destination. To what extent the volume should be divided can easily be estimated by conducting sensitivity analyses on some trial volumes.

Therefore, with the use of the introduced operational research model, the cost of an earthmoving operation can be minimized by obtaining the optimum distribution of cut and fill quantities.

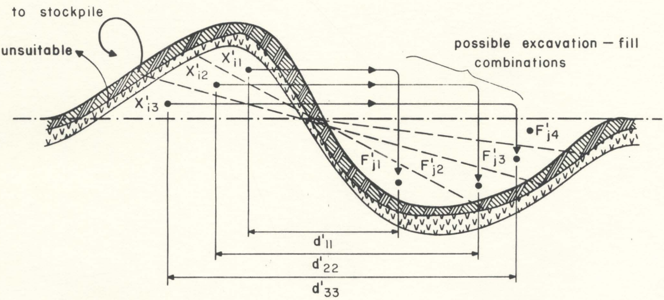

Fig. 7.2 Division of large excavation and fill volumes

CHAPTER 8

CONCLUSIONS AND DISCUSSION

The micro-computer based decision support system described in this thesis can be used as a tool in selecting the most economical group of machines from the available fleet, for an earthworks operation, by any user who has a little knowledge in earthmoving equipment and computer programming. Even an expert can benefit from the system as it could be used as a datum in obtaining a quick selection of earthmoving equipment when time is an important factor, such as during the bidding process.

The system can also be used for production and cost estimation purposes of different types and sizes of earthmoving equipment given in the system. Furthermore, the ability to perform sensitivity analyses, by changing the parametric inputs or the answers to the questions contained, is a major advantage of this system. Sensitivity analysis or post-optimality analysis creates a simple diagnostic capability, and identifies the most productive and economic alternatives.

In deciding the suitable types of equipment from the available machines for earthworks operations, the capabilities and the limitations of individual machines have been considered. However, for example, when traction problems arise due to poor ground conditions, the assistance of a pusher tractor, for loading, is a common practice. Therefore, the inclusion of such possible external assistances in enhancing the capabilities of machines would further improve the system.

In finding the production rates of various types and models, only the production rates with the standard or the most versatile attachments have been evaluated. However, the production rates can vary with the type of the tractor blade, the loader bucket, or the type of attachment. Therefore, the system may be improved by incorporating the evaluation of production rates with different attachments as well.

Some of the earthmoving machines considered in the system needed a separate loading machine to load them. In such situations, the production rates of those loading machines had to be provided by the user. However, it would also be possible to improve the system in the future by developing and incorporating a separate system which finds the production rates, cycle times, and unloading times of loading machines.

The operational research model technique used in this thesis has been developed using the transportation algorithm. This technique is simple and can be used as an effective tool in finding the optimum quantities and the distribution of soil of an earthworks operation. The use of this operational research model minimizes the total cost of the earthworks operation with little effort and time.

Therefore, it is possible to make substantial cost savings in earthmoving projects by using the proposed micro-computer based decision support system and the operational research model during the planning and scheduling stage of a construction project.

It is well known that the earthmoving project environment considered, when deciding the most economical group of machines and distribution of cut and fill quantities, at the planning stage, does not remain static during its implementation. Therefore, the accuracy of the predicted cost per unit volume of material, production rates, and the expected earthmoving durations given by the micro-computer based decision support system, and the optimum total earthmoving cost estimated using the operational research model may be limited by the dynamic nature of the input data. Moreover, it is also important to recognize the limitations of the mathematical approximations used and the logical conclusions made in the system. But, inasmuch as these limiting factors and the input parameters would affect each group of machines in a like manner, the selection of the most economical group, which is based on a comparison, can be substantially valid and reliable.

Thus, the developed micro-computer based decision support system (EQUIP-SELECT), and the operational research model are useful additions to the repertoire of existing project planning tools.

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APPENDIX A

HOW TO USE 'EQUIPSELECT'

'EQUIPSELECT' is an easy to use computer program, which selects the most economical group of machines from the available fleet, for an earthworks operation. The fleet of machines in 'EQUIPSELECT' consists of ten types of earthmoving machines containing eighty models, from five different manufacturers. Also, 'EQUIPSELECT' has the provision to include ten models of belt conveyers as well. These types, and the models with manufacturers are given in Table A.1.

'EQUIPSELECT' can be run on an IBM (or compatible) micro-computer with at least 256 kilo-bytes of RAM, under DOS 2.0 or a higher version.

Information required prior to the use of 'EQUIPSELECT'

(i) Number of sectors of the haul and the return routes, which could be slippery or difficult to climb, and their corresponding Grade Resistance Factors (GRF) and soil types.

(ii) Weight and height limitations applicable to the site and to the haul and return routes.

(iii) Type of material to be handled. If the type of material is not compatible with the types of material given in the program, it is required to know the density, the bucket fill factor, and the coefficient of bulking of the material.

(iv) Number of sectors of the haul and return routes, which have different soil types and grade resistance factors, and their respective distances, GRFs, and soil types.

(v) Available models of belt conveyers, and their production rates, or their belt widths and the speeds of travel of belts.

(vi) Available types of loading machines, their production rates, and heaped capacities.

(vii) Anticipated number of actual working minutes per hour, or an idea about the working conditions, equipment conditions, management conditions, and the operators' skill and experience.

(viii) Total quantity of material to be handled.

(ix) Duration allotted for the earthmoving activity and the number of working hours per working day.

(x) Availability of machines, and physical feasibility to operate the number of each model of each machine within the working area.

(xi) Miscellaneous costs involved to transport, mobilize, and demobilize each machine.

(xii) Estimated cost, to construct and maintain the haul and access roads for each type of machine.

(xiii) The rate of expense, or the following factors of each machine :

(a) cost of a new set of tires (if applicable),

(b) fuel consumption rate or power consumption rate (required only for belt conveyers and loading machines),

(c) operator's wages including all the fringe benefits,

and in the event of renting the machine,

(d) hourly rental charge

and (e) anticipated repairs cost per hour.

in the event of owning the machine

(d) F.O.B. price and delivery cost including the tax,

(e) estimated ownership period and estimated salvage/resale value,

(f) age and the number of hours, the machine is to operate during the year,

and (g) annual interest, tax, insurance, and storage rates as a percentage of the book value.

Execution of 'EQUIPSELECT'

(i) Insert the DOS diskette in Drive A and switch on the computer.

(ii) Press return key for the current date and the current time.

(iii) Press caps lock key to use upper case letters.

(iv) When prompt '>' appears, insert the diskette with 'Basic' command.

(v) Type BASICA.

(vi) Replace the diskette in Drive A with 'EQUIPSELECT' diskette.

(vii) Type LOAD "EQUIPSELECT".

(viii) Type RUN.

(ix) Answer the questions as explained in the program using upper case letters.

(x) Type N to the questions similar to "Are you ready to proceed? <Y/N> ", if desired to change the input parameters of the previous question. However, this facility is not provided in all the steps.

(xi) If the required rate of production is higher than the maximum rate of production that can be achieved by combining the available machines in the fleet, none of the machines may form a suitable group of machines for the earthworks operation. Therefore, in such situations, it is suggested to re-run the program considering the earthworks operation as two or more smaller operations.

Table A.1 Equipment types and models with manufacturers, considered in the system

CAT - Caterpillar JDE - John Deere KOM - Komatsu
DRE - Dresser VOL - Volvo

Type of equipment	Model		
Track type tractors	CAT-D3B,	CAT-D4E,	CAT-D4H,
	CAT-D5B,	CAT-D5H,	CAT-D6D,
	CAT-D6H,	CAT-D7G,	CAT-D7H,
	CAT-D8L,	CAT-D9L,	CAT-D11N,
	JDE-350D/6305,	JDE-450E/6405,	JDE-450E/6415,
	JDE-550B/6415,	KOM-D41A-3,	KOM-D53A-17,
	KOM-D85A-18,	KOM-D355A-3,	KOM-D455A-1.

continued.

Type of equipment	Model		
Wheel type tractors	CAT-814B,	CAT-824C,	CAT-834B.
Track type loaders	CAT-931B,	CAT-943,	CAT-953,
	CAT-963,	CAT-973,	KOM-D20S-5,
	KOM-D41S-3,	KOM-D57S-1,	KOM-D66S-1,
	KOM-D155S-1.		
Wheel type loaders	CAT-910,	CAT-916,	CAT-926,
	CAT-930,	CAT-936,	CAT-950B,
	CAT-966C,	CAT-966D,	CAT-980C,
	CAT-988B,	CAT-992C,	DRE-510B,
	DRE-530,	DRE-540.	
Standard scrapers	CAT-621E,	CAT-631E,	CAT-651E,
	KOM-WS16S-2,	KOM-WS23S-1.	
Tandem powered scrapers	CAT-627E,	CAT-637E,	CAT-657E,
	KOM-WS16-2,	KOM-WS23-1.	
Elevating scrapers	CAT-613C,	CAT-615,	CAT-623E,
	JDE-762B,	JDE-862B.	
Push-pull scrapers	CAT-627E/PP,	CAT-637E/PP,	CAT-657E/PP,
	KOM-WS16-2/PP,	KOM-WS23-1/PP.	
Trucks (standard)	CAT-769C,	CAT-773B,	CAT-777B,
	CAT-785,	CAT-789,	VOL-425C,
	VOL-540,	VOL-555,	VOL-565.
Trucks (four-wheel-drive)	VOL-5350B,	VOL-A20 6*6,	VOL-A20 6*4.
Belt conveyers	program has provision	to input ten models.	

APPENDIX B

Appendix B consists of the questions in 'EQUIPSELECT', the input parameters relevant to the fictitious earthmoving problem, and the outputs obtained using the 'EQUIPSELECT'. The inputs are represented in **bold face**, and the outputs are represented in *italics*.

.... Welcome to EQUIPSELECT ....

Menu on earthmoving equipment

1. *Track type tractors*
2. *Wheel type tractors*
3. *Track type loaders*
4. *Wheel type loaders*
5. *Standard scrapers*
6. *Tandem powered scrapers*
7. *Elevating scrapers*
8. *Push-pull scrapers*
9. *Trucks (standard)*
10. *Trucks (four-wheel-drive)*
11. *Belt conveyers*

Now, you are going to select the suitable types of equipment considering the haul distance.

QUESTION 1

What is the intended average haul distance?

Please enter your choice by typing the appropriate number.

1. less than or equal to 100 meters.
2. between 100 and 200 meters.
3. between 200 and 2000 meters.
4. more than 2000 meters.

Please type your choice (1-4)! **1**

The suitable types of equipment are

1. *Track type tractors*
2. *Wheel type tractors*
3. *Track type loaders*
4. *Wheel type loaders*
5. *Standard scrapers*
6. *Tandem powered scrapers*
7. *Elevating scrapers*
8. *Push-pull scrapers*
9. *Trucks (standard)*
10. *Trucks (four-wheel-drive)*
11. *Belt conveyers*

Now, you are going to select the suitable types of equipment from the above set, for the on-off highway requirement.

Are you ready? <Y/N> **Y**

QUESTION 2

Do you intend to transport material on or across a highway?

Please enter your answer by typing the appropriate number.

1. yes.
2. no.

Please enter your answer (1-2)! **2**

The suitable types of equipment are

1. *Track type tractors*
2. *Wheel type tractors*
3. *Track type loaders*
4. *Wheel type loaders*
5. *Standard scrapers*
6. *Tandem powered scrapers*
7. *Elevating scrapers*
8. *Push-pull scrapers*
9. *Trucks (standard)*
10. *Trucks (four-wheel-drive)*
11. *Belt conveyers*

In the next step, you are going to select the suitable types of equipment from the above set depending on the type of operation.

Are you ready to proceed? <Y/N> **Y**

QUESTION 3

How would you describe the type of operation from the following set?

1. clearing of land of timber or stumps.
2. clearing of construction sites or debris, or clearing of floors of borrow or quarry pits.
3. excavating from slope or excavating from wide cutting, and hauling.
4. clearing of stock pile or handling of bulk material.
5. clearing of snow.
6. opening up pilot roads through mountains and rocky terrain.
7. maintaining of haul roads.
8. back filling of trenches.
9. spreading of earth fill.
10. final spreading
11. excavating from vertical face or cutting with wide slopes (Vee shaped ditches), and hauling.
12. scraping and spreading or dumping.
13. shallow cutting or cutting trenches, and hauling.

Out of the above earthworks operations, how many of them are similar to yours?

2

Please enter the operations by selecting the appropriate numbers.

1 **2**

2 **4**

The suitable types of equipment are

1. Track type tractors *7. Elevating scrapers*

2. Wheel type tractors *8. Push-pull scrapers*

3. Track type loaders *9. Trucks (standard)*

4. *Wheel type loaders*
5. *Standard scrapers*
6. *Tandem powered scrapers*
10. *Trucks (four-wheel-drive)*

Are you ready to proceed? <Y/N> **Y**

Now, you are going to check the traction ability and the gradability of the above set of equipment depending on the soil type and the grade resistance.

QUESTION 4a

Do you intend to operate the machines in a high altitude?

Please enter your choice <Y/N> **Y**

QUESTION 4b

What is the altitude of the working area?

Please enter your choice by typing the appropriate number.

1. no idea or less than 2300 meters.
2. between 2300 and 3000 meters.
3. between 3000 and 3800 meters.
4. greater than 3800 meters.

Please type your choice (1-4)! **2**

QUESTION 5a

As far as traction ability and gradability are concerned, how many sections of the haul and return routes would be slippery or difficult to climb?

The number of section are = **2**

Are you ready to proceed? <Y/N> **Y**

In deciding the soil type of each sector, please use the corresponding numbers given below.

The soil types :

1. very hard or concrete
2. hard or well compacted gravel
3. dry clay or gravel
4. wet clay or loose earth
5. dry sand
6. wet sand or loose gravel
7. snow.

QUESTION 5b

Please enter the grade as a percentage and the number corresponding to the soil type of each section in the following table.

Section	Grade (indicate - sign if downhill)	Soil type number
1	**10**	**3**
2	**-5**	**4**

The suitable types of equipment are

1. *Track type tractors*
2. *Wheel type tractors*
3. *Track type loaders*
4. *Wheel type loaders*
5. *Standard scrapers*
6. *Tandem powered scrapers*
7. *Elevating scrapers*
8. *Push-pull scrapers*
9. *Trucks (standard)*
10. *Trucks (four-wheel-drive)*

Now, you are going to consider the constraints and the options that may be applicable to the earthworks operation.

Are you ready to proceed? <Y/N> **Y**

The suitable types of equipment are

1. Track type tractors
2. Wheel type tractors
3. Track type loaders
4. Wheel type loaders
5. Standard scrapers
6. Tandem powered scrapers
7. Elevating scrapers
8. Push pull scrapers
9. Trucks (standard)
10. Trucks (four-wheel- drive)

QUESTION 6a

If you feel that some of the above types of equipment are not suitable for the earthworks operation due to any reason, please indicate how many of them are not suitable.

If there are no such constraints on the type of equipment, please type '0'.

Please type how many of them are not suitable. **6**

Now, please enter the number(s) corresponding to the unsuitable type(s) of equipment (1-11)!

	Number(s) corresponding to unsuitable type(s)
1	**1**
2	**3**
3	**5**
4	**6**
5	**8**
6	**9**

The suitable types of equipment are	Menu on the earthmoving equipment
	1. Track type tractors
2. Wheel type tractors	2. Wheel type tractors
	3. Track type loaders
4. Wheel type loaders	4. Wheel type loaders
	5. Standard scrapers
	6. Tandem powered scrapers
7. Elevating scrapers	7. Elevating scrapers
	8. Push pull scrapers
	9. Trucks (standard)
10. Trucks (four-wheel drive)	10. Trucks (four-wheel drive)
	11. Belt conveyers

QUESTION 6b

If you believe that some of the equipment types in the main menu could be used, in addition to the selected types of equipment for the earthworks operation, by fixing special attachments or by changing the operating conditions. Please indicate how many of them could be used.

If there are no such types of equipment, please enter '0'.

Please type how many of them could be used. **1**

Now, please enter the number(s) corresponding to suitable type(s) of equipment (1-11)!

	Number(s) corresponding to suitable type(s)
1	**11**

The suitable types of equipment are

2. *Wheel type tractors*
4. *Wheel type loaders*
7. *Elevating scrapers*
10. *Trucks (four-wheel-drive)*
11. *Belt conveyers*

The next part of the program finds the production rates of the following models and sizes of the above machines.

Models of wheel type tractors
CAT - Caterpillar

CAT-814B, CAT-824C, CAT-834B

Models of wheel type loaders
CAT - Caterpillar   DRE - Dresser

CAT-910, CAT-916, CAT-926, CAT-930, CAT-936, CAT-950B, CAT-966C, CAT-966D, CAT-980C, CAT-988B, CAT-992C, DRE-510B, DRE-530, DRE-540.

Models of elevating scrapers
CAT - Caterpillar   JDE - John Deere

CAT-613C, CAT-615, CAT-623E,   JDE-762B, JDE-862B

Models of trucks (four-wheel-drive)

VOL - Volvo

---

*VOL-5350B, VOL-A20 6*6, VOL-A20 6*4.*

Now you are going to check the weight and height constraints applicable to the site and to the haul roads.

Are you ready to continue with the program? <Y/N> **Y**

QUESTION 7

What is the equipment weight limitation on the site or of the haul road? Please enter the value in kg. If not applicable, please type '0'.

100000

QUESTION 8

What is the equipment height limitation on the site? Please enter the value in meters. If not applicable, please type '0'.

0

QUESTION 9

What is the equipment height limitation of the haul or return routes? Please enter the value in meters. If not applicable, please type '0'.

4.75

Are you ready to proceed? <Y/N> **Y**

QUESTION 10a

How do you describe the type of material to be handled?

Please enter your choice by typing the appropriate number.

1. decomposed rock - poorly blasted.
2. decomposed rock - well blasted.
3. crushed stone or gravel.
4. dry clay.
5. wet clay.
6. dry sand.
7. wet sand.
8. gravel sand, silt, clay mixture.
9. snow.
10. any other material.

Enter your choice (1-10)! **10**

QUESTION 10b

Please enter the density, the bucket fill factor, and the coefficient of bulking of the material to be handled.

density [kg/m^3(loose)] = **1000**

bucket fill factor = **0.7**

coefficient of bulking = **0.15**

QUESTION 11

How do you describe the type of the stock pile or the hardness of the material to be excavated?

Please enter your choice by typing the appropriate number.

1. loose stock pile.
2. hard to cut or frozen.
3. dry non-cohesive or sticky.
4. ripped or blasted rock.

Please enter your choice (1-4)! **3**

In the following section of the program, you will be asked to provide the distances, the corresponding grade resistances, and the soil types of the haul and return routes separately.

Therefore, now you need to break the haul and return distances into a number of sectors according to their soil types and the grade resistance factors.

The number of sectors in the haul route are = **2**

The number of sectors in the return route are = **1**

In deciding the soil type of each sector, please use the corresponding numbers given below.

The soil types :

1. very hard or concrete
2. hard or well compacted gravel
3. dry clay or gravel
4. wet clay or loose earth
5. dry sand
6. wet sand or loose gravel
7. snow.

QUESTION 12

Please enter the distance in meters, the grade resistance factor (GRF) as a percentage, and the number corresponding to the soil type of each section of the haul and return routes separately.

	Section	Distance (meters)	GRF (indicate - sign if downhill)	Soil type number
haul	1	**75**	**0**	**2**
	2	**25**	**12**	**3**
return	1	**105**	**-5**	**4**

Now we need the available sizes of belt conveyers and their production rates.

Are you ready to proceed? <Y/N> **Y**

QUESTION 13a

Do you know the production rates of the available sizes of belt conveyers?

Please type your choice <Y/N> **N**

QUESTION 13b

Please enter the number of models of belt conveyers available in your fleet.

2

Now, please enter the names of the available models or the sizes of belt conveyers, widths of the belts in meters, and the speeds of travel of belts in meters/min.

Model or the size	Width (m)	Speed of travel (m/min)
belt 1	**0.75**	**40**
belt 2	**0.75**	**105**

QUESTION 14

What are the types of loading machines available in your fleet?

Please enter your choice by typing 'Y' or 'N' in front of each machine in the following menu. Please enter the number of models available of each type also in the given space.

Type of loading machine	<Y/N>	Number of models
front end loaders	**Y**	**2**
hydraulic backhoes or face shovels	**N**	
cable operated power shovels	**N**	
draglines	**N**	
any other type of machine	**Y**	**1**

Now, we are needed to find the types of other available loading machines, the available models of those types, and their production rates in m^3 (in-situ)/hr.

If belt conveyers are available among the other loading machines, please type 'BELT' in the space given for type of machine. If you do not know the production rates of the available belt conveyers, please type '0' in the space given for production rate.

Type of the machine	Name of the model	Production rate m^3(in-situ)/hr
BELT	**BC 1**	**550**

Now, please type the names of the models of front end loaders and their respective heaped capacities in m^3 in the following table.

Name of the model	Heaped capacity m^3
FEL 1	**3.1**
FEL 2	**6.2**

The following section considered the overall job efficiency of the earthworks operation.

QUESTION 15a

Do you have any idea about the anticipated number of actual working minutes per hour of the operation? <Y/N> **N**

QUESTION 15b

Do you intend to perform the earthmoving operation under any of the following conditions?

Dusty, rainy, snowy or foggy environment, or during dark or night working hours <Y/N> **N**

QUESTION 15c

How would you rate the following factors of your earthworks operation?

In deciding the ratings, please use the corresponding numbers given below.

1. excellent 2. average 3. poor.

Please enter your rating (1-3), in the appropriate place of the following chart!

Influencing factor on job efficiency	Number corresponding to the rating
machine operators' skill, experience, and working attitude	**2**
equipment condition considering the age of the equipment and the maintenance records, and the working space	**1**
management condition considering the degree of supervision, motivation, etc.	**3**

According to the input parameters given by you, following are the actual production rates of the machines.

Type	*Model*	*Actual production rate* m^3*(loose)/hr*
Wheel type tractors	*CAT-814B*	*241.8576*
	CAT-824C	*386.9723*
CAT - Caterpillar	*CAT-834B*	*532.0869*
Wheel type loaders	*CAT-910*	*23.7351*
	CAT-916	*35.4857*
CAT - Caterpillar	*CAT-926*	*44.3571*
DRE - Dresser	*CAT-930*	*39.1127*
	CAT-936	*63.1821*
	CAT-950B	*83.3909*
	CAT-966C	*78.6430*
	CAT-966D	*108.0330*
	CAT-980C	*137.9941*
	CAT-988B	*184.3768*
	DRE-510B	*32.8395*
	DRE-530	*60.8136*
	DRE-540	*103.2320*

Type	*Model*	*Actual production rate* m^3*(loose)/hr*
Elevating scrapers	*CAT-613C*	*110.6048*
	CAT-615	*167.7391*
CAT - Caterpillar	*CAT-623E*	*239.4470*
JDE - John Deere	*JDE-762B*	*120.2925*
	JDE-862B	*171.0279*
Belt conveyers	*belt 1*	*101.2500*
	belt 2	*265.7813*

Trucks (four-wheel-drive)

VOL - Volvo

Model	*Actual production rate* m^3*(loose)/hr*	*Cycle time min*	*Loading time min*
VOL-5350B + FEL 1	*79.9263*	*5.0121*	*2.0000*
VOL-5350B + FEL 2	*96.0999*	*4.0121*	*1.0000*
VOL-5350B + BC 1	*101.2258*	*3.8089*	*0.7968*
*VOL-A20 6*6 + FEL 1*	*70.5157*	*5.0121*	*2.0000*
*VOL-A20 6*6 + FEL 2*	*88.0916*	*4.0121*	*1.0000*
*VOL-A20 6*6 + BC 1*	*94.4367*	*3.7425*	*0.7304*
*VOL-A20 6*4 + FEL 1*	*78.8466*	*4.9367*	*2.0000*
*VOL-A20 6*4 + FEL 2*	*93.8591*	*3.9367*	*1.0000*
*VOL-A20 6*4 + BC 1*	*99.8545*	*3.7003*	*0.7636*

Loading machine type	*Model*	*Actual production rate* m^3*(loose)/hr*
Front end loaders	*FEL 1* *FEL 2*	*205.6320* *417.6900*
Belt	*BC 1*	*483.8625*

QUESTION 16

What is the total quantity of material to be handled in this earthworks operation in m^3(loose)?

600000

QUESTION 17

As per the project schedule, what is the duration allotted to this earthmoving activity in working days?

132

QUESTION 18

Due to the seasonal variations, to allow for the maximum usage of daylight, it may be required to divide the time span of the earthworks operation into a number of time intervals depending on the number of working hours per day.

Please indicate the number of such intervals in the time span of the earthworks operation.

3

Please indicate the number of working hours per day during each time interval, and the corresponding durations in working days in the following table in chronological order.

Time interval number	Working hours per day	Intended number of working days
1	**6**	**43**
2	**10**	**43**
3	**8**	**129**

QUESTION 19

Please enter the maximum number of earthmoving machines available and the maximum number of machines which are possible to operate on the site, of each model.

Please limit the maximum number to 10.

Type of machine	Model	Availability (numbers)	Feasibility (numbers)
Wheel type tractors	CAT-814B	2	10
	CAT-824C	10	2
	CAT-834B	0	10
Wheel type loaders	CAT-910	8	10
	CAT-916	0	10
	CAT-926	0	10
	CAT-930	0	10
	CAT-936	0	10
	CAT-950B	2	10
	CAT-966C	0	10
	CAT-966D	0	10
	CAT-980C	0	10
	CAT-988B	0	10
	DRE-510B	0	10
	DRE-530	8	9
	DRE-540	7	10
Elevating scrapers	CAT-613C	6	10
	CAT-615	6	10
	CAT-623E	0	10
	JDE-762B	3	10
	JDE-862B	0	10
Trucks (four-wheel-drive)	VOL-5350B	10	10
	VOL-A20 6*6	4	10
	VOL-A20 6*4	0	10
Belt conveyers	belt 1	3	5
	belt 2	4	3
Loading machine	FEL 1	4	6
	FEL 2	6	1
	BC 1	1	2

QUESTION 20

What is the owning and operating cost, or in the event of renting, the total rental cost including the operators' wages of each machine? Also, please enter the transportation, and mobilization and demobilization cost of each machine.

If you have no idea about the rate of expense, please type '0' in the corresponding space.

(Note : Here, each machine of each model is represented by a lower case letter at the end of the model name).

Type of machine	Model	Rate of expense (dollars/hr)	Transportation and mobilizing cost (dollars)
Wheel type tractors	CAT-814B(a)	**100**	**100**
	CAT-814B(b)	**105**	**100**
	CAT-824B(a)	**160**	**110**
	CAT-824B(b)	**175**	**110**

(Note : The total rates of expense, and the transportation and mobilizing cost of all the other types and models of machines are also obtained asking the same question. Those rates are tabulated below for information.)

Type of machine	Model	Total rate of expense (dollars/hr)	Transportation and mobilizing cost (dollars)
Wheel type loaders	CAT- 910(a)-910(d)	45	120
	CAT- 910(e)-910(f)	47	120
	CAT-910(g)	48	120
	CAT-910(h)	50	120
	CAT-950B(a)	50	120
	CAT-950B(b)	52	120
	DRE- 530(a)-530(d)	60	125
	DRE- 530(e)-530(f)	62	125
	DRE-530(g)	65	125
	DRE-530(h)	64	125
	DRE- 540(a)-530(d)	62	125
	DRE- 540(e)-530(f)	64	125
	DRE-540(g)	65	125
Elevating scrapers	CAT- 613C(a)-613C(d)	75	130
	CAT- 613C(e)-613C(f)	80	130
	CAT- 615(a)-615(d)	78	130
	CAT- 615(e)-615(f)	80	130
	JDE- 762B(a)-762B(b)	80	135
	JDE-762B(c)	85	135
Trucks (four-wheel-drive)	VOL- 5350B(a)-5350B(h)	45	80
	VOL- 5350B(i)-5350b(j)	50	80
	VOL- A20 6*6(a)-A20 6*6(b))	40	80
	VOL- A20 6*6(c)-A20 6*6(d))	42	80
Belt conveyers	belt 1(a)	0	150
	belt 1(b)	105	150
	belt 1(c)	110	150
	belt 2(a)-belt 2(b)	95	200
	belt 2(c)	100	200
Loading machines	FEL 1(a)	0	100
	FEL 1(b)-FEL 1(d)	102	100
	FEL 2(a)	115	100
	BC 1(a)	110	100

QUESTION 21

In order to use the following types of machines, how much do you expect to spend on construction and maintenance of haul or access roads?

Please enter the values in the appropriate space.

Type of machine	Cost (dollars)
Wheel type tractors	**5000**
Wheel type loaders	**5500**
Elevating scrapers	**6000**
Trucks (four-wheel-drive)	**6000**
Belt conveyers	**3000**

QUESTION 22a

What is the cost of a new set of tires of each machine?

If not applicable, please type '0'.

Type of machine	Model	Cost (dollars)
Belt conveyers	belt 1(a)	**0**
Loading machines	FEL 1(a)	**10000**

QUESTION 22b

How would you rate the operating condition of each type of machine on tires?

1 FAVORABLE - Excellent maintenance program, well maintained and reasonably leveled roads, recommended loads, no sharp curves.

2 AVERAGE - Average maintenance program, poorly maintained roads, 20% over loading, medium curves, grade is less than 5%.

3 UNFAVORABLE - Poor maintenance program, sharp rocky roads, 40% or more over loading, severe curves, grade is 15% or more.

Please type your choice (1-3)! If not applicable, please type '0'.

Type of machine	Operating condition
Belt conveyers	0
Loading machines	2

QUESTION 22c

How would you describe the operating conditions of the earthworks operation on the fuel or power consumption of each type of machine?

1 Heavy dozing, long haul time or distance with frequent adverse grades, continuous use on very poorly maintained roads, overloading or continuous loading operation

2 Production dozing, varying load and haul road conditions, some adverse grades, basic loader cycle with idling periods.

3 Considerable amount of idle times and travel with no load, short to medium haul on well maintained roads. Easy loading material or light utility work.

Type your choice (1-3)!

Type of machine	Operating condition
Belt conveyers	1
Loading machines	1

QUESTION 22d

What is the average fuel consumption rate or the power consumption of the following machines? If not applicable, please type '0'.

Type of machine	Model	Fuel consumption (liters/hr)	Power consumption (kW)
Belt conveyers	belt 1(a)	**0**	**2**
Loading machines	FEL 1(a)	**50**	**0**

QUESTION 22e

What is the cost of a liter of fuel of the following machines, or the electric tariff charge, in the construction area?

If not applicable, please type '0'.

Type of machine	Model	Fuel cost (dollars/liters)	Tariff charge (dollars/kWh)
Belt conveyers	belt 1(a)	**0**	**0.30**
Loading machines	FEL 1(a)	**0.60**	0

QUESTION 22f

What is the operators' wages of each machine including all the fringe benefits?

Type of machine	Model	Operators' wages (dollars/hr)
Belt conveyers	belt 1(a)	**32**
Loading machines	FEL 1(a)	**35**

QUESTION 22g

Do you intend to rent the following machines?

Please enter your choice <Y/N>!

Type of machine	Model	Choice <Y/N>
Belt conveyers	belt 1(a)	**Y**
Loading machines	FEL 1(a)	**N**

QUESTION 22h (own)

What was the Free On Board (FOB) price, and the delivery cost including tax, freight, and transportation cost, of each machine with accessories at the time of purchase?

Please enter the values in dollars in the appropriate places of the following table.

Type of machine	Model	FOB price (dollars)	Delivery cost (dollars)
Loading machines	FEL 1(a)	**95000**	**10000**

QUESTION 22i (own)

What were the estimated ownership period in years of each machine at the time you bought it, and the expected salvage/resale value in dollars after that period?

Please enter the values in the appropriate places of the following table.

Type of machine	Model	Ownership period (years)	Salvage value (dollars)
Loading machines	FEL 1(a)	**8**	**11000**

QUESTION 22j (own)

How old would be the following machines at the time of earthworks operation and what would be the estimated number of operating hours during that year ? Please enter the values in the appropriate places of the following table. If you have no idea about the number of working hours, please enter '2000'.

Type of machine	Model	Age (years)	Working hours
Loading machines	FEL 1(a)	**3**	**2100**

QUESTION 22k (own)

What are the interest, tax, insurance, and storage cost rates as a percentage per annum during the time of the earthworks operation?

interest rate (%) = **6**

tax rate (%) = **1**

insurance rate (%) = **2**

storage cost rate (%) = **1**

QUESTION 22l (own)

How would you rate the operating conditions and maintenance attention of your fleet of machines?

1 favorable 2 average 3 unfavorable

Please type your choice (1-3)! **2**

QUESTION 22h (rent)

What is the rental charge in dollars per hour of the following machines?

Type of machine	Model	Rental cost (dollars/hour)
Belt conveyers	belt 1(a)	**100**

QUESTION 22i (rent)

According to the past maintenance records of similar type of machines, approximately how much would you expect to spend on repairs on the following machines under the expecting operating conditions, in dollars per hour?

Type of machine	Model	Repairs cost (dollars/hour)
Belt conveyers	belt 1(a)	**3.50**

Following are the usable groups of machines for the earthworks operation.

GROUP 1 - Wheel type tractors

CAT - Caterpillar

CAT - 814B(a)
CAT - 814B(b)

cost per unit volume	*[dollars/m^3(loose)]*	= *0.4321*
scheduled duration	*[working days]*	= *132*
expected duration	*[working days]*	= *155.0*
required production rate	*[m^3(loose)/hr]*	= *568.1818*
expected production rate	*[m^3(loose)/hr]*	= *483.7153*

Press any key to continue ...

GROUP 2 - Wheel type tractors

CAT - Caterpillar

CAT - 824C(a)
CAT - 824C(b)

cost per unit volume	*[dollars/m^3(loose)]*	= *0.4412*
scheduled duration	*[working days]*	= *132*
expected duration	*[working days]*	= *96.9*
required production rate	*[m^3(loose)/hr]*	= *568.1818*
expected production rate	*[m^3(loose)/hr]*	= *773.9446*

Press any key to continue ...

GROUP 3 – Wheel type loaders

CAT - Caterpillar *DRE - Dresser*

DRE - 530(a)
DRE - 530(b)
DRE - 530(c)
DRE - 530(d)
DRE - 530(e)
DRE - 530(f)
DRE - 530(g)
DRE - 530(h)
CAT - 950B(a)

cost per unit volume	*[dollars/m^3(loose)]*	*= 0.9620*
scheduled duration	*[working days]*	*= 132*
expected duration	*[working days]*	*= 131.6*
required production rate	*[m^3(loose)/hr]*	*= 568.1818*
expected production rate	*[m^3(loose)/hr]*	*= 569.8997*

Press any key to continue ...

GROUP 4 – Wheel type loaders

DRE - Dresser

DRE - 540(a)
DRE - 540(b)
DRE - 540(c)
DRE - 540(d)
DRE - 540(e)
DRE - 540(f)

cost per unit volume	*[dollars/m^3(loose)]*	*= 0.6162*
scheduled duration	*[working days]*	*= 132*
expected duration	*[working days]*	*= 121.1*
required production rate	*[m^3(loose)/hr]*	*= 568.1818*
expected production rate	*[m^3(loose)/hr]*	*= 619.3921*

Press any key to continue ...

GROUP 5 – Elevating scrapers

CAT - Caterpillar

CAT - 613C(a)
CAT - 613C(b)
CAT - 613C(c)
CAT - 613C(d)
CAT - 613C(e)

cost per unit volume	*[dollars/m^3(loose)]*	$= 0.6971$
scheduled duration	*[working days]*	$= 132$
expected duration	*[working days]*	$= 135.6$
required production rate	*[m^3(loose)/hr]*	$= 568.1818$
expected production rate	*[m^3(loose)/hr]*	$= 553.0239$

Press any key to continue ...

GROUP 6 – Elevating scrapers

CAT - Caterpillar *JDE - John Deere*

JDE - 762B(a)
JDE - 762B(b)
JDE - 762B(c)
CAT - 613C(a)

cost per unit volume	*[dollars/m^3(loose)]*	$= 0.6887$
scheduled duration	*[working days]*	$= 132$
expected duration	*[working days]*	$= 159.1$
required production rate	*[m^3(loose)/hr]*	$= 568.1818$
expected production rate	*[m^3(loose)/hr]*	$= 471.4821$

Press any key to continue ...

GROUP 7 – Elevating scrapers

CAT - Caterpillar *JDE - John Deere*

JDE - 762B(a)
JDE - 762B(b)
JDE - 762B(c)
CAT - 615(a)

cost per unit volume	*[dollars/*m^3*(loose)]*	= *0.6210*
scheduled duration	*[working days]*	= *132*
expected duration	*[working days]*	= *141.9*
required production rate	*[*m^3*(loose)/hr]*	= *568.1818*
expected production rate	*[*m^3*(loose)/hr]*	= *528.6165*

Press any key to continue ...

GROUP 8 – Elevating scrapers

CAT - Caterpillar

CAT - 615(a)
CAT - 615(b)
CAT - 615(c)
CAT - 615(d)

cost per unit volume	*[dollars/*m^3*(loose)]*	= *0.4750*
scheduled duration	*[working days]*	= *132*
expected duration	*[working days]*	= *111.8*
required production rate	*[*m^3*(loose)/hr]*	= *568.1818*
expected production rate	*[*m^3*(loose)/hr]*	= *670.9563*

Press any key to continue ...

GROUP 9 – Trucks (four-wheel-drive)

VOL - Volvo

hauling machines	*loading machines*
VOL - 5350B(a)	*FEL 1(a)*
VOL - 5350B(b)	*FEL 1(b)*
VOL - 5350B(c)	*FEL 1(c)*
VOL - 5350B(d)	*FEL 1(d)*
VOL - 5350B(e)	
VOL - 5350B(f)	
VOL - 5350B(g)	
VOL - 5350B(h)	

cost per unit volume	*[dollars/m^3(loose)]*	= 1.0857
scheduled duration	*[working days]*	= 132
expected duration	*[working days]*	= 121.9
required production rate	*[m^3(loose)/hr]*	= 568.1818
expected production rate	*[m^3(loose)/hr]*	= 615.4101

Press any key to continue ...

GROUP 10 – Trucks (four-wheel-drive)

VOL - Volvo

hauling machines	*loading machines*
VOL - 5350B(a)	*FEL 2(a)*
VOL - 5350B(b)	
VOL - 5350B(c)	
VOL - 5350B(d)	
VOL - 5350B(e)	

cost per unit volume	*[dollars/m^3(loose)]*	= 0.8240
scheduled duration	*[working days]*	= 132
expected duration	*[working days]*	= 179.6
required production rate	*[m^3(loose)/hr]*	= 568.1818
expected production rate	*[m^3(loose)/hr]*	= 417.6900

Press any key to continue ...

GROUP 11 – Trucks (four-wheel-drive)

VOL - Volvo

hauling machines	*loading machines*
*VOL - A20 6*6(a)*	*FEL 2(a)*
*VOL - A20 6*6(b)*	
*VOL - A20 6*6(c)*	
*VOL - A20 6*6(d)*	

cost per unit volume	*[dollars/m^3(loose)]*	= 0.8018
scheduled duration	*[working days]*	= 132
expected duration	*[working days]*	= 212.8
required production rate	*[m^3(loose)/hr]*	= 568.1818
expected production rate	*[m^3(loose)/hr]*	= 352.3665

Press any key to continue ...

GROUP 12 – Trucks (four-wheel-drive)

VOL - Volvo

hauling machines	*loading machines*
VOL - 5350B(a)	*BC 1(a)*
VOL - 5350B(b)	
VOL - 5350B(c)	
VOL - 5350B(d)	
VOL - 5350B(e)	

cost per unit volume	*[dollars/m^3(loose)]*	= 0.7127
scheduled duration	*[working days]*	= 132
expected duration	*[working days]*	= 155.0
required production rate	*[m^3(loose)/hr]*	= 568.1818
expected production rate	*[m^3(loose)/hr]*	= 483.8625

Press any key to continue ...

GROUP 13 - Belt conveyers

hauling machines	*loading machines*
belt 2(a)	*FEL 1(a)*
belt 2(b)	*FEL 1(b)*
	FEL 1(c)
	FEL 1(d)

cost per unit volume	*[dollars/*m^3*(loose)]*	= *0.9306*
scheduled duration	*[working days]*	= *132*
expected duration	*[working days]*	= *141.1*
required production rate	*[*m^3*(loose)/hr]*	= *568.1818*
expected production rate	*[*m^3*(loose)/hr]*	= *531.5625*

Press any key to continue ...

GROUP 14 - Belt conveyers

hauling machines	*loading machines*
belt 2(a)	*FEL 2(a)*
belt 2(b)	

cost per unit volume	*[dollars/*m^3*(loose)]*	= *0.7352*
scheduled duration	*[working days]*	= *132*
expected duration	*[working days]*	= *179.6*
required production rate	*[*m^3*(loose)/hr]*	= *568.1818*
expected production rate	*[*m^3*(loose)/hr]*	= *417.6900*

Press any key to continue ...

GROUP 15 - Belt conveyers

hauling machines	*loading machines*
belt 2(a) *belt 2(b)*	*BC 1(a)*

cost per unit volume	*[dollars/m^3(loose)]*	= *0.6353*
scheduled duration	*[working days]*	= *132*
expected duration	*[working days]*	= *155.0*
required production rate	*[m^3(loose)/hr]*	= *568.1818*
expected production rate	*[m^3(loose)/hr]*	= *483.8625*

Press any key to continue ...

****

The most economical group of machines, without considering

the scheduled duration

****

Wheel type tractors

CAT - Caterpillar

CAT - 814B(a)
CAT - 814B(b)

cost per unit volume	*[dollars/m^3(loose)]*	= *0.4321*
scheduled duration	*[working days]*	= *132*
expected duration	*[working days]*	= *155.0*
required production rate	*[m^3(loose)/hr]*	= *568.1818*
expected production rate	*[m^3(loose)/hr]*	= *483.7153*

Press any key to continue ...

****

The most economical group of machines which meets the

scheduled duration

****

Wheel type tractors

CAT - Caterpillar

CAT - 824C(a)
CAT - 824C(b)

cost per unit volume	*[dollars/m^3(loose)]*	$= 0.4412$
scheduled duration	*[working days]*	$= 132$
expected duration	*[working days]*	$= 96.9$
required production rate	*[m^3(loose)/hr]*	$= 568.1818$
expected production rate	*[m^3(loose)/hr]*	$= 773.9446$

The End

APPENDIX C

Table C.1 Altitude derating factors of naturally aspirated equipment as a percentage of flywheel horse power

Type of equipment	Altitude (m)			
	less than 2300	between 2300-3000	between 3000-3800	greater than 3800
track type tractors	100	100	100	100
wheel type tractors	100	93	86	79
track type loaders	100	95	88	80
wheel type loaders	100	100	92	86
standard scrapers	100	100	92	84
tandem powered scrapers	100	96	89	82
elevating scrapers	100	100	92	84
push-pull scrapers	100	96	89	82
trucks (standard)	100	93	86	79
trucks (four-wheel-drive)	100	93	86	79

Table C.2 Percentage weight on driving wheels of the tare weight, α, and 'k' values of equipment

Type of equipment	α %	k
track type tractors	100	1.25
wheel type tractors	100	0.91
track type loaders	100	1.78
wheel type loaders	100	2.0
standard scrapers	67	0.65
tandem powered scrapers	59	0.81
elevating scrapers	63.5	0.82
push-pull scrapers	59	0.79
trucks (standard)	48	0.49
trucks (four-wheel-drive)	100	0.49

Table C.3 Coefficients of traction and rolling resistance factors of different ground surfaces

Type of ground surface	Coeffiecient of traction		Rolling resistance factor%
	Track type	Wheel type	Wheel type
very hard, concrete	0.45	0.9	1.5
hard, well compacted gravel	0.6	0.7	2.5
dry clay, gravel	0.9	0.7	2.75
wet clay, loose earth	0.7	0.45	17.0
dry sand	0.3	0.2	13.0
wet sand, loose gravel	0.5	0.4	8.0
snow	0.25	0.2	3.0

Table C.4 Densities, bucket fill factors, and coefficients of bulking of material

Type of material	Density kg/m^3(loose)	Bucket fill factor	Coefficient of bulking
decomposed rock - poorly blasted	1960	0.7	0.7
decomposed rock - well blasted	1570	0.85	0.3
crushed stone, gravel	1600	0.9	0.2
dry clay	1450	0.95	0.25
wet clay	1600	1.05	0.22
dry sand	1570	0.9	0.14
wet sand	1930	1.0	0.12
gravel sand, silt, clay mixture	1720	0.92	0.15
snow	325	0.95	0.0

Table C.5 Correction factors for hardness or type of stock pile

Hardness or type of stock pile	Correction factor (CH)
loose stock pile	1.2
hard to cut or frozen	0.75
dry non-cohesive or sticky	0.8
rock ripped or blasted	0.65

Table C.6 Correction factors for total resistance

Total resistance factor (TRF%)	Correction factor (CR)
TRF $\geq$ 30	0.25
30 > TRF $\geq$ 20	0.50
20 > TRF $\geq$ 10	0.75
10 > TRF $\geq$ 0	0.95
0 > TRF $\geq$ -10	1.1
-10 > TRF $\geq$ -20	1.2
-20 > TRF $\geq$ -30	1.25
-30 > TRF	1.30

Table C.7a Speed factors of machines - category 1.

CATEGORY 1. [Mass to Power ratio (kg/kW) $\leq$ 180]			
Distance (d)	Speed factor		
(meters)	Downhill	Level	Uphill
0 < d $\leq$ 60	0.67	0.65	0.40
60 < d $\leq$ 120	0.72	0.70	0.51
120 < d $\leq$ 180	0.77	0.75	0.56
180 < d $\leq$ 300	0.83	0.81	0.67
300 < d $\leq$ 460	0.90	0.88	0.75
460 < d $\leq$ 610	0.93	0.91	0.80
610 < d $\leq$ 760	0.95	0.93	0.84
760 < d $\leq$ 1070	0.97	0.95	0.87
1070 < d	1.00	0.98	0.94

Table C.7b Speed factors of machines - category 2

CATEGORY 2. [Mass to Power ratio (kg/kW) $\leq$ 230]			
Distance (d) (meters)	Speed factor		
	Downhill	Level	Uphill
$0 < d \leq 60$	0.64	0.62	0.39
$60 < d \leq 120$	0.68	0.67	0.48
$120 < d \leq 180$	0.74	0.70	0.54
$180 < d \leq 300$	0.83	0.75	0.61
$300 < d \leq 460$	0.88	0.79	0.68
$460 < d \leq 610$	0.91	0.84	0.74
$610 < d \leq 760$	0.93	0.87	0.78
$760 < d \leq 1070$	0.95	0.90	0.84
$1070 < d$	0.97	0.93	0.92

Table C.7c Speed factors of machines - category 3

CATEGORY 3. [Mass to Power ratio (kg/kW) > 230]			
Distance (d) (meters)	Speed factor		
	Downhill	Level	Uphill
$0 < d \leq 60$	0.56	0.55	0.33
$60 < d \leq 120$	0.64	0.58	0.41
$120 < d \leq 180$	0.70	0.65	0.46
$180 < d \leq 300$	0.78	0.75	0.53
$300 < d \leq 460$	0.84	0.77	0.59
$460 < d \leq 610$	0.88	0.83	0.62
$610 < d \leq 760$	0.90	0.86	0.65
$760 < d \leq 1070$	0.92	0.90	0.70
$1070 < d$	0.97	0.93	0.75

Table C.8 Average cycle times of loading machines

Type of loading machine	Cycle time (min)
front end loader	0.50
backhoe, face shovel - hydraulic	0.35
cable operated power shovel	0.40
dragline	0.45

Table C.9 Efficiency rating due to working condition

Working condition	η_w	
	Track type machines	Wheel type machines
dusty, rainy, snowy, foggy, dark or night duty	0.90	0.85
otherwise	1.0	1.0

Table C.10 Efficiency ratings due to equipment condition, management condition, and worker's experience, skill, and working attitude

Efficiency rating on		Condition		
		Excellent	Average	Poor
equipment condition, age, and maintenance attention (η_e)		1.0	0.93	0.85
management condition (η_m)		1.0	0.93	0.85
operator's skill, experience, and working attitude (η_d)	track type	1.0	0.95	0.9
	wheel type	1.0	0.9	0.85

APPENDIX D

D.1 Depreciation cost $(DC)_x$

Using the sum of the year digits method, the depreciation cost during the x^{th} year, $(DC)_x$, in dollars can be found as follows :

Let N = estimated useful life of the equipment (years),

P_o = Free On Board (F.O.B) price of the equipment including the accessories (dollars),

P_d = total delivery cost (dollars),

P_t = cost of a new set of tires (dollars), if applicable,

P_s = salvage or resale value after N years (dollars),

x = year being considered $(1 \leq x \leq N)$,

and z = any whole number $(1 \leq z \leq N)$.

Therefore, the depreciable value of the machine is $(P_o + P_d - P_t - P_s)$.

$$\text{depreciation cost during the } 1^{st} \text{ year} = (P_o + P_d - P_t - P_s) \frac{N}{\sum_{z=1}^{z=N} z},$$

$$\text{depreciation cost during the } 2^{nd} \text{ year} = (P_o + P_d - P_t - P_s) \frac{(N-1)}{\sum_{z=1}^{z=N} z},$$

$$\text{depreciation cost during the } 3^{rd} \text{ year} = (P_o + P_d - P_t - P_s) \frac{(N-2)}{\sum_{z=1}^{z=N} z},$$

Therefore, the depreciation cost during the x^{th} year, $(DC)_x$, would be

$$(DC)_x = (P_o + P_d - P_t - P_s) \frac{[N - (x - 1)]}{\sum_{z=1}^{z=N} z} . \tag{D.1}$$

D.2 Investment cost $(IC)_x$

Let p_x % = interest charges for the x^{th} year,

t_x % = charges for taxes and licenses for the x^{th} year,

j_x % = insurance charges for the x^{th} year,

and s_x % = storage and security charges for the x^{th} year.

Therefore, the investment cost during the x^{th} year $(IC)_x$, is

$$(IC)_x = \left(\frac{i_x}{100} \right) . (ABV)_x , \tag{D.2}$$

where $i_x = p_x + t_x + j_x + s_x$,

and $(ABV)_x$ = average book value of the machine for the x^{th} year (dollars).

Here, the $(ABV)_x$ can be given by [8, 26]

$$(ABV)_x = \frac{1}{2} [(BV)_{x-1} + (BV)_x] , \tag{D.3}$$

where $(BV)_x$ = book value at the end of the x^{th} year (dollars).

To find the book value at the end of each year, the following table can be prepared.

Table D.1 Book values using sum of the year digits method

End of year	Depreciation (dollars)	Book value (BV) in dollars
0	-	$(P_o + P_d - P_t)$
1	$(DC)_1$	$(P_o + P_d - P_t) - (DC)_1$
2	$(DC)_2$	$(P_o + P_d - P_t) - (DC)_1 - (DC)_2$
3	$(DC)_3$	$(P_o + P_d - P_t) - \sum_{z=1}^{z=3}(DC)_z$
(x-1)	$(DC)_{x-1}$	$(P_o + P_d - P_t) - \sum_{z=1}^{z=(x-1)}(DC)_z$
x	$(DC)_x$	$(P_o + P_d - P_t) - \sum_{z=1}^{z=x}(DC)_z$

From the above table

$$(BV)_{x-1} = (P_o + P_d - P_t) - \sum_{z=1}^{z=(x-1)}(DC)_z \,, \tag{D.4}$$

$$(BV)_x = (P_o + P_d - P_t) - \sum_{z=1}^{z=x}(DC)_z \,. \tag{D.5a}$$

(D.5a), can also be written as

$$(BV)_x = (P_o + P_d - P_t) - \left[(DC)_x + \sum_{z=1}^{z=(x-1)}(DC)_z\right]. \tag{D.5b}$$

Substituting (D.4) and (D.5b) in (D.3)

$$(ABV)_x = \frac{1}{2}\left[2\,(P_o + P_d - P_t) - (DC)_x - 2\sum_{z=1}^{z=(x-1)}(DC)_z\right]. \tag{D.6}$$

Substituting (D.6) in (D.2)

$$(IC)_x = \left(\frac{p_x+t_x+j_x+s_x}{100}\right) \cdot \left[(P_o+P_d-P_t) - \frac{1}{2}(DC)_x - \sum_{z=1}^{z=(x-1)}(DC)_z\right]. \tag{D.7}$$

D.3 Load factors on fuel or power consumption (K_1), and repair factors (K_2)

Table D.2 Equipment load factors on fuel or power consumption, and repair factors

Loading and operating conditions	Load factor (K_1)	Repair factor (K_2)	
		Mobile machines	Belt conveyers
(Unfavorable) heavy dozing/long haul time with frequent adverse grades/ continuous use on very poorly maintained roads/continuous loading operation.	1.25	1.05	0.75
(Average) production dozing/varying load and haul road conditions/ some adverse grades/basic loader cycle with idling periods.	1.00	0.90	0.60
(Favorable) considerable amount of idle times and travel with no load/ short to medium haul on well maintained roads/easy loading materials/light utility work.	0.82	0.85	0.50

D.4 Tire life factors (K_3)

Table D.3 Tire life factors of earthmoving equipment

Loading and operating conditions	Tire factor (K_3)
(Favorable) excellent maintenance program/well maintained roads/recommended loading/no sharp curves/ reasonably level road.	1.1
(Average) average maintenance program/poorly maintained roads/20% overloading/ medium curves/grades is less than 5%.	0.8
(Unfavorable) poor maintenance program/sharp rocky roads/ 40% or more overloading/severe curves/ grade is greater than 15%.	0.2