

OPTIMAL MATERIAL HANDLING EQUIPMENT SELECTION USING MIXED  
INTEGER LINEAR PROGRAMMING APPROACH TO MEET LONG-  
TERM PRODUCTION SCHEDULE REQUIREMENTS

By

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## ABSTRACT

Selection of materials handling equipment needs to be carefully conducted as a critical component of mine planning and economics of mining operations. The earth moving operation constitutes almost half of the total operating expenses in an open pit mining application. Maximum operational efficiency and minimum unit cost of mining can only be achieved by selecting an optimum material handling equipment fleet. This study investigates the existing equipment selection problem to provide an optimal solution. This is accomplished by comparing the total ownership and operating costs as well as the unit mining costs of suggested on-highway and off-highway equipment fleets. The reason for evaluating the on-highway and off-highway mining equipment together is to determine the profitability of contractor mining and owner mining methods. To create the dataset, Excel spreadsheets, AutoCAD 3D, MinePlan, and AMPL software were utilized in the data preparation and problem modelling processes.

Given the nature of open pit mining (multiple periods, commodity flow, and locations), a mixed integer programming model was developed to determine the optimal material handling equipment fleet with minimum ownership and operating cost for the entire life of the mine. Several constraints were employed to meet operational requirements set by the mine owner, such as satisfying production demands, equipment compatibility, and the unavailability of the pre-existing equipment fleet. To generate the annual dispatching schedule of the optimum equipment fleet, continuous decision variables were employed in the programming model for calculating the number of trucks and excavators, expressed in fractions, required to produce certain material types.

A case study was introduced for an open pit gold mine, currently in operation in Turkey, to simplify the decision-making process of the mine owner in choosing the optimal mining equipment fleet for the rest of the operation. The optimum result of the case study was achieved by selecting an on-highway equipment fleet with a total ownership and operating cost of \$171 million and a unit cost of \$0.89 per ton of material handled over the entire mine life. With the utilization of on-highway trucks and excavators, overall ownership and operating cost savings between \$80 and \$90 million were achieved compared to other proposed off-highway equipment alternatives.

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## CHAPTER 1

### INTRODUCTION

Production costs comprise the largest portion of a mine's total direct expenditures and are influenced by different operating conditions, many of which are highly variable. Lizotte & Bonates (1987) emphasized that haulage costs have been reported to exceed half of the total direct operating costs. Rock mechanics, resource characteristics such as orebody shape, orientation, and depth; and social and political issues are often primary factors that need to be taken into consideration as part of the pit design process which has a direct effect on the operational spendings. The size, type and capacity of mining equipment selected to purchase have a great effect on the overall capital expenditures as the price and capacity of the equipment are directly proportional to each other.

The long-term production schedules of mining projects fluctuate over time in response to changing economic conditions associated with dynamic commodity prices, market conditions, and the cost of consumable supplies. As such, the quantity of equipment needed to achieve specific production targets varies annually until the end of the life of a mine. As described by Dagdelen & Artittong (n.d.), defining the number of trucks required for an operation, also called truck allocation, is based on short-term plans for daily movement of material. In general, the size of the truck fleet required can be defined as the minimum number of trucks that a truck/shovel operation needs in order to meet the production target for each production period according to the short-term mine plan. This process depends on many factors, such as the size of the trucks, the mine haul road profile, the production target, and the operational delays. To keep the whole fleet at its highest possible level of utilization and productivity, the allocation of individual pieces of equipment needs to be considered with skill and great care. However, even in today's economic climate, a large number of junior mining contractors in Turkey use on-highway mining trucks for earth removal because of their market availability and low operating costs, which is due to the local sourcing of this equipment.

In this thesis, a comparative analysis will be performed to estimate the required fleet size and overall ownership and operational costs of on-highway versus off-highway mining equipment in order to meet the long-term production targets of a given operation. The proposed study uses empiric data obtained from an active mining project in which the earth-moving operation is being conducted by a Turkish mining contractor. The data needed for the

calculations was collected by the author during a visit to the mine site in order to establish confidence in the data set and to objectively observe the operation. The intent of this research is to provide conclusions that will aid the mine owner in making strategic decisions regarding the two design alternatives and the types of equipment configurations to be utilized.

## **1.1 Objectives**

The primary objective of this study is to choose the optimal mining equipment fleet and conduct a comparative analysis of two different mining systems: one that utilizes on-highway trucks for the primary material handling operation, which is then compared with an alternative approach where the mine operator purchases a fleet of appropriately sized conventional off-highway equipment. The option of using off-highway truck fleets will consider the pit design parameters, equipment capacities, and the original equipment manufacturers (OEM) predefined operational constraints for each excavator and truck model. For the purposes of this comparison, the cost of the two mining methods will be analyzed as an overall cost of mining on a per ton basis of material excavated and handled. The rationale behind not using the cost of mining per ton of ore recovered is due to the lack of information concerning the mining and processing recovery rates. This cost of mining per ton of material extracted will be determined by conducting an analysis of ownership and operating costs estimation by utilizing a linear programming approach for each equipment combination and option.

The goal of the optimization model presented in this study is to minimize the ownership and operating costs of the on-highway or off-highway material handling equipment fleet while determining the number of different types of equipment required to cover production targets that were set by the mine owner.

The primary aim of this study is to determine the optimal mining equipment fleet by calculating the overall ownership and operating cost of the proposed material handling operation for the remaining life of the mine, either by using on-highway or by adopting an alternative fleet of off-highway mining trucks and excavators. The objective function of the proposed model was formulated as the minimization of total ownership and operating cost of proposed equipment fleets to determine the best option among on-highway and off-highway trucks. The boundaries of the problem were defined by operational constraints, such as meeting the production demand, purchasing and using same type of fleet for the rest of the mine life, minimum material movement requirements to each haul destination, and the

maximum number of trucks that each haulage path can accommodate at minimum queuing time and maximum productivity.

The result of the proposed linear programming model is important to provide information to the mine owner in the decision-making process for choosing the optimal equipment fleet for the given set of parameters. The mine owner's decision will be either purchasing and operating a fleet of on-highway trucks or, as an alternative, off-highway trucks.

The raw data gathered from the mine site serves as the primary basis of all calculations used in this study. The first step of data preparation is merging the five different phase designs of the mine plan with the topography to connect haul roads with the pits and hauling destinations such as dumps, mill, leach pad, and tailing storage facility.

The material handling operation is comprised of oxide and sulfide mineral mining projects throughout the mine life. The mining of the oxide operation is planned to be completed at the end of 2028, while the ore production and waste stripping operations for sulfide mining project is planned to be started in the first half of 2024.

The approach used to achieve the objectives of research are as follows:

- With the utilization of MinePlan design software, calculations will be made to determine the haul road grades and the haul distances to each destination for each operating period,
- Calculation of the loaded and empty truck travel times along the routes by using the manufacturer charts for off-highway trucks,
- By referring to the assumed average speeds of on-highway trucks, the loaded and empty truck travel times for on-highway trucks were calculated by following the same steps for off-highway trucks,
- The adjustment of truck travel speeds according to the conditions of the haul road profile,
- The loading and traveling cycle time calculations by taking into consideration individual machine capacities and performances,
- The hourly and yearly productivity of proposed truck and excavator combinations,
- The determination of the required number of excavators and the optimal number of trucks in consideration of the long-term production schedule of the mining operation by utilizing a linear programming model, and

- Comparison of the direct unit cost associated with the mining operation for each equipment option.

## 1.2 Limitations

For the determination of fleet productivity on an hourly basis, the first requirement is to ascertain the number of production units (excavators and trucks) needed. The cycle time of the excavators can be estimated by averaging the empiric data collected from the mine site. However, for the on-highway and off-highway trucks, the number of units required should be estimated by determining the cycle times between each possible route. For that purpose, the rimpull and the retarder charts will be used to determine the velocities of trucks under the loaded and empty conditions on the varying grades of haul segments. The limitation for the on-highway trucks is that these charts are not publicly available from the on-highway truck manufacturers, which makes it necessary to make assumptions about the average truck speeds for cycle time determination.

As described by Hustrulid et al. (n.d.), the mining costs are generally calculated against the quantity of ore produced, waste stripped or a combination of both. In this research study, the cost factor will be calculated for the total amount of material handled based on a given long-term production schedule. The reason for using the cost per total amount of material produced is due to the lack of information on the process recovery rates for the ore mined. Therefore, the cost comparison will be based on cost per ton of material extracted and hauled for the proposed on-highway and off-highway mining fleets.

The equipment fleet currently being utilized has been designed and selected according to oxide project stripping capacity requirements. For that reason, the actual size of the equipment fleet for the sulfide project has yet to be defined at the time of the study.

One of the other major limitations of the data provided is that the pit shells generated with mine design and planning software do not include the possible in-pit ramps extending from the main haul roads to the production faces on different benches. For that reason, during the calculations of hauling equipment cycle times, the connection between production benches and main haulage roads will be assumed by considering annual mine plans, which show the production locations on each pit shell.

The selection of larger capacity off-highway haul trucks is limited to the maximum allowable haul road width, which was initially designed by considering the existing weak

rock conditions, the level of underground water table, and the space limitations. These conditions prohibit the selection and utilization of larger capacity off-highway haul trucks. Therefore, the widest haul road width was selected according to the maximum possible inter-ramp angle and the selection of the off-highway equipment was conducted based on this consideration.

In addition, the haul roads inside the pits and between other destinations have some narrow segments and tight radius corners on the ramps, which reduce the maneuverability of the trucks. This situation will result in additional truck queuing times, which will likely translate into increased travel times. Therefore, the pit design parameters should be taken into account in order to utilize larger capacity off-highway mining trucks.

Another limitation to consider is the availability of equipment prices and operating costs in Turkey. Since the study focuses on mining operations in Turkey, each equipment price should be sourced from local markets, or utilize manufacturer retail prices that are based on assumed worldwide base costs. Since it is comparatively harder to get local pricing of different types of equipment, local market prices in the manufacturer country can be taken as the base cost before taxes.

The equipment availabilities experienced by local mining operators are not publicly shared for each type of equipment. For that reason, the availability of trucks and excavators used in this research relies on general assumptions common in other mining applications.

### **1.3 Methodology**

This study will determine the lengths of individual haul road segments and their grades; travel times of trucks between each source and destination points; cycle time calculations of trucks; optimal number of trucks to meet the long and short-term production targets; operational cost analysis of trucks and excavators; and implementation of linear programming algorithm to find the optimal size of the truck fleet to achieve the production targets with minimum owning and operational costs.

By using AutoCAD drawings of the site topography and the pre-prepared pit shell designs provided by the mine owner, the topography and the pit shells were merged using MinePlan design and mine planning software. After combining topography with the pit shells of each phase, the final three-dimensional surfaces for the calculation of truck routes to each separate destination was determined by using the Autodesk AutoCAD software.

The possible routes of trucks to each destination point (e.g., Mineral Processing Facility, Non-Acid Generating Waste Stockpile, Potentially Acid Generating Waste Stockpile, Leach Pad and Tailings Storage Facility (TSF)) were tabulated with lengths and grades of each segment using a Microsoft Office Excel spreadsheet. According to the manufacturers' charts, the travel times of each truck with chosen capacity were calculated for loaded and empty traveling conditions. To get a realistic result, this analysis also considers the rolling resistance of the tires and the performance derations due to the elevation of mine site. In addition to these adjustments, the maximum speeds of trucks were reduced by applying speed factors that consider whether the truck starts traveling from a standstill or is starting to decelerate at uphill or downhill grade. In accordance with the number of cycles that an individual truck can achieve in a scheduled shift, the life of each tire and their required replacement time were predicted by referring to manufacturers' tire life estimation charts and the site-specific ground conditions. In addition, the amount of fuel consumption per shift for these specific truck types was calculated in order to estimate the operating cost of the equipment.

As the required database is prepared with deterministic calculation methods, a linear programming algorithm was applied to estimate the required number of excavators and trucks and their total ownership and operating costs for different production zones and routes in different phases during the mine life.

In order to aid in the decision-making process of the mine owner, this comparison between the on-highway and off-highway trucks will provide insights into the efficiency and economical aspects of choosing each fleet over the entire mine life.

#### **1.4 Thesis Outline**

This thesis is divided into the following chapters:

- Chapter 1- Introduction: This chapter addresses the problem statement, study objectives, limitations, and research methodology.
- Chapter 2 - Literature Review: This chapter presents the literature review on the application of linear programming models for loading and hauling equipment selection.
- Chapter 3 - Data Preparation and Methodology: This chapter explains how truck routes were calculated with AutoCAD and MinePlan software, how the truck cycle times were generated by using manufacturers' charts, how the truck queuing times

related with assigned number of trucks on each haul path and how the productivity of optimal number of excavator and truck fleets was calculated.

- Chapter 4 - Ownership and Operating Cost Calculations: This chapter presents the utilization of ownership and operating cost estimate form for the selected off-highway and on-highway equipment. Capital cost estimation, operating cost estimation, present value calculation of total expenditures, equipment rebuilding, and depreciation schedules were also evaluated.
- Chapter 5 - Optimum Material Handling Equipment Fleet Selection: This chapter addresses the formulation of a mixed integer linear programming model developed for the optimization of equipment selection and explains objective function, decision variables and constraints included in the model.
- Chapter 6 - Implementation of the MILP Model: This chapter explains the results of optimization model and suggests the optimal equipment fleet for the case study presented.
- Chapter 7 - Conclusions and Recommendations: This chapter discusses the results obtained and makes recommendations for further studies.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Introduction

The linear programming approaches applied today for the purposes of equipment selection will form the primary objective of this study. It will also form the basis of future recommendations for the utilization of different combinations of on-highway and off-highway truck fleets by taking into consideration productivity, and ownership and operating costs.

Mixed Integer Linear Programming models were utilized to analyze truck dispatching and equipment selection problems since the early 1970's because of their capability of solving complex problems in a short period of time.

The primary objectives of many of the optimization models used were related to maximizing the overall production with available fleets, minimizing the total cost of material handling operations, or minimizing the number of trucks and shovels needed to achieve production targets. These optimization models employ the same type of truck and shovel fleet throughout the life of the mine, as using heterogeneous fleets makes optimization problems increasingly complicated because of different operating conditions and requirements. To achieve an optimal result, the most common constraints utilized in the literature were meeting the production demands, compatibility of trucks and shovels in terms of design considerations and truck queuing times.

Recent studies have started to take the uncertainties associated with mining operation into account to achieve more realistic results. The inherent nature of mining operations includes some operational uncertainties about changing truck and shovel cycle times, the delays resulting from unexpected breakdowns of equipment, and the varying operational objectives.

The primary focus of optimization models has traditionally utilized two different methodologies: single and multi-stage approaches. The utilization of single stage approaches does not consider primary operational constraints and they achieve results with deterministic calculation techniques. However, the multi-stage approaches focus on meeting production targets for each equipment combination available in the fleet. In this study, the developed

programming model considers the multi-period and multi-location nature of the mining operation.

## **2.2 Previous Work on Equipment Selection Optimization**

White J.Wm. et al. (1982) proposed to view a mining operation with two types of nodes which are called source and sink nodes. These nodes are connected to each other with travelling routes called paths. Some of these nodes are accepted as rate limiting nodes because of their operational capacity. Ore stockpiles and waste dumps were assumed to be non-rate limiting nodes as they don't cause any delays in the operation. The developed linear programming model takes digging rates; and dump and travel times as the inputs and gives the result as an average number of trucks per minute that are travelling between the nodes. The objectives of the linear programming model are to maximize the shovel utilization by minimizing the idle time of shovels and to minimize load misrouting with the dispatching algorithm in a single period approach. However, the two major drawbacks of this truck dispatching algorithm are; that they do not consider the short and long-term production targets and availabilities of equipment fleets. These drawbacks make this linear programming model more difficult to implement as it will not yield an optimal solution for any mining operation.

Lizotte & Bonates (1987) described several dispatching rules to optimize truck and shovel productivities. These dispatching rules were subdivided as maximizing truck dispatching, maximizing shovel dispatching, application of match factor, mixed heuristic rules and mathematical programming. A case study was used to compare the effectiveness of these dispatching rules on the productivity of semi-automated dispatching systems. One of the major drawbacks of semi-automated dispatching systems is the communication problem between the operator and the dispatcher as it is difficult to receive, record, and give instructions to the operator. Although it is possible to gain productivity increases with the application of semi-automated dispatching systems in small to medium-scale mining operations, it is difficult to implement such systems as there are several limitations associated with their applicability in large-size open pit mining operations.

Alarie & Gamache (2002) provided a critical analysis of available dispatching systems in open-pit mines. The study also reviewed the vehicle dispatching applications outside the mining industry to investigate and classify different problems. In the last section of the study,

they also highlighted several considerations that needed to be taken into account in future works to increase efficiency and applications of dispatching systems.

Unlike previous publications, an equipment selection model that considers minimizing the operating cost of trucks and loaders was first developed by Burt et al. (2005). The presented mixed integer linear programming model matches the mixed-type fleets and considers the available equipment fleet while meeting the production requirements. They underlined that if the objective of the developed model were to maximize profit, a more detailed production schedule needed to be considered in the optimization model. Since the compatibility of heterogeneous fleets presents a major problem, this compatibility issue included as a constraint within the model. In this model, to obtain the consistency of constraints that forms the lower and upper bounds of the unit productivities of each equipment, an estimate of equipment productivities must be available which are unit capacity, cycle times, and fleet availabilities. Although results stated that the utilization of heterogeneous fleets are possible, the implementation of heterogeneous fleets together presents operational and economic difficulties which also makes the operation more complex than using the same type of fleet in a mining operation.

Dodin & Elimam (2008) further improved equipment selection models by combining project scheduling and equipment planning. The proposed study integrates project scheduling and equipment planning by taking into consideration the trade-offs that yield efficient and practical project schedules. These trade-offs include equipment idle times, operation stopping, equipment mobilization, and operator performance where they are rewarded in the case of early completion and penalized in not finished job on time. To implement these trade-offs with planned study, a mixed integer programming model was utilized to optimize the project schedule coupled with equipment sequencing. However, for the scheduling of complex projects, they introduced heuristic computation techniques. The introduced model utilizes the pre-existing equipment fleet and does not consider the need for purchasing additional equipment where the production schedule forces it to acquire new equipment.

The mining operating cost is divided into subcategories that include fuel consumption and equipment maintenance cost and parts. Topal & Ramazan (2010) applied a new approach that focuses primarily on optimizing truck fleet utilization to achieve production targets for the entire mine life by minimizing the maintenance cost for each existing equipment fleet. The proposed model considers the truck age, total maintenance cost, and minimum operating

hours required per year to meet production requirements. Although the study tries to optimize truck scheduling over the life of mine by minimizing maintenance cost, it does not consider determining the fleet size and selecting the appropriate type of equipment to meet production requirements with the lowest achievable cost.

The literature on optimization of truck allocation problems addresses the minimization of the quantity of equipment required to meet the long and short-term production targets or either maximizing the productivity of available fleet of trucks and shovels. Gurgur et al. (2011) stated that there was no model within the available approaches at the time that maximized the net present value of any project. Gurgur et al. (2011) combined linear programming and mixed integer linear programming models to optimize truck allocation problems. The model developed considers economic parameters associated with mine planning, multi-time period nature of mining and uncertainties experienced in material handling operations. The contribution of this model to the existing literature was the integration of uncertainty associated with earth moving operations and multi period mining operations. In order to test the reliability and the efficiency of the proposed model, a case study was performed at a gold mine. The results of the study showed that the proposed approach yields an increase in the net present value by minimizing the size of the equipment fleet.

Unlike previously published research, Eskandari et al. (2013) proposed a simulation modelling approach that tried to determine the size of the mining equipment fleet used in an open pit mine that was subject to budget limitations. The efficiency of the current haulage system was evaluated, and a simulation-based programming approach utilized to maximize productivity and minimize the amount of equipment required. The research study considered the truck loading area holistically throughout the whole mining area which tried to utilize the available haulage system by meeting long and short-term production schedules. The results of the study indicated a certain increase in equipment utilization of up to 20%.

Santelices et al. (2017) introduced an equipment selection and replacement model by applying a stochastic production rate constraint. Unlike the previous citation, the linear programming model simultaneously considered the mining equipment selection, sizing, and replacement problems to allow mine owner to make reliable and faster decisions in a multi-period production schedule. Initially, the author developed a deterministic model that aimed to buy and sell equipment and leave them idle when the rate of production is lower than the

previous period. The optimum result of deterministic model was achieved by minimizing the ownership, operating, and salvage costs of equipment, while meeting the production demands. Additionally, an alternative stochastic modeling approach was developed to consider the interdependent availabilities of trucks and shovels to achieve more realistic results. The results of the models gave a certain number of heterogeneous fleet of trucks and shovels that work together to meet simulated production demands in a multi-time period model.

In contrast to the previous studies, C. Burt et al. (2016) developed a deterministic modelling approach for optimum equipment selection purposes with accounting multi-location and multi-period natures of any mining operation. It was realized that using a stochastic modelling approach would increase the complexity and computation time of the problem as it utilizes different concepts at the same time. For that reason, the application of a deterministic modeling approach was found to be more appropriate. Apart from the existing literature, compatibility of heterogeneous fleets with pre-existing equipment was also considered for the first time in a mixed integer linear programming model. It was suggested that for large sets of fleets and long-term production schedules, consideration of purchasing and salvaging of equipment at the start and end of each period is necessary to keep expenses at a minimum. The assumptions made in this research study are fixed equipment cycle time, having a fixed mine plan over the life of the mine, salvaging of all available equipment within the beginning of each period, and fixed operating hours and availability of equipment. Another important consideration made in the study is the decrease in the performance of each equipment as the age of equipment increases. With that assumption, the authors aimed to achieve more realistic results rather than assuming the same productivity rate for all available equipment. To test the effectiveness of the model, two case studies were conducted. The results indicated that the developed model can be applicable to real-world problems.

Mohtasham et al. (2021) proposed a study that tries to optimize the required size of trucks by utilizing a mixed integer non-linear programming model using the match factor concept. Since the match factor methodology only considers the operational performance of available trucks and shovels for finding the size of material handling equipment fleet, two new strategies, coupled with a simulation model, were developed to evaluate the result of using different match factors. The results of these two proposed strategies and stochastic model were compared with the current operation to analyze the performance of approaches developed. The first strategy tries to assign the best match of compatible trucks with each

shovel for all the available equipment. However, the second strategy tries to assign all types of loaders and trucks to each other in order to evaluate the results of all possible equipment combinations. The contribution of this study to the literature is the ability of comparing simulation and optimization concepts together. The provided simulation-based methodology considers the uncertainties associated with cycle times of trucks and shovels which enables operators to see changes in equipment productivities, stripping ratio and the rate of utilization of shovels. The results of comparisons proved the effectiveness of simulation model and provided an optimal schedule that matches heterogeneous fleet of material handling equipment.

The objectives of equipment selection, replacement, and truck allocation models in the literature are about maximizing the productivity to meet long and short-term mine plans, minimizing the equipment idle time and maintenance costs, and maximizing the net present value of the mining projects. Most of the optimization techniques in the literature only use a single period and discrete commodity flow considerations which makes them unapplicable in real world scenarios. Another major drawback in current applications is the idea of mixing different types and models of trucks and loaders for meeting different sets of objectives over the life of mine. However, this consideration of using heterogeneous equipment fleet brings out availability and compatibility problems which may also create different maintenance and staffing problems.

In this thesis study, a deterministic linear programming model was developed in order to meet unique objectives defined by the mine plan and the specific mining method of an active mining operation in Turkey. The objective of the developed model is to minimize overall operating and ownership costs of the truck and excavator fleet to meet operational objectives over the life of the mine. For that purpose, several operational constraints were defined in the optimization model that set the boundaries of the problem. These constraints are composed of selecting and using the same type of excavator and truck fleet over the life of the mine, the annual maximum capacity requirements of each dump location (such as waste dump, ore stockpile and leach pad), optimum number of trucks that each haul road profile can accommodate at maximum productivity and salvaging the equipment fleet at the end of the mine life. By using this approach, the optimal truck and excavator fleet can be selected among the on-highway and off-highway truck and hydraulic excavator options for the current mining operation.

## CHAPTER 3

### DATA PREPERATION AND METHODOLOGY

This chapter provides a detailed discussion of the equipment selection process and the methodology used in data preparation.

The first step of the data preparation process includes the combination of phase designs with the pit topography to get the final layouts for the operational life of the mine. The excavation of materials associated with open pit mining leaves large, disturbed areas with steeply dipping benches throughout the extent of the pit. These pit layouts experience frequent changes as a consequence of the mining process and slope failures caused by stability problems.

This study uses two well-known software packages, AutoCAD and MinePlan 3D. These software packages were used for merging surfaces and calculating the lengths and grades of individual haul road segments that connect the production areas with dump locations. The dump locations are defined as Non-Acid Generating (NAG) waste rock stockpile, Potentially Acid Generating (PAG) waste rock stockpile, Leach Pad, Tailing Storage Facility, and Stockpile for Processing Facility.

The collected data was imported manually to Excel spreadsheets for truck and excavator production calculations. With the evaluation of production summaries of seven different sets of truck and excavator fleets, a linear programming algorithm was developed to calculate the overall ownership and operating costs of different fleet configurations, as well as the number of required trucks and excavators for each mining location during the mines' operational life.

#### **3.1 Introduction of Mining Operation**

The deposit is mined using the conventional open pit mining methods and it is formed of oxide and sulfide mineralization where the oxide zone is enriched with gold and silver and the sulfide zone contains gold, silver, copper, and zinc.

The open pit mining method will be accomplished by utilizing small capacity, diesel-powered trucks, and excavator fleet. To be more selective and to decrease the amount of dilution, 5 meter and 2.5-meter bench heights were employed. The earth removal and loading operation is done with the face loading mining method in which the excavators and blasthole drills work off the bench above the operating bench to load the mining trucks (Figure 3.1).

The oxide ore production will transition to sulfide production after 4 years of operation and is planned to be completed by the end of 2034. Beginning in 2023, the mine owner plans to purchase its own equipment fleet by evaluating the possible utilization of on-highway versus off-highway mining trucks.

### **3.1.1 Face Loading**

The face loading operation involves the excavation of ore and waste and is accomplished by hydraulic backhoe excavators that sit on top of the bench to fill the mining trucks positioned on the bench below. Wheel loaders are normally employed for the excavation and loading of loose materials, such as sand and gravel, where the ground is compatible and dry enough for their operation. Another requirement for utilizing wheel loaders is that the bench height should not exceed the maximum reach of the equipment for scaling and excavation purposes.

The first step in the overburden removal operation is the excavation of the fertile soil layer, which generally has a thickness of 1 to 20 meters above the mineralized zones; this soil is later stockpiled and stored in suitable locations around the mine site for later use in the reclamation process. Waste materials are also excavated and taken to an engineered waste storage dump. Subeconomic materials and ore materials are stockpiled close to the processing facilities for short- and long-term time periods. Because of the probability of oxidation for sulfide materials, they are only stockpiled for short periods of time, whereas oxide materials stored for short- and long-term periods. With the completion of the overburden stripping operation, haul roads and other infrastructure are constructed to provide required services to the mine site, such as power lines, administrative offices, and maintenance shops (Darling, 2011).



Figure 3.1 Hydraulic Backhoe Excavator Operating on a Bench Top

Table 3.1 presents the operational advantages and disadvantages of both hydraulic excavators and wheel loaders in terms of production flexibility, operational capacity, and equipment characteristics.

Table 3.1 Comparison of Hydraulic Excavators and Wheel Loaders

<b>Hydraulic Backhoe Excavators</b>	<b>Wheel Loader</b>
High Productivity	Unstable productivity
Lower Fuel Consumption	Higher Fuel Consumption
Highly durable Tracks	Lower tire life
Lower mobility	Higher mobility
Longer reach	Limited reach
High braking force	Low breaking force
Easy operation	Easy operation
Low vibration	High vibration

The mining operation presented in the case study utilizes the advantageous face loading mining method of hydraulic backhoe excavators for excavation and loading operations. The primary motives behind the utilization of face loading mining method with hydraulic backhoe excavators are to increase selectivity while decreasing overall mining cost of the operation. Future excavating equipment will be selected based upon this mining system and will reflect

the optimization of equipment production capacities of commercially available hydraulic backhoe excavators in Turkey.

### 3.1.2 Operating Schedule of Mining Operation

The contractor company is currently operating 2 shifts per day totaling 17 hours per day, and 300 days per year. Table 3.2 shows the daily schedule of operating hours. According to the laws of Turkey, an hour of lunch break time is a constitutional right of all employees working for a mining company.

Table 3.2 Operating Schedule of Mining Operation

Shifts	Shift Start Time	Break Time	Shift End Time
Morning Shift	7:00 AM	12:00 PM-13:00 PM	17:30 PM
Night Shift	20:30 PM	01:00 AM-02:00 AM	5:00 AM

### 3.1.3 Equipment Fleet

The remaining life of the mining project is planned for 12 years, beginning in January 2023 and ending in December 2034. Table 3.3 shows the currently utilized models of loaders and trucks to meet the production requirements for the remainder of the project. The actual quantity of equipment to be used has yet to be determined by the mine owner.

Table 3.3 Contractors Planned Fleet for the Sulfide Project

Equipment Type	Model
Loading Equipment	Hitachi ZX 490
Hauling Equipment	Man 41400

### 3.1.4 Production Schedule

Production scheduling determines the amount of material that needs to be extracted according to the production targets set for the life of the mine. Fytas et al. 1993 defined production scheduling as sequencing of the dilution of the orebody as a consequence of mine production. Based on the duration of the scheduling periods, production scheduling can be distinguished as short-term or long-term.

Fytas et al. 1993 also described the primary concerns of long and short-term scheduling, as long-term production scheduling is concerned with such items as ore reserves, stripping ratios, and major investment plans, usually on a year-by-year basis. Short-term production scheduling is the development of a sequence of reserve depletion on a daily, weekly, or monthly basis, which complies with restrictions imposed by long-term plans, plant capacities, inventory restrictions, equipment availability, and existing mining conditions.

The mining and processing schedule was prepared monthly for the first five years including a one-year period of pre-stripping. Thereafter, the mining and processing schedule were prepared quarterly for the rest of the life of the mine. The production goals of waste mining, including the pre-stripping period, aimed to obtain a minimum amount of waste material excavation for the construction of a clean water pond and Tailings Storage Facility, which guaranteed the utilization of tailings storage when sulfide ore processing started.

Minimizing the amount of waiting time for sulfide ore in stockpiles is one of the main goals of the mining production schedule. The inventory of sulfide ore will be reduced by revising the production schedule to minimize the oxidation risk of sulfide ore for high-grade stocks. Table 3.4 represents the life of mine production according to the pre-determined production targets.

Table 3.4 The Life of Mine Production Schedule

<b>Years/Material</b>	<b>Oxide</b>	<b>Sulfide</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>
<b>2023</b>	847,000	-	3,040,000	10,260,000	5,960,000
<b>2024</b>	794,000	53,000	3,240,000	14,060,000	5,960,000
<b>2025</b>	308,000	1,791,000	5,680,000	6,770,000	5,960,000
<b>2026</b>	55,000	1,800,000	4,280,000	9,440,000	5,960,000
<b>2027</b>	40,000	1,800,000	6,350,000	11,260,000	-
<b>2028</b>	23,000	1,800,000	3,710,000	14,380,000	-
<b>2029</b>	-	1,800,000	3,250,000	11,880,000	-
<b>2030</b>	-	1,800,000	3,580,000	10,410,000	-
<b>2031</b>	-	1,800,000	2,970,000	4,420,000	-
<b>2032</b>	-	1,800,000	2,540,000	3,560,000	-
<b>2033</b>	-	1,720,000	2,670,000	3,550,000	-
<b>2034</b>	-	873,000	1,940,000	2,590,000	-

### 3.1.5 Stage (Phase) Designs

The phase designs of the mining project were determined by relying on the pit optimization results for the scheduling flexibility of mining ore and waste. The first stages of the operation were based on oxide ore production to generate early cash flows, considering its lower cost of processing. Given the production schedule provided by the mine owner, the early stages of the mining operation will have higher stripping ratios due to the need to expose enough ore to recover development costs. Table 3.5 shows the corresponding years for each of the 5 phase designs covering the 12-year mine life.

Table 3.5 Periods of Each Phase Designs

Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
2023	2025	2028	2031	2033
2024	2026	2029	2032	2034
-	2027	2030	-	-

### 3.2 Final Pit Layouts

The surface topography of the mine includes a pit shell merged within the surface on the Northern side (Northern Pit) as it is the only active pit. The other locations are named Middle Pit and Southern Pit.

In merging topography with each different pit shell, it is essential to create separate topographies representing the different pit shells for each phase design. This operation was accomplished with MS3D software's "Surface" menu by the following steps (one by one for all topographies and pit shells):

- 1) Establishing a project folder containing the topography and the pit shell designs files.
- 2) File → Import Datamine files
- 3) Surface → Intersect Surfaces/Solids Tool → Choose solids to be merged → Merge

After merging each surface, it is essential that the coordinates of intersecting surfaces are matched to align and connect the haul road segments to each other. The results of the merging operations are presented in Figure 3.2, 3.3, 3.4, 3.5, and 3.6.

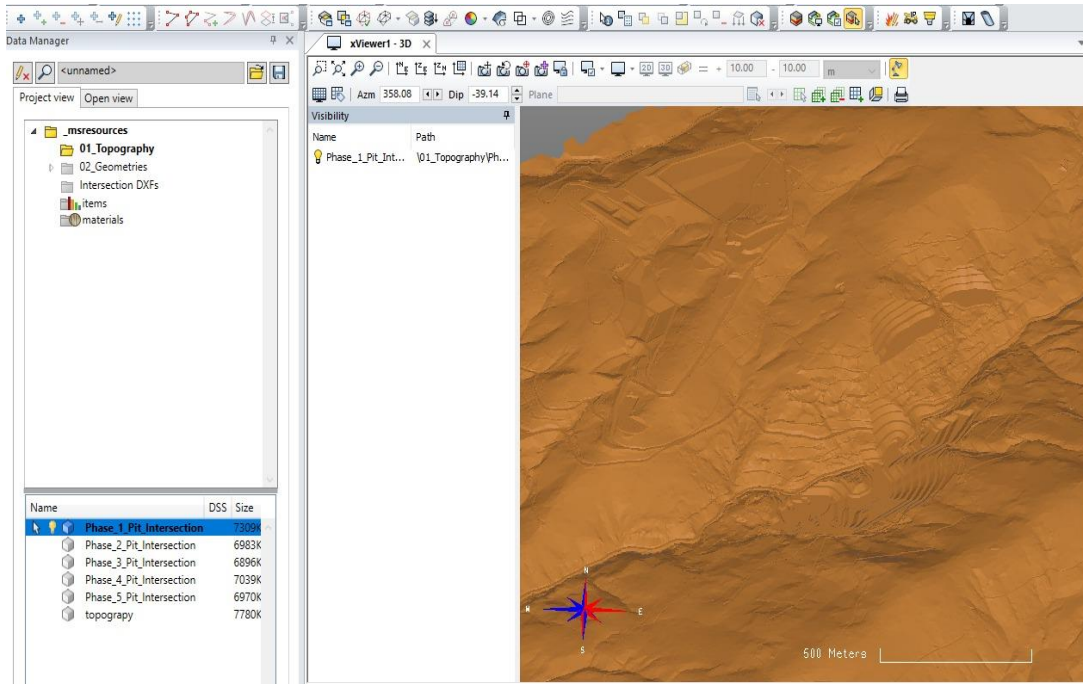


Figure 3.2 Topography Merged with Phase 1 Pit Shell

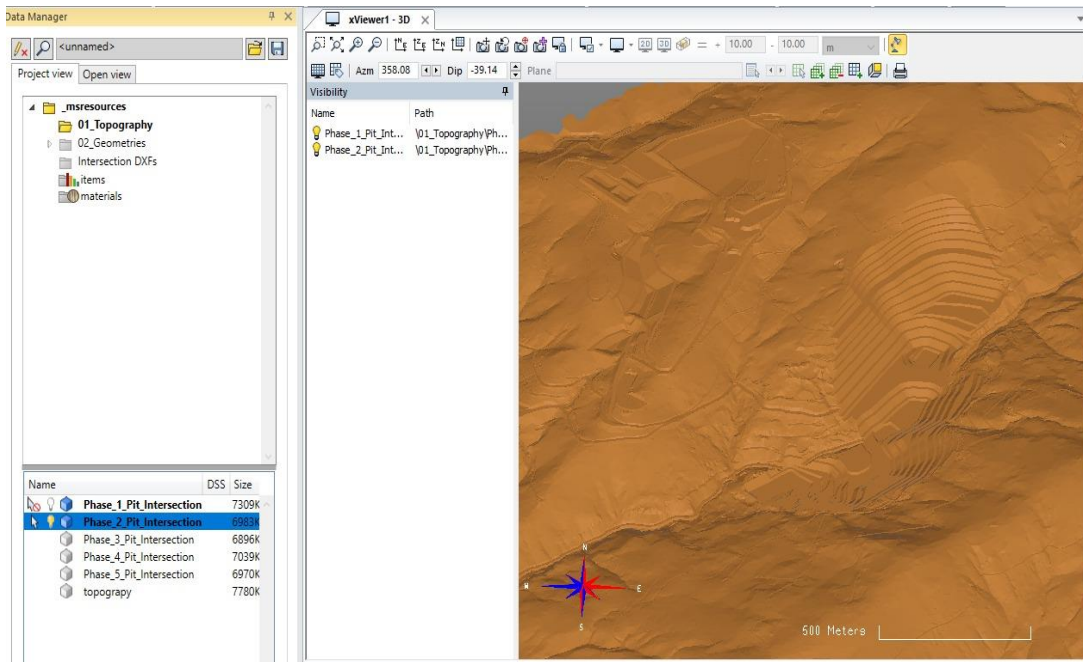


Figure 3.3 Topography Merged with Phase 2 Pit Shell

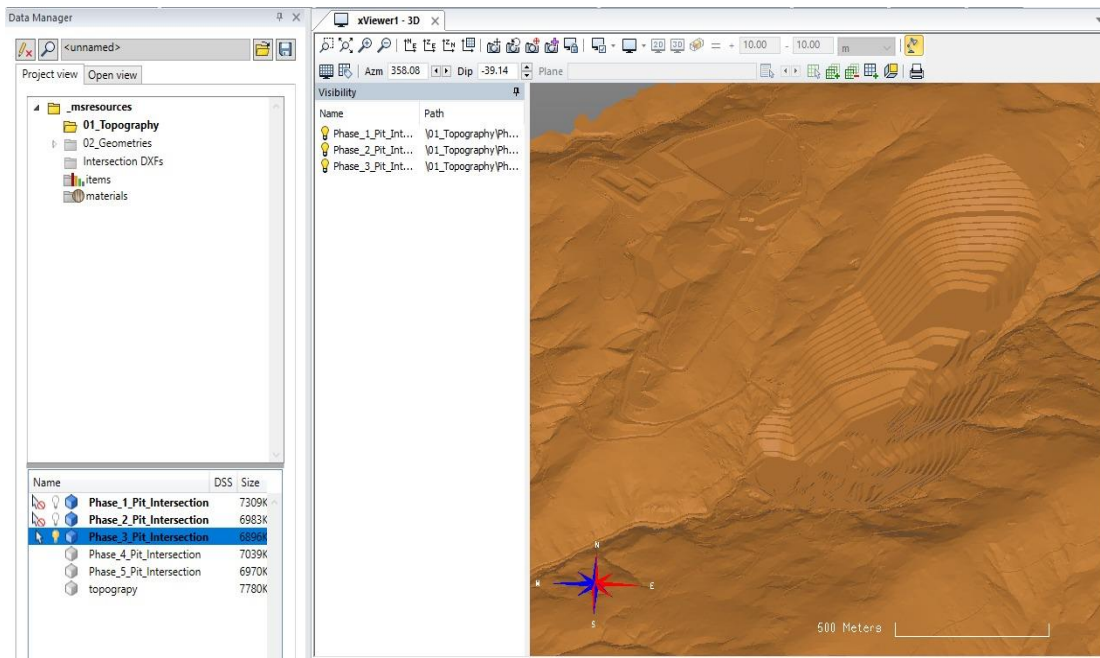


Figure 3.4 Topography Merged with Phase 3 Pit Shell

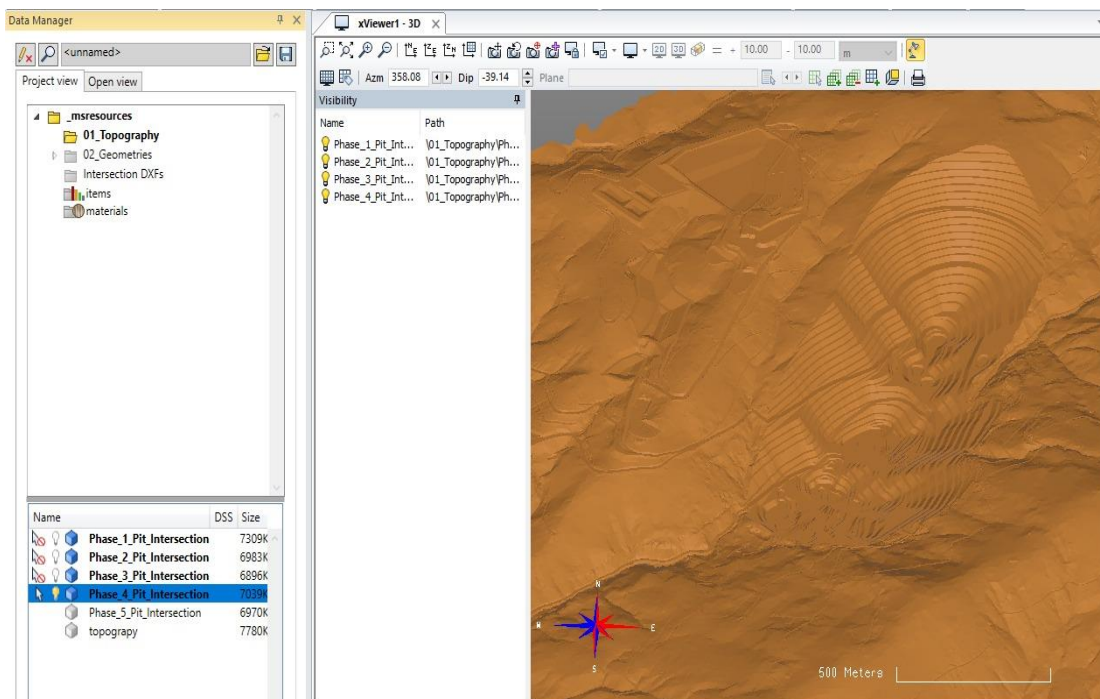


Figure 3.5 Topography Merged with Phase 4 Pit Shell

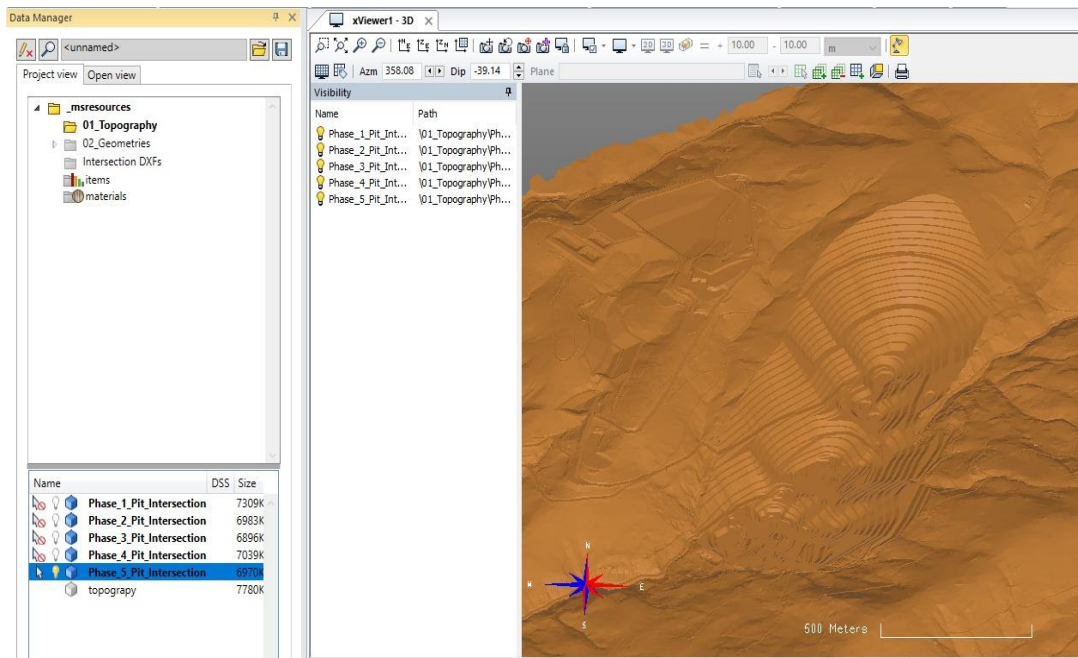


Figure 3.6 Topography Merged with Phase 5 Pit Shell

### 3.2.1 Material Dump Sites

There are 5 different dump locations on the mine-site for the storage and processing of each material type mined at the operation. Each type of material excavated in the mine is delivered to the appropriate locations. The layout of the mine and dump locations are represented in Figure 3.7.

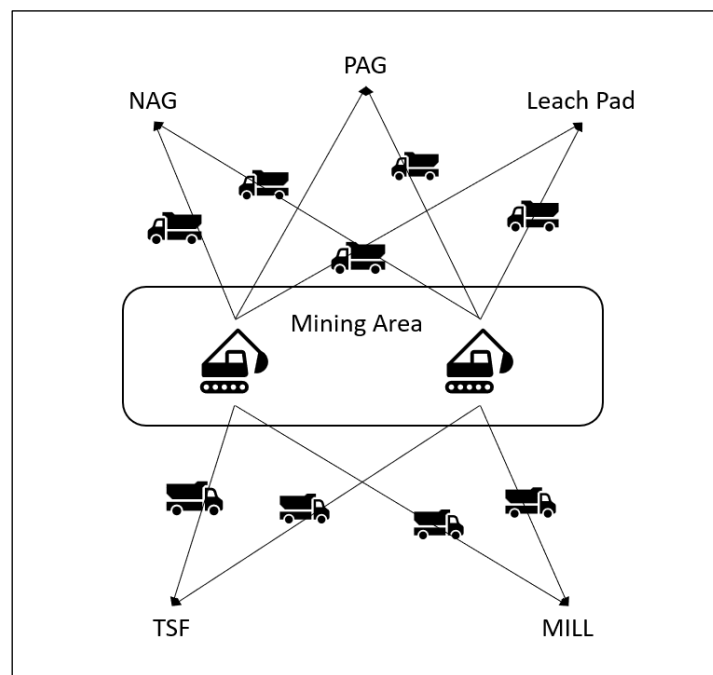


Figure 3.7 The Layout of the Mining Area and Dump Sites

### **3.3 Design Conditions of Haul Road Segments**

Determining the grades and haul distances between destinations, combined with the production face, forms the basis of equipment selection. This determines the number and capacity of the maximum equipment size that can operate as a fleet.

Some design conditions are referenced in the literature. As part of the process, equipment selection and haul road widths should correspond with the maximum size of the largest equipment in the fleet. As it was described by Darling (2011), depending on the location and use, haul roads are generally 3 to 3.5 times wider than the largest truck size on two-way straights and in two-way curves, respectively. For one-way haul roads, a width of 2 to 2.5 times that of the largest truck size is generally considered sufficient. It is also important to keep the grade as constant as possible to make truck operations easier to manage and to increase efficiency.

#### **3.3.1 Haul Road Lengths**

In determining the equipment fleet, the following haul road conditions should be considered: width of the segments, overall grades of the segments, distances between each destination point, turning radius, and ground conditions. Each element impacts the fleet's productivity in terms of travel times. The productivity of a mining equipment fleet is also in direct relation with the number of trucks and total truck travel time on a haul path. An increase in the number of operating trucks does not contribute to the overall productivity of the equipment fleet if the optimum number of trucks is reached, as it leads to additional truck queuing times. This increase in the queuing time limits the productivity of operating trucks, which is also called maximum fleet productivity.

AutoCAD 2018 software was used to calculate lengths, grades and turn radii of haul road segments. After the pit topography and phase designs were merged by using MinePlan, it was saved as a .dwg file and imported to AutoCAD 2018 software. To import drawing files for haul road calculations, the following steps were used (one by one for each drawing file):

- 1) Importing each drawing file(.dwg) representing all merged phase designs and topography
- 2) File → Open → Drawing

After importing all surface drawings, the destination points associated with waste stockpiles (NAG, PAG), Leach Pad, Tailings Storage Facility (TSF) and Mill (or stockpile)

were located and the possible routes between production faces were subsequently determined. The average distance from each production face's mid-bench contour to the start of in-pit ramps was calculated after the line segments representing the distances, grades, and turn radii along the sharp curves were drawn using the line tool. The advantage of using the line tool is the availability of three-dimensional coordinates on x, y and z axis for each drawn line segment, which enables the haul road grade calculation. Figure 3.8 illustrates the haul road geometries and the locations of dump sites in Phase 1.

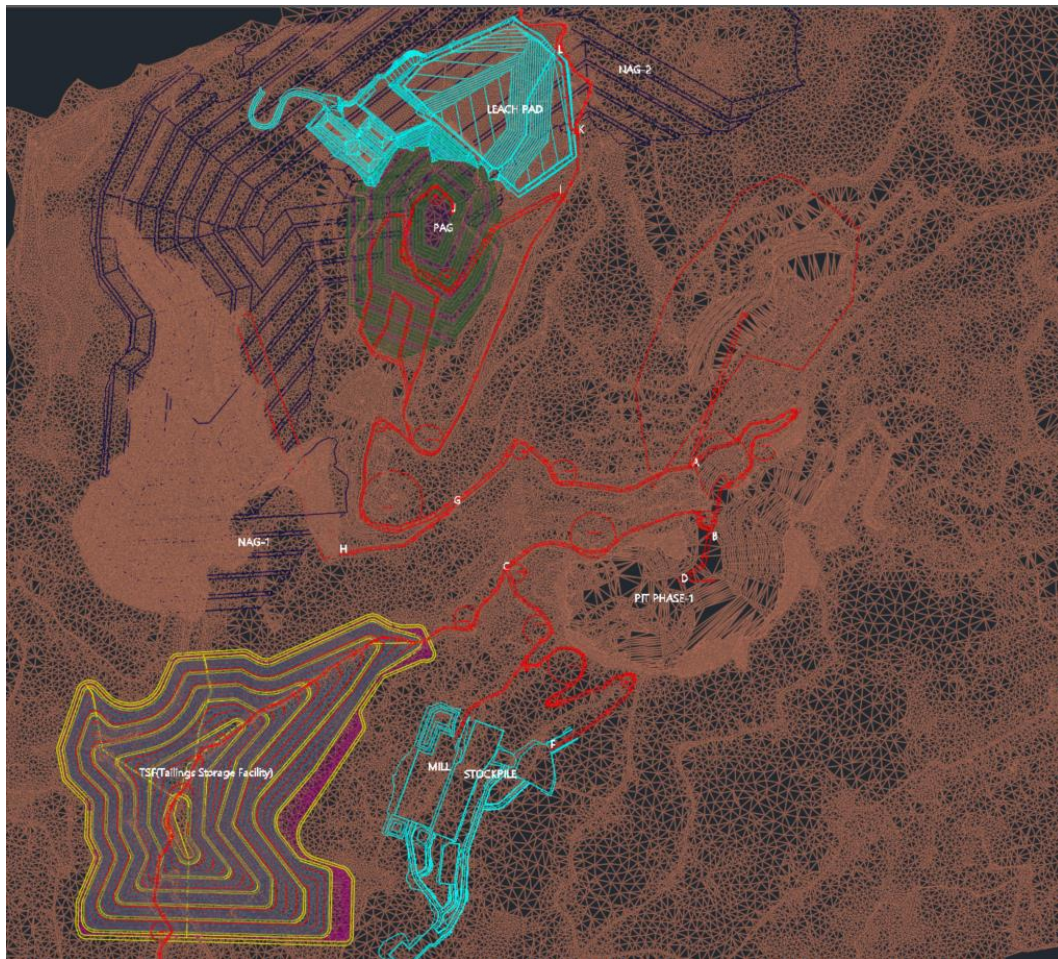


Figure 3.8 Haul Road Lengths, Grades and Turn Radiuses for Phase-1

The letter symbols were placed on road intersections and at the end of haul road segments. There are five different destinations, shown by their names in accordance with their locations. Sharp turns and corners are indicated by red circles. After all small segments were drawn, the length and grade data were logged into Excel Spreadsheets. Table 3.6 shows the overall distances for all phase designs.

Table 3.6 Lengths of Routes Between Working Benches and Destinations

<b>Phases</b>	<b>NAG (m)</b>	<b>PAG (m)</b>	<b>TSF (m)</b>	<b>Leach Pad (m)</b>	<b>Mill (m)</b>
<b>2023</b>	2,100	3,530	3,450	2,590	2,970
<b>2024</b>	2,100	3,530	3,450	2,590	2,970
<b>2025</b>	2,340	3,860	3,220	2,920	2,740
<b>2026</b>	2,340	3,860	3,220	2,920	2,740
<b>2027</b>	2,340	3,860	3,220	2,920	2,740
<b>2028</b>	2,030	3,650	3,150	2,710	2,670
<b>2029</b>	2,030	3,650	3,150	2,710	2,670
<b>2030</b>	2,030	3,650	3,150	2,710	2,670
<b>2031</b>	1,950	3,570	3,160	2,630	2,680
<b>2032</b>	1,950	3,570	3,160	2,630	2,680
<b>2033</b>	1,710	3,430	3,020	2,490	2,540
<b>2034</b>	1,710	3,430	3,020	2,490	2,540

### 3.3.2 Haul Road Widths

Designs of haul road segments are made in consideration of the largest operating equipment, generally off-highway trucks. To provide safe and efficient transportation of material extracted from pits, at least two lanes are required from the operating face to the dump points. Table 3.7, developed by Darling (2011), was used to calculate minimum haul road widths according to the size of the largest available equipment.

Table 3.7 Factors for Determining Minimum Haul Road Width

<b>Number of Lanes</b>	<b>Factor*Maximum Vehicle Width</b>
1	2
2	3.5
3	5
4	6.5

The mine owner noted that the widths of the haul road segments can be expanded up to 18 meters as a result of the preliminary analysis and the appropriate changes made in overall inter-ramp angles. By using the factor for 2 laned roads, the maximum equipment width is found to be:

$$\text{Maximum Equipment Width} = 18/3.5 = 5.14 \text{ meters}$$

### 3.4 Truck Performance Calculations

Equipment performance plays a major role in terms of mine economics and meeting the short-term and long-term production targets. There are several efficiency calculations that affect the overall operational limits of a specific type of equipment. Pit geometry and production plans are two of the major considerations prior to the determination of the mining fleet.

#### 3.4.1 Rolling Resistance

Frictional forces occur when equipment tires contact road surfaces that resist the forward movement of the vehicle. The loss of energy caused by these friction forces, or the rolling resistance, must be overcome by generating higher energy by the machine powerplant of the haulage unit and gravity. There are several factors that have positive or negative impacts on the rate of rolling resistance, such as the load of the hauling unit, tire sizes and types, and the condition of the haul road segments.

Table 3.8 Rolling Resistance Rates (Caterpillar, 2018)

UNDERFOOTING	ROLLING RESISTANCE, PERCENT*			
	Tires Bias	Tires Radial	Track **	Track +Tires
A very hard, smooth roadway, concrete, cold asphalt or dirt surface, no penetration or flexing	1.5%	1.2%	0.0%	1.0%
A hard, smooth, stabilized surfaced roadway without penetration under load, watered, maintained	2.0%	1.7%	0.0%	1.2%
A firm, smooth, rolling roadway with dirt or light surfacing, flexing slightly under load or undulating, maintained fairly regularly, watered	3.0%	2.5%	0.0%	1.8%
A dirt roadway, rutted or flexing under load, little maintenance, no water, 25 mm (1") tire penetration or flexing	4.0%	4.0%	0.0%	2.4%
A dirt roadway, rutted or flexing under load, little maintenance, no water, 50 mm (2") tire penetration or flexing	5.0%	5.0%	0.0%	3.0%
Rutted dirt roadway, soft under travel, no maintenance, no stabilization, 100 mm (4") tire penetration or flexing	8.0%	8.0%	0.0%	4.8%
Loose sand or gravel	10.0%	10.0%	2.0%	7.0%
Rutted dirt roadway, soft under travel, no maintenance, no stabilization, 200 mm (8") tire penetration or flexing	14.0%	14.0%	5.0%	10.0%
Very soft, muddy, rutted roadway, 300 mm (12") tire penetration, no flexing	20.0%	20.0%	8.0%	15.0%

The rolling resistance table developed by Caterpillar, (Table 3.8, Adapted from “Caterpillar Performance Handbook”, 2018), provides a rough estimate of the rolling resistance according to the type of tire and the ground condition. According to the site-specific conditions, it was decided to use radial tires for hauling trucks as radial tires can travel farther and faster because they can disperse heat more effectively than bias-ply tires. Radials are considerably more effective in dissipating heat because they have a firm tread, a single steel body ply structure, and also no multiple nylon plies. For total effective grade calculations, a 1.7% rolling resistance was applied by referring to the site-specific haul road conditions.

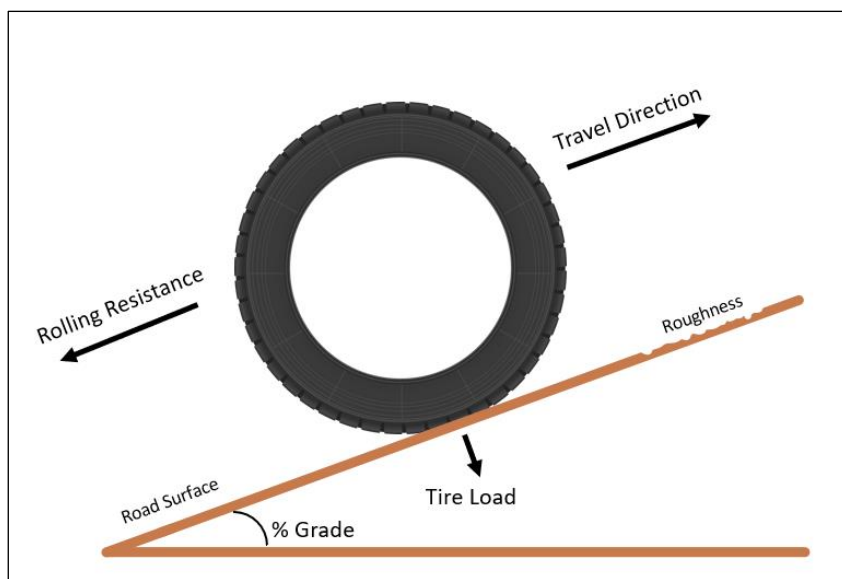


Figure 3.9 Rolling Resistance Acting on a Truck Tire

### 3.4.2 Grade Resistance and Total Effective Grade

Total effective grade, or total resistance, is expressed as a sum of all the resistance forces acting against the movement of the vehicle. In general, the total effective grade is found by summing the grade resistance percentage and the rolling resistance percentages on uphill, flat, and downhill conditions. Although grade resistance can vary in favor of or against the movement of equipment, rolling resistance is always acting against the movement direction. On the flat surfaces, the grade resistance is always 0% as it does not have any effect on movement. The total effective grade for uphill and downhill conditions is calculated according to the Equations (3.1) and (3.2) below.

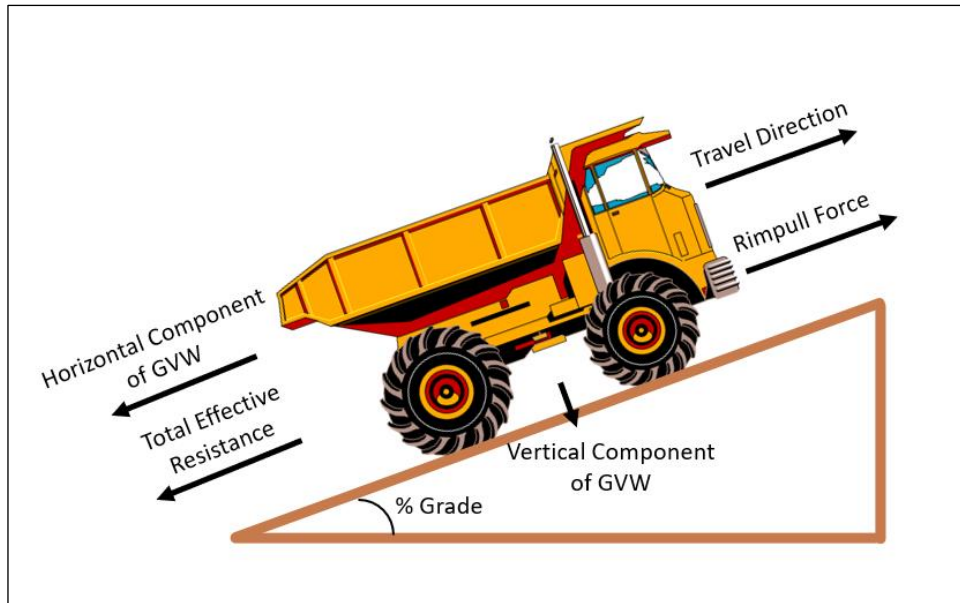


Figure 3.10 Effecting Forces and Resistances on a Mining Truck

$$\text{Total Resistance (Up)} = \text{Grade Resistance}(\%) + \text{Rolling Resistance}(\%) \quad (3.1)$$

$$\text{Total Resistance (Down)} = \text{Grade Assistance}(\%) - \text{Rolling Resistance}(\%) \quad (3.2)$$

Total effective grade or total resistance is defined as the total resistance that truck must overcome to start its motion and keep moving on a haul road. There are two factors that comprise the total effective grade which are the gravitational force and the gross vehicle weight of truck. The Equations (3.1) and (3.2) were utilized to calculate total effective grades of each haul road segment. Table 3.9 shows the lengths of each haul road segment in meters, their corresponding gravitational grade, and total effective grades in percentages.

- Using the rolling resistance of 1.7%, the total effective resistance at Segment 2, where the grade resistance is higher than 0%:

$$\text{Total Effective Resistance} = \text{Grade Resistance}(\%) + \text{Rolling Resistance}(\%)$$

$$\text{Total Effective Resistance} = 2\% + 1.7\% = 3.7\%$$

- The total effective resistance at segment 10 where the grade resistance is lower than 0:

$$\text{Total Effective Resistance} = -1\% + 1.7\% = 0.7\%$$

Table 3.9 Total Effective Resistance Calculation from Face to Leach Pad

<b>FACE TO LEACH PAD</b>				
<b>Segment</b>	<b>Up or Flat</b>	<b>Down</b>	<b>Grade Resistance</b>	<b>Total Effective Resistance</b>
<b>Face-A</b>	416	-	0%	1.7%
<b>1-A</b>	58.88	-	2%	3.7%
<b>2</b>	59.69	-	1%	2.7%
<b>3</b>	62.29	-	2%	3.7%
<b>4</b>	42.61	-	3%	4.7%
<b>5</b>	62.95	-	4%	5.7%
<b>6</b>	42.45	-	3%	4.7%
<b>7</b>	48.59	-	5%	6.7%
<b>8</b>	45.7	-	7%	8.7%
<b>9</b>	44.1	-	3%	4.7%
<b>10</b>	-	147.7	-1%	-2.7%
<b>11</b>	54.38	-	1%	2.7%
<b>12</b>	-	158.67	-3%	-4.7%
<b>13</b>	52.90	-	3%	4.7%
<b>14</b>	93.32	-	5%	6.7%
<b>15-G</b>	49.64	-	3%	4.7%
<b>16</b>	73.97	-	4%	5.7%
<b>17</b>	43.9	-	4%	5.7%

### 3.4.3 Retarder and Rimpull Charts

Equipment manufacturers provide retarder and rimpull charts for their equipment that specify the maximum speeds achievable in different load and grade conditions. Rimpull is the maximum pulling force that an engine can deliver to the drive wheels of rubber-tired equipment (Lowrie, 2002).

When the gross machine weight and total effective grade values are known, the maximum speed, gear range, and the available rimpull values can be obtained. If a mining truck is climbing uphill or moving on a flat surface with a known effective grade and weight, the maximum attainable speed and the gear ratio can be obtained by using the rimpull charts.

While travelling down slope, retarder charts should be used to obtain the desired information. For example, the rimpull and retarder charts for Caterpillar 770G (see “Caterpillar Performance Handbook”, pages 767 and 768) can be used by drawing lines from the effective grade column until it intersects with the weight of the equipment. Then, a horizontal line should be drawn until it intersects with a gear ratio. The maximum speed is obtained by drawing a vertical line down to the horizontal speed axis from the previously intersected point.

### 3.4.4 Altitude Deration (Correction)

A change of altitude creates performance loss for internal combustion engines. The major reasons for these losses are associated with changes in the temperature, density, humidity and pressure in the air. At altitude, engines start to generate more heat as heat transfer becomes harder, due to less air density. To overcome these power losses, the engines must spin faster which increases equipment maintenance requirements and can reduce the engine’s operating lifespan.

To keep productivity and efficiency of equipment at an optimal level, altitude deration factors should be applied. These factors are determined by each equipment manufacturer according to their optimal operating conditions. They provide altitude deration charts that show how much deration should be applied at each elevation range.

### 3.4.5 Maximum and Average Speed of Hauling Equipment

Traffic protocols on haul roads are determined with respect to haul road geometry and design characteristics and are intended to protect all employees and equipment from potential hazards throughout the mine site. These traffic protocols, or rules, mandate vehicle speed and equipment right of ways, including at intersections. Operators of haulage vehicles inside the active working zones must obey the traffic regulations and be aware of their environment.

Global mining equipment manufacturers provide safe operating limits in terms of maximum allowable speeds on sharp curves and uncontrolled ground conditions. Table 3.10 (Adapted from “Caterpillar Performance Handbook”, 2018) sets the limits of maximum allowable speeds with respect to the turning radiuses along designed haul segments.

Table 3.10 Maximum Speeds on Curves (Caterpillar, 2018)

TURN RADIUS		Flat Curve		5% Super-elevation		10% Super-elevation	
m	ft	km/h	mph	km/h	mph	km/h	mph
7.6	25	14	9	16	10	17	11
15.2	50	20	12	22	14	24	15
30.5	100	28	17	31	19	34	21
45.7	150	34	21	38	24	42	26
61	200	39	24	44	27	48	30
91.5	300	48	30	54	34	59	37
152	500	62	39	70	43	76	47
213	700	74	46	-	-	-	-

Mine management also establishes speed limits on haul roads for all vehicles that are operating within the active mining zone. At the mine used for this case study, the maximum speed on haul roads is limited to 40 km/h and 30 km/h on ramps.

The maximum speed that rubber-tired haulage equipment can achieve for a section of road with a known total resistance can be determined from the manufacturer's specifications (i.e., performance and retarding curves). Calculating an average speed requires allowance for acceleration, deceleration, shifting, and braking, as well as the ability to safely negotiate curves, steep downhill grades, and congested areas (Lowrie, 2002).

As with the calculation of the average speed of rubber-tired haulage equipment, the production rates and haulage cycle times can provide more realistic results in the dynamic operating environment. For the purposes of average speed calculations, after the maximum speeds of trucks from rimpull and retarder charts were achieved, the following factors were used.

Table 3.11 considers whether the haulage equipment is travelling loaded or empty from the starting point to a given destination. For safety and truck performance considerations, the average speed of a truck starting from a stopped condition or while in motion is calculated. The average speed is expected to be less when the haul truck is loaded compared to when its traveling empty. For this reason, the speed multipliers for loaded condition given in Table 3.11 show relatively lower rates than empty conditions. In some cases, the speed of a unit entering a haulage section may be more than the vehicle's maximum attainable speed due to steep gradients.

The net power of equipment per unit of gross vehicle weight was initially calculated to determine which half of Table 3.11 should be used. From the results obtained, corresponding factors were applied for average speeds along the specific segments on the haul road. The lengths stated in Table 3.11 were interpolated to compute factors for different haul road lengths (Table 3.11, Adapted from "Open Pit Mine Planning and Design", Hustrulid et al., n.d.).

Table 3.11 Average Speed Conversion Factors (Hustrulid et al., n.d.)

under 300 lbs/hp				
Haul Road Length in Feet	Level Haul Unit Starting From 0 MPH	Unit in Motion When Entering Haul Road Section		
		Level	Downhill Grade	Uphill Grade Factor
0-200	0.40	0-.65	0-.67	1  (Entrance Speed greater than maximum attainable speed on section)
201-400	.40-.51	.65-.70	.67-.72	
401-600	.51-.56	.70-.75	.72-.77	
601-1000	.56-.67	.75-.81	.77-.83	
1001-1500	.67-.75	.81-.88	.83-.90	
1501-200	.75-.80	.88-.91	.90-.93	
2001-2500	.80-.84	.91-.93	.93-.95	
2501-3500	.84-.87	.93-.95	.95-.97	
3501 & Up	.87-.94	.95-	.97-	
300-380 lbs/hp				
0-200	0-.39	0-.62	0-.64	1  (Entrance Speed greater than maximum attainable speed on section)
201-400	.39-.48	.62-.67	.64-.68	
401-600	.48-.54	.67-.70	.68-.74	
601-1000	.54-.61	.70-.75	.74-.83	
1001-1500	.61-.68	.75-.79	.83-.88	
1501-200	.68-.74	.79-.84	.88-.91	
2001-2500	.74-.78	.84-.87	.91-.93	
2501-3500	.78-.84	.87-.90	.93-.95	
3501 & Up	.84-.92	.90-.93	.95-.97	

The truck manufacturer’s performance charts were used to determine the maximum safe speeds for mining trucks traveling on haul roads with various turning radiuses. Since the super elevation grades of the curves were not provided, it is assumed that the curves are all flat. The procedures given below were followed for the calculation of maximum safe speeds on the curves:

- The turning radiuses were determined on all curves along the haul road.
- The maximum safe speed for a given turning radius is determined using Table 3.10
- As necessary, an interpolation of turn radius was made to calculate estimated speed on the curve and all turns were assumed as flat.
- Table 3.12 shows the segments with curves on the haul road from face to the leach pad.

Table 3.12 Curves Along the Route from Face to the Leach Pad

<b>FACE TO LEACH PAD</b>			
<b>Segments</b>	<b>Length(meters)</b>	<b>Turn Radius (meters)</b>	<b>Maximum Speed(km/h)</b>
7	48.6	32.8	28.9
8	45.7	32.8	28.9
9	44.1	32.8	28.9
11	54.4	21	23
12	158.7	21	23
13	52.9	21	23
18	56.5	78	44
19	79.3	78	44
20	51.4	78	44
21	62.3	78	44
22	61.4	78	44
23	51.1	78	44
24	73.4	78	44
25	50.3	78	44
27	53.6	38.7	31.2
28	48.5	38.7	31.2

Unlike the maximum speed calculations on curves, the average speeds of mining trucks were calculated on each haul road segment according to the considerations given below:

- The load condition of truck was determined (Empty or Loaded).
- The haul road profile in terms of grades (uphill, flat, downhill) was determined for each segment.
- The vehicle's motion status (starts from 0 or in motion) on each segment was determined.

The following example shows how the average speed of a truck on a haul road segment in loaded condition was calculated. For the first haul road segment (Face to A) on the Table 3.9, the average speed multiplier is calculated with respect to the steps provided below:

- The truck is loaded as it moves from face to the leach pad (the second half of the table used).
- The haul road is flat (0% grade resistance).
- Vehicle starts its motion from 0 km/h.
- Segment Length = 416 meters = 1365 feet.

- The length of haul road segment falls in between the range of (1001 – 1500) on the Table 3.11.
- By employing the linear interpolation formula, the average speed factor on the haul road segment is:

$$y = \frac{(y_2 - y_1)}{(x_2 - x_1)} * (x - x_1) + y_1 \quad (3.3)$$

Where:

- y is the corresponding speed multiplier for segment length of 1364.83 feet
- y<sub>1</sub> is the corresponding speed multiplier for segment length of 1001 feet which is 0.61
- y<sub>2</sub> is the corresponding speed multiplier for segment length of 1500 feet which is 0.68
- x<sub>1</sub> is the segment length of 1001 feet
- x<sub>2</sub> is the segment length of 1500 feet

$$y = \frac{(0.68 - 0.61)}{(1500 - 1001)} * (1365 - 1001) + 0.61$$

$$y = 0.66$$

The remaining speed multipliers for the other road segments were calculated by using Excel spreadsheets. Table 3.13 is an example of average speed multipliers for the haul road from the face to the Leach Pad.

Table 3.13 Speed Multipliers of Haul Road from Face to the Leach Pad

<b>FACE TO LEACH PAD</b>					
<b>Segment</b>	<b>Up or Flat(m)</b>	<b>Down(m)</b>	<b>Grade Resistance</b>	<b>Total Effective Resistance</b>	<b>Speed Multipliers</b>
<b>Face - A</b>	416	-	0%	1.70%	0.66
<b>1-A</b>	58.9	-	2%	3.70%	1
<b>2</b>	59.7	-	1%	2.70%	1
<b>3</b>	62.3	-	2%	3.70%	1
<b>4</b>	42.6	-	3%	4.70%	1
<b>5</b>	62.9	-	4%	5.70%	1
<b>6</b>	42.4	-	3%	4.70%	1
<b>7</b>	48.6	-	5%	6.70%	1
<b>8</b>	45.7	-	7%	8.70%	1
<b>9</b>	44	-	3%	4.70%	1
<b>10</b>	-	147.7	-1%	-2.70%	0.64
<b>11</b>	54.4	-	1%	2.70%	1

Table 3.13 continued

<b>12</b>	-	158.7	-3%	-4.70%	0.64
<b>13</b>	52.9	-	3%	4.70%	1
<b>14</b>	93.3	-	5%	6.70%	1
<b>15-G</b>	49.6	-	3%	4.70%	1
<b>16</b>	74	-	4%	5.70%	1
<b>17</b>	44	-	4%	5.70%	1

The average speed of selected truck models can be obtained by utilizing the total effective resistance and speed multipliers in Table 3.13.

### 3.5 Equipment Productivity Calculations

The production costs of trucks and excavators constitute a large part of the total operating costs for a mine. For a fleet to operate at maximum capacity, the waiting time of the excavators should be kept to a minimum. The main reason for this is the operating and ownership costs of the excavators are higher than that of the trucks. As production is dependent upon the lowest-capacity equipment, the fleet’s total production capability will be restricted by this equipment. Fleet production capacity calculations can be made with the truck and excavator production calculation formulas.

The efficiency of mining equipment decreases in direct proportion to the total operation time. To take this into account, production calculations were made by reducing the efficiency of the trucks by 5% for every 15000 hours of operation. The table below shows the assumed efficiency rates of trucks in each mining period.

Table 3.14 Assumed Equipment Productivity Rates on each Mining Period

<b>Period</b>	<b>Efficiency Rate (%)</b>
2023	90%
2024	90%
2025	90%
2026	85%
2027	85%
2028	85%
2029	80%
2030	80%
2031	80%
2032	75%
2033	75%
2034	75%

The calculation of the fleet productivity is usually limited by loader and truck productivity rates as the operation is dependent on one another. Table 3.15 contains data for the on-highway truck and excavator fleet which was obtained from the mine site.

Table 3.15 Site-Specific Parameters Collected from Mine Site

Parameters	Value	Units
Loader Cycle Time	26.6	seconds
Bucket Fill Factor	95	%
Bank Density of Oxide and Waste Material	2.65	tons/bcm
Bank Density of Sulfide Material	3.5	tons/bcm
Swell Factor	25	%
Job and Management Factor	90	%

### 3.5.1 Loader Productivity

The loader production rate is calculated using Equation (3.4).

$$O = [B * BF * D * A * J * 3600] / [(1 + S) * C] \quad (3.4)$$

Where:

- $O$  = Loading production output (tons/hour)
- $BF$  = Bucket Fill Factor (%)
- $B$  = Bucket capacity (loose cubic meters)
- $D$  = Density (tons/bank cubic meters)
- $A$  = Availability of loader (%)
- $J$  = Job and management factor (%)
- $S$  = Swell factor of material (%)
- $C$  = Average cycle time for loading (seconds)
- 3600 = Seconds per hour

### 3.5.2 Truck Productivity

The truck production rate is calculated with Equation (3.5).

$$P = [60 * N_T * L * A * J] / [TC] \quad (3.5)$$

Where:

- $P$  = Haulage production (tons/hour)
- 60 = Minutes in an hour (min/hour)

- $N_T$  = Optimal number of haulage units
- $L$  = Haul load (tons)
- $A$  = Availability of loader (%)
- $J$  = Job and management factor (%)
- $TC$  = Time with wait time for haulage cycle corrected for truck availability (min)

Where the corrected haulage cycle time ( $TC$ ) is calculated by dividing the total cycle time of a truck (which includes the loader waiting ( $T_w/W$ )) by the truck availability ( $TA$ ), which is also represented by Equation (3.6).

$$TC = (T_w/W) / TA \quad (3.6)$$

### 3.5.3 Truck Loading Parameters

Truck and loader matching is an essential parameter to get the optimal amount of productivity as both should work as a unit. The literature outlines several considerations in matching different trucks and excavators.

Lowrie (2002) described the optimum truck load per haulage cycle and the number of passes required to fill a truck to its heaped capacity. Trucks and loading equipment are typically matched in size so that between three and six passes by the loading equipment are required to load each truck. For less-dense materials, it may be necessary to determine the number of passes required to load a truck to its heaped volume capacity. For estimating purposes, the two  $NC$  values are rounded down to determine the optimal number of cycles for loading a mining truck. Equations (3.9), (3.10), and (3.11) can then be used to estimate the actual load per truck.

$$NC = CTW / [(B * BF * D) / (1 + S)] \quad (3.7)$$

$$NC = CTV / (B * BF) \quad (3.8)$$

$$L = NC * B * BF * D / (1 + S) \quad (3.9)$$

$$L = CTW(tons) \quad (3.10)$$

$$L = CTV(tons) \quad (3.11)$$

Where:

- $NC$  = Number of cycles to load a truck (integer)
- $CTW$  = Capacity of truck by weight (tons)
- $B$  = Bucket capacity (loose cubic meters)
- $BF$  = Bucket fill factor (%)

- $S$  = Swell factor (%)
- $D$  = Density of material (tons / bank cubic meters)
- $CTV$  = Capacity of truck by volume (loose cubic meters)
- $L$  = Load per haul (tons)

### 3.5.4 Truck Loading Time

Truck cycle time calculation also includes contributions for truck spotting and loading time. To determine the amount of time required to load a truck to its maximum capacity, the number of passes and the cycle time of the excavator should be first determined. According to Lowrie (2002), the optimum number of passes to fill a truck is between three to six passes. The number of passes to fill each truck is calculated by using Equations (3.7) and (3.8).

In some cases, loaders can load their bucket and get themselves ready to dump their load while the truck is spotting to get filled. In this case, the truck spotting time is larger than the cycle time for loading. The load time calculation is done by multiplying the total number of passes with the cycle time of the loader, which is represented by Equation (3.12). If the time associated with the truck getting ready for loading is longer than the cycle time of the loader, the total loading time is calculated by multiplying the loader cycle time with one less of the total number of passes and adding that amount with the truck's spotting time. This situation is represented by Equation (3.13).

$$TL = NC * C \quad (3.12)$$

$$TL = TS + (NC - 1) * C \quad (3.13)$$

Where:

- $TL$  = Time for loading truck (minutes)
- $NC$  = Number of cycles or passes (integer)
- $C$  = Cycle time for loading-average (minutes)
- $TS$  = Time to spot truck (minutes)

### 3.5.5 Maximum Truck Load Capacity

The actual amount of load a truck can carry in a safe and operationally feasible way is calculated according to the truck's capacity. The carrying capacity of a truck is limited by its weight capacity, volume capacity, and the capacity of the loader. Therefore, a truck's load per haul is estimated as the minimum of three capacity values. The lowest value achieved by using Equations (3.14), (3.15), and (3.16) is accepted as the load capacity of a truck.

$$L = NC * B * BF * D / (1 + S) \quad (3.14)$$

$$L = CTW \quad (3.15)$$

$$L = CTV \quad (3.16)$$

Where:

- $L$  = Load per haul (tons)
- $NC$  = Number of cycles or passes (integer)
- $B$  = Bucket capacity (loose cubic meters)
- $BF$  = Bucket fill factor (fraction)
- $D$  = Bank density (tons/bank cubic meters)
- $S$  = Swell factor (percentage)
- $CTW$  = Capacity of the truck by weight (tons)
- $CTV$  = Capacity of the truck by volume (loose cubic meters)

### 3.5.6 Total Truck Cycle Time

The truck haulage time, also called the truck cycle time, is the sum of the truck loading time, hauling time to its destination, returning from its destination to the loader it is assigned, and dumping time. If there is no queue for the truck loading, meaning the returned truck is loaded as soon as it arrives. Equation (3.19) is used to calculate the cycle time of a truck. Sometimes trucks need to wait for each other because of operational delays. In this case, the expected wait time for loading is added to the truck cycle time. Equations (3.18) and (3.20) can be used to calculate truck cycle time with the queuing time.

The optimum number of trucks for each loader is determined by dividing the total cycle time of the truck (without waiting time) by the truck loading time. The idea behind achieving the optimum number of trucks depends on getting the minimum waiting times, while keeping the loader's productivity at its maximum rate. Equation (3.17) is used to determine the optimum number of trucks for each loader that is assigned for the excavation of specific types of materials.

$$NT = Tw/oW / TL \quad (3.17)$$

$$Tw = [(NT - 1) * TL] - (TH + TD + TR) \quad (3.18)$$

$$Tw/oW = TL + TH + TD + TR \quad (3.19)$$

$$Tw/W = Tw/oW + Tw \quad (3.20)$$

Where:

- $NT$  = Optimum number of trucks (integer)
- $Tw/oW$  = Time without wait time for haulage cycle (minutes)
- $TL$  = Time for loading truck
- $Tw$  = Time waiting by truck (minutes)
- $TH$  = Time to haul loaded (minutes)
- $TD$  = Time to dumping load (minutes)
- $TR$  = Time to return empty (minutes)
- $Tw/W$  = Time with wait time for haulage cycle (minutes)

### 3.6 Application of Equipment Productivity Equations

Equipment productivity equations provided in Chapters 3.5.1 and 3.5.2 were applied with the data collected from the field to calculate the capacity of the current equipment fleet operated by the mine owner. For that purpose, on-highway truck capacity, total cycle time, and excavator productivity values were calculated.

#### 3.6.1 On-Highway Mining Truck Loading Parameters

In the current mining operation, on-highway trucks are employed which have a maximum carrying capacity of 41 tons and a tipper capacity of 20 m<sup>3</sup>. The trucks, manufactured by MAN, are all the same size and model (TGS 41400).

Excavation and loading operations are accomplished by Hitachi hydraulic excavators of model (490 LCH). The excavators have a volumetric bucket capacity of 2.3 m<sup>3</sup> and a cycle time of 26.6 seconds. Table 3.16 summarizes the operating parameters of currently operated trucks and excavators on the mine site.

Table 3.16 Operational Parameters of the Current Mining Operation

Operational Parameters for Loading	
CTW (tons)	41
CTV (m <sup>3</sup> )	20
B (loose m <sup>3</sup> )	2.3
BF (%)	95
C (seconds)	26.6
D <sub>Waste-Oxide</sub> (tons/bcm)	2.65
D <sub>Sulfide</sub> (tons/bcm)	3.5
S (%)	25

To calculate the number of passes required to fill a truck, Equations (3.7) and (3.8) were used for on-highway trucks as given below.

For waste and oxide material, the number of passes to fill on-highway trucks was calculated as follows:

- $NC = CTW / [(B * BF * D) / (1 + S)]$
- $NC = 41 / [(2.3 * 0.95 * 2.65) / (1 + 0.25)]$
- $NC = 9$  (*rounded up*)
- $NC = CTV / (B * BF)$   $NC = 20 / (2.3 * 0.95)$
- $NC = 10$  (*rounded up*)

For the waste and oxide material, the number of passes required to fill a truck was taken as the minimum number which is 9 passes. For the sulfide ores, the number of passes to fill on-highway trucks was calculated as follows:

- $NC = 41 / [(2.3 * 0.95 * 3.5) / (1 + 0.25)]$
- $NC = 7$  (*rounded up*)
- $NC = 20 / (2.3 * 0.95)$
- $NC = 10$  (*rounded up*)

For the sulfide material, the number of passes required to fill a truck was taken as the minimum number, which is 7 passes. The load for each haul cycle of an on-highway truck that can carry waste, oxide, and sulfide material was calculated by using the Equations (3.14), (3.15), and (3.16).

For the waste and oxide ores, the load for each haul cycle of an on-highway truck was calculated as follows:

- $L = NC * B * BF * D / (1 + S)$
- $L = 9 * 2.3 * 0.95 * 2.65 / (1 + 0.25)$
- $L = 41.7$  tons
- $L = CTW$
- $L = 41$  tons
- $L = CTV$  (tons)
- $L = 20 * (2.65 / (1 + 0.25))$

➤  $L = 42.4 \text{ tons}$

For the waste and oxide material, the load for each haul cycle was taken as the minimum tons calculated using the Equations (3.14), (3.15), and (3.16) which is 41 tons per truck. For sulfide material, the load for each haul cycle that an on-highway truck can carry was calculated as follows:

➤  $L = 7 * 2.3 * 0.95 * 3.5 / (1 + 0.25)$

➤  $L = 42.83 \text{ tons}$

➤  $L = 41 \text{ tons}$

➤  $L = 20 * (3.5 / (1 + 0.25))$

➤  $L = 55 \text{ tons}$

For the sulfide material, the load for each haulage cycle was taken as the minimum tons calculated using the three Equations (3.14), (3.15), and (3.16) which is 41 tons per truck.

### **3.7 On-Highway Mining Truck Loading and Total Cycle Time Calculation**

The mine plans to either purchase a new fleet of off-highway mining trucks and excavators or purchase the same type of equipment that the contractor currently has. In this study, several off-highway mining trucks and loaders were selected to compare the productivity of different fleets.

The time required to fill a truck is dependent on both the load capacity of a truck and the excavator capacity. The loading time of a truck is inversely proportional to the bucket size and cycle time of an excavator. The following example shows the total time required to fill an on-highway and off-highway truck using Equations (3.12) and (3.13).

➤ The on-highway truck spotting time is 60 seconds.

➤ The excavator cycle time that matches with the on-highway mining trucks is 26.6 seconds.

Since the given truck spotting time is larger than the excavator cycle time, Equation (3.13) was used to calculate loading time for on-highway trucks:

The loading time for waste and oxide material:

➤  $NC = 9 \text{ passes}$

➤  $C = 26.6 \text{ seconds}$

➤  $TS = 60 \text{ seconds}$

- $TL = TS + (NC - 1) * C$
- $TL = (60 + (9 - 1) * 26.6)/60 = 4.54 \text{ minutes}$

The loading time for sulfide material:

- $NC = 7 \text{ passes}$
- $C = 26.6 \text{ seconds}$
- $TS = 60 \text{ seconds}$
- $TL = (60 + (7 - 1) * 26.6)/60 = 3.66 \text{ minutes}$

The amount of time spent for a complete cycle of a dump truck was calculated by summing the truck's loading, hauling, dumping, and returning times. Equations (3.19) and (3.20) are utilized for the calculation of the complete cycle of a truck. The travel time calculation of a truck from the excavator to a dump point and from a dump point to a loader is given by Equations (3.21) and (3.22).

The haul road between each loading and dumping point was divided into individual sections to increase the accuracy of travel time calculations. This method of using individual road segments for travel time calculations simplifies the adjustment of speed in curves and the average speed calculations for each segment. The total time required for hauling loaded is found by dividing the distance of each road segment ( $D_{x,y}$ ,  $D_{y,x}$ ) by the corresponding speed of the truck ( $V_{x,y}$ ,  $V_{y,x}$ ) for each total effective grade, where the subscripts  $x$  and  $y$  denote the start and end point of a haul road segment.

$$TH_{Total} = D_{x,y}/V_{x,y} \tag{3.21}$$

$$TR_{Total} = D_{y,x}/V_{y,x} \tag{3.22}$$

Utilizing the Equations (3.21) and (3.22), the total cycle times of on-highway trucks in 2023 were calculated as given in Table 3.17.

Table 3.17 Total Cycle Time of On-Highway Mining Trucks in 2023

Haul Destination	Load Time	Haul Time	Dump Time	Return Time	Cycle Time
PAG	4.5	12.3	1	12.3	30.1
NAG	4.5	7.9	1	4.9	18.4
TSF	4.5	23	1	8.7	37.3
STOCKPILE	3.7	15.2	1	11.9	31.8
LEACH PAD	4.5	8.5	1	8.1	22.2

### **3.8 Off-Highway Mining Equipment Selection and Matching**

When trying to determine the model and quantity of mining equipment for a mining operation, there are several key factors that must be taken into consideration:

- Truck capacity
- Bench height
- Maximum reach of the excavator
- Production demand
- Material density
- Minimum loading height
- Loading cycle time
- Total cycle time

Based on these considerations, a list of off-highway mining trucks and hydraulic backhoe excavators were selected for the determination of optimal mining equipment fleet.

#### **3.8.1 Hydraulic Backhoe Excavator Selection**

The selection of material handling equipment is one of the most important factors in mine economics as it accounts for more than half of the total ownership and operating costs in a mining operation. According to the geometry of the mine site, the most appropriate model of hydraulic backhoe excavators needs to be selected for maximum productivity and efficiency rates.

Truck load times have a direct effect on the maximum productivity that a mine owner or a contractor can get from their available equipment fleet. As such, truck loading times can decrease the total cycle time of a truck and increase the optimal number of operating trucks on each haul path. Additionally, truck loading times also decrease the total waiting time of a truck to get loaded. For these reasons, in consideration of geometrical constraints of the mine site and equipment compatibility, the largest possible hydraulic backhoe excavators should be employed to get maximum productivity rates.

Apart from the operational cost considerations, the most important parameters in the selection of mining excavators are maximum reach height, minimum loading height, loading cycle time and bucket capacity. By taking these factors into account, two possible excavator models were selected from the Caterpillar Performance Handbook as presented in Table 3.18.

Table 3.18 Parameters for the Selection of Hydraulic Backhoe Excavators

<b>HYDRAULIC EXCAVATORS</b>		
<b>Specifications</b>	<b>390 F L</b>	<b>374 F L</b>
Maximum Reach Height (meters)	9.8	9
Minimum Loading Height (meters)	1.9	2.3
Loader Cycle Time (seconds)	35	30
Bucket Capacity (loose cubic meters)	4.6	3.8
Loader Productivity (tons/hour)	772	744

The potential excavator models were listed in consideration of the current excavator's operational capacities. The specifications of Hitachi 490 LCH are listed as:

- Bucket capacity of 2.3 m<sup>3</sup>,
- Cycle time of 26.6 seconds,
- Maximum reach of 10 meters,
- Minimum loading height of 3.7 meters
- Production capacity of 508 tons/hour

The operating parameters of the currently operating excavator given above form the basis of the selection. For that reason, the excavators listed in Table 3.18 have higher capacity than the contractor's excavator in terms of bucket capacity and hourly production.

### **3.8.2 Off-Highway Mining Truck Selection and Equipment Matching**

The excavated waste materials and ore are loaded and transported to processing and storage facilities within the mine site by mining trucks. There are two main types of haul trucks commonly operating in modern open pit mines. They include rigid haul trucks (RHT) and articulated haul trucks (AHT).

The rigid-body haul trucks (or off-highway mining trucks) have either multi or two-axle designs to support the forces caused by the weight of hauled material. Their capacity ranges from a minimum of 30 tons to a maximum of more than 300 tons. High-capacity models are usually employed in a wide variety of surface mines predicated by the economics of the individual operation. In addition, they are also used in some rock quarries and, sand and gravel operations, which have good haul road and bench conditions in terms of inclination, drainage, and surface compactness (Darling, 2011).

The articulated haul trucks have a payload range of approximately 20 to 50 tons which is significantly lower as compared to the capacity of rigid-body haul trucks. They have six-wheel-drive capabilities that provide them with more traction control on wet, uneven, and rocky terrains. They are primarily utilized in sand and gravel quarries, where maneuverability plays an important role. However, they are generally not preferred in traditional metal and nonmetal mining applications due to their high ownership and operating costs.

When making purchasing decisions between rigid-body and articulated dump trucks, the following factors should be taken into consideration:

- While articulated trucks are performing better in muddy and uneven ground conditions, rigid-body trucks have better performance on maintained haul roads.
- Although articulated trucks provide better performance on short and uneven road conditions, rigid-body trucks are ideal on long and smooth haul roads as they can travel at higher speeds.
- The bed of rigid-body trucks is more durable under abrasive rock conditions compared to articulated trucks.

In terms of these parameters and the preference of the mine owner, rigid-body trucks will be the most appropriate choice given the well-maintained haul road and even terrain conditions on the mine site.

The overall road widths play an important role in selecting the largest capacity mining trucks. As such, narrow road widths decrease the maneuverability and safe distance between two lane haul roads which directly decreases the overall fleet productivity by increasing the total cycle time of mining trucks. Decreasing productivity rates will force the mine operator to employ additional equipment and assign them on each haul route. For these reasons, it is essential to initially determine the maximum size of the possible equipment alternatives.

In the current mining operation, the mine operator plans to increase the overall inter-ramp angles to widen the widths of current haul road segments. The reason behind making that decision is to increase the maneuverability of currently operating on-highway trucks and to prevent unnecessary waiting times of on-highway trucks on narrow haul road segments. As a result of the preliminary analysis and the necessary adjustments made in overall inter-ramp angles, it was observed by the owner that the widths of the haul road segments can be increased up to 18 meters. By referring to Table 3.7 the maximum width of the largest mining truck in terms of two laned haul roads was determined as:

$$\text{Truck Width} = \frac{18}{3.5} = 5.14 \text{ meters}$$

A list of rigid-body haul trucks from the Caterpillar Performance Handbook is provided in Table 3.19. This table shows potential alternatives in terms of models and their specifications that should be taken into consideration in matching with the correct model of excavator.

Table 3.19 Parameters Considered in the Selection of Rigid Body Trucks

<b>OFF-HIGHWAY (RIGID BODY) TRUCKS</b>			
<b>Specifications</b>	<b>773E</b>	<b>772G</b>	<b>770G</b>
Width (meters)	5.1	4.8	4.7
Payload (tons)-CTW	55.1	44.2	35.2
Heaped Capacity(m <sup>3</sup> )-CTV	35.2	31.3	25.9
Struck Capacity (m <sup>3</sup> )	26.6	24	18
Gross Power (Hp)	760	598	515
Loading Height (meters)	3.8	3.6	3.2

Equipment matching was done by pairing each possible excavator model with the identified truck models. For the optimum results, the number of passes required to load each truck needs to be kept between 3 to 6 passes as the truck loading time has a direct effect on the overall productivity of fleets and waiting time of trucks to get loaded. In this study, all possible matches of given truck and excavator models were evaluated to observe the effects of different operating conditions of mining trucks and excavators. Equipment matches evaluated in this study are:

- CAT 390F L – 773 E,
- CAT 390F L – 772G,
- CAT 390F-L – 770G,
- CAT 374F L – 773 E,
- CAT 374F L – 772 G,
- CAT 374F L – 770 G,
- Hitachi 490LCH – MAN 41400

By utilizing Equations (3.7), (3.8), (3.12), and (3.13), the number of cycles, maximum truck loads, and time required for loading each truck model was determined by matching with

each excavator model. The calculated data is presented in Tables 3.20 and 3.21, respectively for the PAG-NAG-TSF-Oxide and Sulfide materials.

Table 3.20 Equipment Matching Results for Caterpillar 390F L

<b>CAT 390F L</b>						
<b>Truck Models</b>	<b>PAG-NAG-TSF-OXIDE</b>			<b>SULFIDE</b>		
	<b>NC</b>	<b>L (tons)</b>	<b>TL (min)</b>	<b>NC</b>	<b>L (tons)</b>	<b>TL (min)</b>
<b>770G</b>	4	35.2	2.8	3	35.2	2.2
<b>772G</b>	5	44.2	3.3	4	44.2	2.7
<b>773E</b>	6	55.1	3.9	5	55.1	3.3

Table 3.21 Equipment Matching Results for Caterpillar 374F L

<b>CAT 374F L</b>						
<b>Truck Models</b>	<b>PAG-NAG-TSF-OXIDE</b>			<b>SULFIDE</b>		
	<b>NC</b>	<b>L (tons)</b>	<b>TL (min)</b>	<b>NC</b>	<b>L (tons)</b>	<b>TL (min)</b>
<b>770G</b>	5	35.2	3.0	4	35.2	2.5
<b>772G</b>	6	44.2	3.5	5	44.2	3.0
<b>773E</b>	8	55.1	4.5	6	55.1	3.5

As can be observed from Tables 3.20 and 3.21 above, the number of cycles required to fill an off-highway truck with sulfide material is less than other material types. The reason behind this is that the sulfide material has a higher weight per unit volume. Therefore, the maximum truck capacity is achieved with lower number of passes and it also causes lower truck loading time.

### 3.8.3 Off-Highway Mining Truck Speed and Cycle Time Calculations

The geology of the mine has a great impact on the performance of the mining trucks. One of the major parameters that should be taken into consideration while calculating the productivity of trucks is rimpull which represents the sum of all resistive forces acting against the movement of the truck. Equipment manufacturers provide rimpull charts for accurate truck cycle time calculations. The rimpull curves enable the calculations of truck's traveling speed on varying haul grades that are greater and equal to the 0% haul road grade. Retarder charts provide the same data that can be obtained from rimpull charts, however, they are only utilized when the trucks are moving down the grade.

The rolling resistance and the haul road grade are the critical parameters in determining the total effective grade. The ground condition of haul roads creates a resistive effect on the

truck tires as it increases the rate of friction and decreases the forward propelling of the truck. Regular maintenance of haul road segments, such as compacting the loose material along these segments, helps to decrease rolling resistance on tires. Therefore, the accurate determination of haul road grades and rolling resistances plays a crucial role in truck cycle time calculations. (C. N. Burt & Caccetta, 2014).

The cycle time of trucks is calculated by summing the times associated with truck loading, hauling, dumping, and returning. In the current mining operation, the truck’s hauling cycle begins from the active operating benches and terminates at dumpsites. These dumpsites consist of stockpiles, processing plant, and waste dumps which are listed as:

- Non-Acid Generating Waste Dump (NAG)
- Potentially-Acid Generating Waste Dump (PAG)
- Leach Pad
- Processing Plant (Mill)
- Tailings Storage Facility (TSF)

For the uphill grades, the total effective grades were tabulated in Table 3.22 for rimpull and maximum speed calculations for the selected off-highway mining truck and excavator fleets. As previously stated, the total effective resistance is calculated by summing the haul road grades and the assumed rolling resistance rate over different segments.

Table 3.22 Total Effective Grades for Speed Calculations on Uphill Grades

<b>Grade (%)</b>	<b>Rolling Resistance (%)</b>	<b>Total Effective Grade (%)</b>
0%	1.70%	1.70%
1%	1.70%	2.70%
2%	1.70%	3.70%
3%	1.70%	4.70%
4%	1.70%	5.70%
5%	1.70%	6.70%
6%	1.70%	7.70%
7%	1.70%	8.70%
8%	1.70%	9.70%
9%	1.70%	10.70%
10%	1.70%	11.70%

After the trucks empty their loads at the dump sites, they return empty to the loaders where they are assigned by the dispatching system. The trucks travel to their destinations

either by climbing or descending the grades into a given pit. In the descending cases, the grade resistances are in favor of movement direction. Therefore, the total effective grades while descending are calculated by subtracting the rolling resistances from the haul road grades. Table 3.23 shows the calculation of total effective grades on various inclinations of the haul roads.

The speeds of truck models 773E, 772G, and 770G on each total effective grade were calculated by utilizing the rimpull and retarder charts provided by Caterpillar in the Caterpillar Performance Handbook.

Table 3.23 Total Effective Grades for Speed Calculations on Downhill Grades

<b>Grade (%)</b>	<b>Rolling Resistance (%)</b>	<b>Total Effective Grade (%)</b>
-1%	1.7%	0.7%
-2%	1.7%	0.3%
-3%	1.7%	1.3%
-4%	1.7%	2.3%
-5%	1.7%	3.3%
-6%	1.7%	4.3%
-7%	1.7%	5.3%
-8%	1.7%	6.3%
-9%	1.7%	7.3%
-10%	1.7%	8.3%
-11%	1.7%	9.3%
-12%	1.7%	10.3%
-13%	1.7%	11.3%
-14%	1.7%	12.3%
-15%	1.7%	13.3%

To calculate the speed and rimpull values for each truck, the total effective grades are marked on the secondary y-axis of the graph, and a horizontal line is drawn until it intersects with the rimpull and retarder axes. Following the line just drawn to calculate the rimpull value, another line is drawn to the gear ratio curve. A perpendicular line is then drawn from this intersection point extending to the x-axis to find the corresponding speed of the truck on the haul road grade.

The calculated speed values for each effective grade value were entered into an Excel worksheet with corresponding segment lengths for each haul road section in order to calculate the hauling and returning times of trucks. The travel time of the trucks on each haul road segment was calculated by dividing the length of each segment by the speeds of trucks.

The following example shows the travel time calculation for the segment “Face to A” in Table 3.13.

$$\text{Travel Time} = \text{Segment Length(meters)} / [\text{Speed(km/h)} * (1000\text{m/km}) * (1\text{hour}/60\text{min})]$$

$$\begin{aligned} \text{Travel Time} &= 416 \text{ meters} / [(43 \text{ km/h}) * (1000 \text{ m/km}) * (1 \text{ hour}/60 \text{ min})] \\ &= 0.62 \text{ min} \end{aligned}$$

### 3.8.4 Off-Highway Mining Equipment Productivity Calculations

After calculating each individual travel time, all travel times are summed to determine the total travel time between two destination points, which is from the working face to the Leach Pad. The total haul time for truck type 773E (390FL-773E) from the face to the Leach Pad was found to be 8.99 minutes in 2025. By following the steps given above, the return time of the truck from the Leach Pad can also be calculated. The total cycle time of truck model 773E from the working face and the Leach Pad is calculated as shown in the example below.

- *Truck Load Time = 3.92 minutes*
- *Truck Haul Time = 8.99 minutes*
- *Truck Dump Time = 1 minute*
- *Truck Return Time = 4.97 minutes*
- *Total Cycle Time(Tw/oW) = 3.92 min + 8.99 min + 1 min + 4.97 min*
- *Total Cycle Time(Tw/oW) = 18.88 minutes*

With the calculation of truck cycle times, the equipment fleet productivity can also be calculated by using Equations (3.17), (3.18), (3.20), and (3.6). To achieve maximum productivity from the materials handling fleet, excavators need to be over-trucked to prevent idling. After the calculation of truck productivity, the fleet capacity is found by comparing the productivity values of trucks and excavators and taking the minimum productivity rate as the fleet capacity. The calculation of truck and excavator fleet productivity is shown in the example below.

- The optimum number of trucks by using Equation (3.17) will be:
  - $N_T = Tw/oW / TL$
  - $N_T = 18.88 \text{ minutes} / 3.92 \text{ minutes} = 4.82 \cong 5 \text{ trucks}$
- The truck waiting time for loading by using Equation (3.18) will be:

- $T_w = [(NT - 1) * TL] - (TH + TD + TR)$
- $T_w = [(5 - 1) * 3.92] - (8.99 + 1 + 4.97) = 0.71 \text{ minutes}$
- The truck cycle time with waiting time by using Equation (3.20) will be:
  - $T_w/W = T_w/oW + T_w$
  - $T_w/W = 18.88 + 0.71 \text{ minutes} = 19.59 \text{ minutes}$
- The corrected truck cycle time (TC) by using equation (3.6) will be:
  - $TC = (T_w/W) / TA$
  - $TC = (T_w/W) / TA = 19.59 \text{ minutes} / 90\% = 21.76 \text{ minutes}$
- Values for the calculation of truck (Cat 773E) productivity using Equation (3.5) are:
  - $N_T = 5$
  - $L = 55.07 \text{ tons}$
  - $A = 90\%$
  - $J = 90\%$
  - $P = [60 * N_T * L * A * J] / [TC]$
  - $P = [60 * 5 * 55.07 * 90\% * 90\%] / [21.76] = 615 \text{ tons/hr}$
- Values for the calculation of excavator (Cat 390F L) productivity using formula (3.4) are:
  - $B = 4.6 \text{ loose } m^3$
  - $BF = 95\%$
  - $D_{waste-oxide} = 2.65 \text{ tons/bank } m^3$
  - $A = 90\%$
  - $J = 90\%$
  - $S = 25\%$
  - $C = 35 \text{ seconds}$
  - $O = [B * BF * D_{waste-oxide} * A * J * 3600] / [(1 + S) * C]$
  - $O = [4.6 * 95\% * 2.65 * 90\% * 90\% * 3600] / [(1 + 25\%) * 35] = 771.8 \text{ tons/hr}$

The capacity of the fleet is taken as the minimum of the truck and excavator productivity values as given below:

$$\text{Fleet Capacity} = \text{lesser of } O(\text{loader}) \text{ or } P(\text{trucks}) = 615 \text{ tons/hr}$$

The capacity of Caterpillar 390F L and 773E excavator and truck fleet was calculated as 615 tons/hour. By repeating the same steps used above, the capacities of other equipment fleets were found as shown in Tables 3.24, 3.25, and 3.26.

After the truck and excavator matches were completed, the optimal number of trucks (NT), truck waiting time (Tw), total truck cycle time (Tw/w) including the truck waiting times, corrected truck cycle time (TC) and fleet productivities per hour (P) were calculated on each haul route. To observe the results of matching the same model of excavator with 3 possible off-highway trucks in the same mining period, the following tables were generated. Tables 3.24, 3.25, and 3.26 show the productivity calculations of CAT 390F L-773 E, CAT 390F L-772 G, and CAT 390F L-770G in the year 2025.

It can readily be observed from these tables that matching an excavator with a higher capacity truck provides a higher productivity rate on each haul path. Although truck loading (TL) times decrease and the optimal number of trucks on each haul route increases with lower capacity trucks, hourly fleet productivity shows a decrease. The optimization model developed will help us to evaluate the financial results of the truck and excavator matches made in this chapter.

Table 3.24 Productivity Calculations for Fleet 390FL-773E in 2025

<b>390FL-773E</b>						
<b>Locations</b>	<b>NT</b>	<b>Tw/ow</b>	<b>Tw</b>	<b>Tw/w</b>	<b>TC</b>	<b>P (tons/hr)</b>
<b>NAG</b>	4	13.5	2.2	15.7	17.4	615
<b>PAG</b>	7	24.6	2.8	27.4	30.5	615
<b>TSF</b>	5	18.4	1.2	19.6	21.8	615
<b>Oxide</b>	5	18.9	0.7	19.6	21.8	615
<b>Sulfide</b>	6	17.6	2.4	20.0	22.2	723

Table 3.25 Productivity Calculation for Fleet 390FL-772G in 2025

<b>390FL-772G</b>						
<b>Locations</b>	<b>NT</b>	<b>Tw/ow</b>	<b>Tw</b>	<b>Tw/w</b>	<b>TC</b>	<b>P (tons/hr)</b>
<b>NAG</b>	4	12.9	0.4	13.3	14.8	579
<b>PAG</b>	8	23.9	2.8	26.7	29.6	579
<b>TSF</b>	6	17.6	2.4	20.0	22.2	579
<b>Oxide</b>	6	18.3	1.7	20.0	22.2	579
<b>Sulfide</b>	7	17.0	2.2	19.2	21.4	702

Table 3.26 Productivity Calculation for Fleet 390FL-770G in 2025

<b>390FL-770G</b>						
<b>Locations</b>	<b>NT</b>	<b>Tw/ow</b>	<b>Tw</b>	<b>Tw/w</b>	<b>TC</b>	<b>P (tons/hr)</b>
<b>NAG</b>	5	12.2	1.5	13.7	15.3	560
<b>PAG</b>	10	25.0	2.5	27.5	30.6	560
<b>TSF</b>	8	20.9	1.1	22.0	24.4	560
<b>Oxide</b>	7	18.5	0.7	19.2	21.4	560
<b>Sulfide</b>	9	18.1	1.4	19.5	21.7	679

To observe the effect of optimal number of trucks and truck waiting times on the overall productivity associated with each mining fleet, the tables below were generated. Attaining the optimal number of trucks provides the highest productivity rate with the lowest truck waiting time for each equipment fleet. The optimal number of trucks (CAT 390 FL-773E) was found to be 4 in 2025. As it can be seen from the Table 3.27, adding more trucks over optimal number of trucks has no contribution to the overall productivity rate of equipment fleets.

Table 3.27 Effect of Number of Trucks on Overall Productivity

<b>NAG</b>				
<b>NT</b>	<b>TW (min)</b>	<b>Tw/W (min)</b>	<b>TC (min)</b>	<b>P (tons/hr)</b>
1	-9.6	13.5	15.0	178
2	-5.7	13.5	15.0	356
3	-1.8	13.5	15.0	535
4	2.1	15.7	17.4	615
5	6.1	19.6	21.8	615
6	10.0	23.5	26.1	615
7	13.9	27.4	30.5	615
8	17.8	31.3	34.8	615

## CHAPTER 4

### OWNERSHIP AND OPERATING COST CALCULATIONS

The hourly ownership and operating costs for mining equipment can be affected by numerous economical and operational parameters: such as the ownership period and operating hours for each mining period, life of the mining operation, maintenance and labor costs, fuel prices and consumption rates, finance costs and interest rates, and the geological conditions of the mining environment (Caterpillar, 2018).

The mining company expects high rates of productivity with low ownership and operating costs from the equipment that they intend to purchase. In addition, another important criterion in the equipment selection process is the reliability of material handling equipment, as availability will significantly impact the overall rate of productivity. In consideration of all these influential factors, the first step that needs to be considered in the optimal fleet selection process is the calculation of ownership and operating costs of the equipment alternatives. Caterpillar's "Owning & Operating Costs Estimating Form" was utilized in this study for the hourly material handling equipment cost calculations.

#### **4.1 Estimation of Ownership Costs**

Ownership cost estimation helps to determine the short and long-term cost of a product or a system. It provides a better understanding of the investment made. As such, it helps to make a better purchasing decision between multiple alternatives of options. Therefore, the primary objective of making an ownership cost estimation is to obtain a better value from an investment in the long term.

Impacting by applying the appropriate depreciation schedules over the operating period of an equipment, this analysis is the ability to recover the investment made and to facilitate the replacement of equipment reaching its end of service life. The Unit Depreciation Method was used in this study to offset high costs of production and to avoid unnecessary depreciation charges over each operating period.

The ownership period, annual operating hours, and the total hours worked over the life of the mining operation are of great importance in determining the operating and ownership costs of equipment. Since the operating time of equipment is different for each mine, the ownership and operation costs should not be calculated by making assumptions in order to

avoid misleading results. For this reason, the ownership and operating cost calculations were made using the work schedule of the mine to achieve a realistic result.

The hourly owning and operating cost estimate template from Caterpillar’s Performance Handbook was used as the guidance for calculating the ownership and operating costs of the selected equipment fleets.

#### 4.1.1 Delivered Price to The Customer

The delivered price of equipment comprises all of the costs associated with making the equipment suitable for use by the customer. The additional costs included in the delivered price of equipment are mobilization costs and sales tax. For rubber-tired equipment, like trucks, tires are normally included in the operating costs by their users since they are considered to be a consumable commodity.

By averaging the inflation rates of the past 10 years in Turkey, the estimated base price for equipment purchased in the future is calculated by applying an annual inflation rate of 10.5%. Additionally, Turkey imposes an 18% value-added tax on imported equipment. The mobilization cost of each piece of equipment was assumed to be 2% of its base price. The calculation of each equipment’s delivered price at year 2023 is shown in Table 4.1.

Table 4.1 Delivered Prices of Mining Trucks and Excavators in 2023

<b>Equipment</b>	<b>Base Price (\$)</b>	<b>VAT (18%)</b>	<b>MOB (2%)</b>	<b>Delivered Price(\$)</b>
773E	971,800	174,900	19,440	1,166,000
770G	662,300	119,200	13,250	863,600
41400	248,300	44,700	4,967	298,000
390F L	1,050,000	208,800	21,000	1,260,000
374F L	630,600	113,500	12,610	756,700
490LCH	380,100	68,420	7,602	456,100
772G	873,600	157,200	17,470	1,048,000

#### 4.1.2 Equipment Depreciation Calculations

Most types of mining equipment have a salvage value at any given point in their lives, including the time of sale. Some owners depreciate their investment until the value of their equipment reaches zero, while others depreciate their machinery up to its resale price. In this study, the operational life of mining trucks and excavators were assumed to be 30,600 hours. Under this pretext, equipment that reaches its operational life is assumed to require a rebuild. In certain situations (numerous rebuilds), the equipment may need to be taken out of service

and scrapped or salvaged. Since purchasing new equipment will normally cost the company significantly more than rebuilding it, ownership cost calculations were made including rebuild cost calculations.

The proposed mining equipment was amortized until the end of its operational life and an appropriate rebuilding schedule was also applied according to the operational requirements. The main purpose behind this procedure is to minimize the loss arising from the high capital costs of the equipment. This procedure also aims to minimize the loss associated with the work accomplished, hourly ownership costs, and the customer's depreciation costs.

In this study, the Unit of Production Depreciation method was used to calculate the total cost of equipment ownership. Under this method, the hourly fixed depreciation costs were calculated by dividing the total delivered price of equipment to its projected operating life, which is assumed to be 30,600 hours. After each equipment reaches 30,600 hours of operating time, it will be rebuilt and placed back into service as needed. After consultation with equipment suppliers, it was assumed that the rebuild costs of off-highway and on-highway equipment should be assumed to equal 40% and 25% of their total delivered price, respectively. The following example shows the calculation of the unit depreciation costs for a Caterpillar model 773E rigid frame haul truck purchased in 2023.

- Items to note:
  - Assumed average operating hours of equipment = 5100 hours/year
  - Projected operating life of equipment before rebuild = 30,600 hours (end of year 6)
  - Truck delivered price in 2023 = \$1,166,000
  - Truck delivered price at the end of projected operating hours = \$1,601,000
  - Truck rebuild cost =  $\$1,601,000 * 40\% = \$768,500$
  - Depreciation Cost per hour (before rebuilding) =  $\$1,166,000 / 30,600 \text{ hours} = 38.11 \text{ \$/hr}$
  - Depreciation Cost per year (before rebuilding) =  $38.11 \text{ \$/hr} * 5100 \text{ hours/year} = 194,400 \text{ \$/year}$
  - Depreciation Cost per hour (after rebuilding) =  $\$768,500 / 30,600 \text{ hours} = 25.11\text{\$/hr}$
  - Depreciation Cost per year (after rebuilding) =  $25.11\text{\$/hr} * 5100 \text{ hours} = 128,100 \text{ \$/year}$

Table 4.2 Salvage Value Calculation for Caterpillar 773E

Years	First Book Value (\$)	Depreciation	Remaining Book Value (\$)
2023	\$1,166,000	\$194,400	\$971,800
2024	\$1,014,000	\$194,400	\$777,400
2025	\$811,000	\$194,400	\$583,100
2026	\$648,800	\$194,400	\$388,700
2027	\$519,000	\$194,400	\$194,400
2028	\$415,200	\$194,400	0
2029	\$768,500	\$128,100	\$640,400
2030	\$640,400	\$128,100	\$512,300
2031	\$512,300	\$128,100	\$384,200
2032	\$384,200	\$128,100	\$256,200
2033	\$256,200	\$128,100	\$128,100
2034	\$128,100	\$128,100	0

Using the data and assumptions given above, the depreciation schedule of the Caterpillar model 773E haul trucks purchased in year 2023 was calculated in Table 4.2.

#### 4.1.3 Net Value to be Recovered Through Work

The total capital cost of the equipment was calculated by subtracting the salvage value from the equipment's delivered price. To maintain the value of the purchased asset, the total delivered price of equipment was divided by the annual operating time of the equipment.

The examples shown below represent the calculation of the net value to be recovered through work for the Caterpillar model 773E haul truck in 2023 and for 6 years of ownership before rebuilding.

- Items to note:

- *Delivered Price* = \$1,166,000
- *Salvage (Resale) Value* = \$0
- *Net Value to be Recovered Through Work* = \$1,166,000
- *Total Projected Operating Hours* = 5100 hours \* 6 years = 30,600 hours

$$\text{Hourly Cost} = (\text{Delivered Price} - \text{Residual Value}) / \text{Total Operating Hours} \quad (4.1)$$

$$\text{Hourly cost to be recovered} = (\$1,166,160) / 30,600 = 38.1\$/\text{hr}$$

#### 4.1.4 Finance and Interest Charges

Finance charges are the total amount paid when using a loan, which includes interest rates, origination fees, service fees and late fees. Whereas interest is considered as the cost of capital used to purchase equipment. If equipment is purchased without any financial support, the annual interest cost does not need to be included in hourly ownership cost calculations. Therefore, since the equipment is purchased at the beginning of the operation and will be amortized/depreciated through its projected operating life, the interest costs were not included in the ownerships cost calculations after equipment undergoes a scheduled rebuild. A simple interest rate of 10.5% is applied to the hourly investment cost calculations.

The hourly interest cost of equipment is calculated by the equation given below:

$$\text{Interest Cost} = \frac{\left[ \frac{P * (N + 1) + S * (N - 1)}{2N} \right] * \text{Simple Interest Rate}\%}{\text{Operating Hours/Year}} \quad (4.2)$$

Where:

- $P = \text{Delivered Price}$
- $N = \text{Operating Years}$
- $S = \text{Salvage Price}$

The following example shows how the interest cost is calculated for the truck model 773E with a simple interest rate of 10.5%.

$$\frac{\left[ \frac{\$1,166,160 * (6 + 1) + \$0 * (6 - 1)}{2 * 6} \right] * 10.5\%}{5100} = 14 \text{ \$/hour}$$

#### 4.1.5 Insurance Cost and Property Taxes

Equipment insurance covers the costs of damaged, lost, or broken equipment that may occur during any kind of work done at the mining site. Capital losses that may occur due to deliberate theft or operator abuse can also be covered by equipment insurance.

Property taxes in Turkey are determined according to the type of equipment purchased. The mining industry is also responsible for paying property taxes annually for all equipment owned. In this study, the annual insurance and property tax rates were assumed to be 1% and

0.1% of average annual investment made during the use period, respectively. Equations (4.3) and (4.4) were utilized to find the annual insurance and tax costs of trucks.

$$Insurance\ Cost = \frac{\left[ \frac{P * (N + 1) + S * (N - 1)}{2N} \right] * Insurance\ Rate\%}{Operating\ Hours/Year} \quad (4.3)$$

$$Property\ Tax = \frac{\left[ \frac{P * (N + 1) + S * (N - 1)}{2N} \right] * Tax\ Rate\%}{Operating\ Hours/Year} \quad (4.4)$$

The examples given below show the calculation of the insurance cost and property tax for Caterpillar truck model 773E.

$$Insurance\ Cost = \frac{\left[ \frac{\$1,166,160 * (6 + 1) + \$0 * (6 - 1)}{2 * 6} \right] * 1\%}{5100} = 1.3\$ / hour$$

$$Property\ Tax = \frac{\left[ \frac{\$1,267,130 * (6 + 1) + \$0 * (6 - 1)}{2 * 6} \right] * 0.1\%}{5100} = 0.1 \$ / hour$$

## 4.2 Estimation of Operating Costs

The operating cost of earthmoving equipment is included in the cost calculations from the moment the equipment is placed into service and is influenced by several important factors. The major components of operating costs are fuel consumption, regular maintenance (engine oil and labor), hourly tire replacement costs, undercarriage costs, special consumables and operator's hourly wage.

### 4.2.1 Equipment Fuel Consumption

The most accurate fuel consumption data for equipment can be obtained from the field: when the collection of field data is not possible, the estimation of fuel consumption should be made according to the conditions in which the equipment is operating and the assumed capabilities of the operator.

The process of determining the fuel consumption for a given piece of equipment is significantly easier using an engine load factor. In this study, the fuel consumption calculations for both trucks and excavators were made with an assumption of a 50% engine load factor. By using the hourly fuel consumption tables of selected material handling equipment, an average of the fuel consumption interval was used to calculate hourly fuel

consumptions of each machine. In addition, the unit price of diesel fuel is assumed to be \$1 per liter at the time of this study.

The following example shows the calculation of fuel consumption of a Caterpillar truck model 773E with 50% engine load placed into service in 2023. For subsequent years, the fuel price cost can be estimated by applying a 10.5% annual inflation rate to the cost below.

- Items to note:
  - Fuel consumption per hour of operation= 28 – 35 liters
  - Unit price of diesel = \$1/liter
  - Engine load factor = 50%
  - Hourly fuel consumption =  $[28 + (35 - 28) * 0.5] * \$1/\text{liter} = 31.5 \text{ \$/hour}$

#### **4.2.2 Planned Maintenance**

Planned maintenance routines are required to optimize mining equipment mechanical availabilities and life. Repair and maintenance expenses have the highest operational costs as they include the expenses for labor, consumable parts and service facilities. Daily operation causes some parts to wear out and fail faster than others. Maintenance routines that are not performed on schedule can cause costs to increase. While some minor repairs and maintenance can be completed without removing the equipment from the site, many maintenance activities and major repairs will require the equipment to be removed from operations for an extended period of time. By using the mine cost estimation service's data, the total planned maintenance cost, including lube oils, grease and labor, was found to be \$14.72 per hour for a Caterpillar truck model 773E.

#### **4.2.3 Tire Replacement Cost**

Tire costs constitute a significant portion of a truck's overall operating costs and are one of the most difficult costs to estimate. The best tire life estimates can be made from historic data at a particular mine site and field experience gained by the mine operators. Estimates can be made according to field conditions using tire life estimation graphs in new projects, or in cases where no tire history exists. However, these tables do not consider the changes in the life of tires after coating and sudden tire punctures that occur from overloading and excessive speed. Tire life estimation chart (see "Caterpillar Performance Handbook", page 2132) was utilized for the life estimation of both off-highway and on-highway truck tires as there was no available field data.

The application zones are categorized according to the considerations listed below:

- Zone A: All tire treads wear out equally because of abrasion on good road surfaces that are maintained regularly.
- Zone B: Some of the tires wear out more quickly than others because of uneven ground conditions.
- Zone C: All tires wear out because of uneven and unmaintained roads.

In the case study, as a consequence of good road conditions within the pit and surface facilities and timely maintenance of haul roads, the default tire life is estimated to be 6000 hours which falls into application zone A. The example below shows the hourly tire replacement cost calculation for a Caterpillar model 773E haul truck placed into service in 2023.

▪ Items to note:

- Estimated Truck tire life = 6000 hours
- Tire model = 24.00R35 2
- Unit tire price = \$8,502
- Number of tires = 6
- Hourly tire replacement cost =  $(\$8,502.4 * 6) / 6000 = 8.5$  \$/hour

#### 4.2.4 Undercarriage Costs

Undercarriage expenses in track-typed equipment constitute a large part of the operating costs associated with excavators and dozers. In some instances, material excavation can be relatively easy, but the ground conditions can cause excessive wear. In these circumstances, it is recommended to include the undercarriage costs as a separate cost item. Undercarriage cost calculations are influenced by 3 primary factors, which include Impact, Abrasiveness and Z factors (Caterpillar, 2018).

The impact factor for tracked equipment is determined by how firm and rough the ground conditions are and can be subdivided into 3 categories: high, medium, and low (as defined below). These 3 categories consider the compactness and irregularities of working surfaces which are also called bumps.

- High Impact: The ground is non-penetrable, and bumps are higher than 6 inches.
- Medium Impact: The ground is moderately penetrable, and bump heights are between 3 to 6 inches.

- Low Impact: The ground is highly penetrable and has fewer bumps.

Abrasiveness is defined as the wear on the track surface and other components caused by varying size of rocks and other abrasive particles on the ground surface. The abrasiveness ratings are categorized into 3 parameters:

- Highly Abrasive Ground: Water-saturated soil containing a large amount of sharp, angular, hard sand, and rock particles.
- Moderately Abrasive Ground: Moist soil containing low amounts of sharp, angular, hard sand, and rock particles.
- Low Abrasive Ground: Dry soil containing little or no sharp, angular, hard sand, and rock particles.

The Z factor represents the cumulative impact of the environmental, operational and maintenance factors on equipment parts. The selection of the Z factor is generally determined by the evaluation of all conditions. In this study, all track type equipment is assumed to be working in moderate impact, abrasive ground, and Z factor conditions.

The undercarriage cost was estimated using the equipment manufacturer's chart to determine the basic factor for each track type model. After determining the range of each condition multiplier, the chosen basic factor was multiplied with the sum of the condition multipliers to find hourly undercarriage costs.

The following example shows how the undercarriage cost of Caterpillar model 390F L excavator was calculated.

- The basic factor for the equipment model 390F L is assumed to be same as 365C since both excavator models have the same hourly capacity.
- Referring to Undercarriage Basic Factors Chart (see "Caterpillar Performance Handbook", page 2136), the basic factor and condition multipliers for 390F L were determined as:
  - Basic Factor = 6.8
  - Impact multiplier (moderate impact) = 0.2
  - Abrasiveness multiplier (moderate abrasiveness) = 0.5
  - Z factor (moderate conditions) = 0.5
  - Undercarriage Cost =  $6.8 * (0.2 + 0.5 + 0.5) = 8.2$  \$/hour

#### **4.2.5 Repair Costs**

Repair costs vary according to the environmental and geological conditions in which the equipment is operating. For this reason, repair costs should be evaluated by making one-to-one evaluations between the customer and the equipment dealer with reference to the site-specific assessments. In that way, a more realistic cost calculation can be made to accommodate various situations (Caterpillar, 2018).

Operational conditions, the total period of time the equipment is used, and regular maintenance are effective considerations in determining repair costs. In some cases, comparisons with similar operations are an effective method for accurate cost estimation. In this study, the repair costs of all selected equipment were collected from the mine cost estimation service's website. The repair cost of a Caterpillar model 773E haul truck is estimated to be \$12.5 per hour.

#### **4.2.6 Special Wear Items**

All equipment parts that are subjected to a high degree of wear and stress, such as bucket teeth, booms, sticks, and welded parts should be included in this category. These costs vary depending on the geological character of the material in the mine, the conditions of the haul road, and the experience of the operator. For this reason, costs should be determined with the assessments of the technical service consultants and equipment operators by examining all of the conditions. In this study, the costs of special wear items were collected from the mine cost estimation service's website. The hourly cost of special wear items for Caterpillar model 390F L was estimated as \$4 per hour for 2023.

#### **4.2.7 Operator's Hourly Wage**

The salaries and additional benefits of the equipment operators are calculated under the heading of operational costs. In this study, the operator's wages were assumed to be 10,000 Turkish Liras per month. It is converted to US dollars per hour by using a Dollar to Turkish Lira exchange rate of 18.5, working 26 days per month at 8 hours per shift. The following example shows the calculation of the operator's hourly wage in US Dollars:

➤ Operator's wage =  $((10,000/18.5)/26)/8 = \$2.6$  per operating hour

### 4.3 Hourly Owning and Operating Cost of Selected Equipment

Using the case examples presented in Chapters 4.1 and 4.2, the operating and ownership costs of the entire equipment fleet can be found. After all the sub-headings in ownership and operation costs are calculated, the total costs of all proposed equipment models before and after rebuilding were calculated as USD per operating hours in Table 4.3 and 4.4 for 2023.

Table 4.3 Ownership and Operating Cost of Equipment Before Rebuilding

<b>Equipment</b>	<b>Ownership Cost</b>	<b>Operating Cost</b>	<b>Total Cost</b>
773E	53.6	61.3	114.9
772G	48.2	51.2	99.4
770G	36.5	49.0	85.6
41400	13.7	29.6	43.3
390F L	57.9	109.9	167.8
374F L	34.8	83.6	118.3
490LCH	21.0	58.6	79.6

Table 4.4 Ownership and Operating Cost of Equipment After Rebuilding

<b>Equipment</b>	<b>Ownership Cost</b>	<b>Operating Cost</b>	<b>Total Cost After</b>
773E	26	61.3	87.3
772G	23.4	51.2	74.6
770G	17.2	49	66.2
41400	4.2	29.6	33.8
390F L	35.2	109.9	145.1
374F L	21.1	83.6	104.7
490LCH	12.7	58.6	71.3

According to the calculated results, the least expensive cost for all possible truck and excavator combinations is the on-highway trucks and excavators. This is because of the availability of locally manufactured equipment in Turkey. Secondly, equipment prices and operating costs increase as the equipment capacity increases. However, savings that will be generated by choosing larger capacity equipment will provide a lower unit cost of mining.

## CHAPTER 5

### OPTIMUM MATERIAL HANDLING FLEET SELECTION

The proposed mixed integer linear programming model is deterministic in nature and developed to find the optimal material handling fleet among the on-highway and off-highway equipment options. The model developed in this study is based on a deterministic MILP approach created by C. Burt et al. (2016). It aims to find an optimal solution to the equipment selection problem with accounting multi-location and multi-period scheduling requirements. The model considers the unavailability of pre-existing equipment fleet and utilizes compatible equipment alternatives to meet production demands.

The modeling approach presented in this study utilizes a homogeneous equipment fleet and uses one type of fleet until the end of the mine life. Since the mineral reserves are small and the production schedule is shorter compared to other mining applications, the idle equipment will be salvaged at the end of the mine life. The model aims to find the equipment fleet that can meet the annual production demand for each type of material and the operational objectives defined by the mining company. Utilizing deterministic modeling via mixed-integer linear programming is preferred as the problem is complex. Also, using the stochastic modeling approach will lead to further difficulties in problem formulation and will decrease the rate of accuracy. For that reason, deterministic modelling approaches are mostly preferred when they give feasible results.

Since the ownership and operating costs of the truck and excavator fleet were not provided by the contractor company, the estimated cost values were imported from the InfoMine Mining Cost Service's online database. The estimated values of the ownership and operating costs were calculated annually over the life of the mine, and a discounting factor was applied to find the total estimated cost. These values were used as parameters in the objective function of the proposed model and multiplied by the quantity of equipment purchased in each corresponding year to find the estimated ownership and operating costs of the mining fleet.

The developed model utilizes the following considerations: a mining plan of multi-location and multi-period requirements to cover annual production, operation of the same type of truck and excavator fleet over the life of the mine, the optimal number of trucks that can cover the production demand on each route, and the maximum capacity of each equipment type operating at maximum productivity after applying the availability factors.

Solving the following model will provide an estimation of the optimal fleet configuration that can achieve the operational targets at the minimum overall cost. The results of the model will show the quantity of equipment that should be bought each year and the amount of this equipment that is working in each location in a specific year.

## 5.1 Model Assumptions

The following assumptions were made to limit the boundaries of the problem:

- The life of mine given in the case study is limited to 12 years which is short compared to typical mining projects. The shorter mine life allows using each type of equipment until its end of operational life. The possibility of fluctuations in the mine plan may require additional equipment purchases during any period. It was assumed that all purchased equipment will be rebuilt as the mine owner is not planning to purchase additional new equipment. The reason behind that assumption is the decreasing rate of truck allocation during the mine life. For that reason, the mining company plans to create its own equipment fleet held in reserve by rebuilding the equipment that will not be placed back into service during the remaining life of the mine.
- The efficiency of each type of equipment is assumed to be decreasing by 5% after every 15,000 operating hours. The reason for this assumption is to reflect the effects of equipment age on productivity.
- Several fixed parameters were employed to simplify the problem. The fixed parameters used as an input are as follows: Fixed equipment cycle times during any given period, fixed operating hours, and decreasing equipment availabilities for the entire mine life (Operating hours and the equipment availabilities were provided by the mine owner).
- An inflation rate of 10.5% was applied to equipment prices to achieve more realistic equipment prices for subsequent years. A depreciation rate of 10% was used to calculate the present value of the total investment made during the entire mine life.

## 5.2 Objective Function

The objective function aims to minimize total ownership and operating cost for the selected material handling equipment fleet. In a mining operation, the capital and operating costs change with the current year's economic conditions. The value of cost coefficients  $H_{t,k}$ ,  $F_{t,k}$ ,  $N_{t,k}$  and  $V_{t,k}$  change according to the inflation and depreciation rates over the life of the mine. The quantity of equipment purchased each year is multiplied by the calculated average

ownership cost for that year in order to find the annual ownership cost of the selected fleet. The calculated annual cost value for the purchased equipment is multiplied by the total years of operation. To find the total operating cost, the amount of equipment that is working actively each year is multiplied by the annual operating cost. The sum of the calculated ownership and operating costs yield the overall cost of the mining operation for the entire mine life.

$$\min \sum_{t \in T} \sum_{k \in K} H_{t,k} * x_{t,k} * ([k] - k + 1) + \sum_{t \in T} \sum_{k \in K} F_{t,k} * y_{t,k} * ([k] - k + 1) + \sum_{t \in T} \sum_{k \in K} \sum_{i \in I} N_{t,k} * h_{t,k,i} + \sum_{t \in T} \sum_{k \in K} \sum_{i \in I} V_{t,k} * f_{t,k,i} \quad (5.1)$$

Where

- k: Time period (k = 1, ...,12)
- t: Type of equipment fleet (t = 1, ...,7)
- i: Truck destinations and type of material hauled (I = 1, ...,5)
- H<sub>t,k</sub>: The discounted truck ownership cost for fleet type t, at year k (\$/year)
- F<sub>t,k</sub>: The discounted excavator ownership cost for fleet type t, at year k (\$/year)
- N<sub>t,k</sub>: The discounted truck operating cost for fleet type t, at year k (\$/year)
- V<sub>t,k</sub>: The discounted excavator operating cost for fleet type t, at year k (\$/year)
- D<sub>k,i</sub>: Production demand at year k, in location I (tons/year)
- P<sub>t,k,i</sub>: Productivity of excavator for fleet type t, at year k, in location i (tons/year)
- G<sub>t,k,i</sub>: Productivity of truck for fleet type t, at year k, in location i (tons/year)
- x<sub>t,k</sub>: Number of trucks for fleet type t, purchased at year k
- y<sub>t,k</sub>: Number of excavators for fleet type t, purchased at year k
- h<sub>t,k,i</sub>: Number of trucks for fleet t, purchased at year k, working in location i
- f<sub>t,k,i</sub>: Number of excavators for fleet t, purchased at year k, working in location i
- z<sub>t</sub>: {1, if same fleet type t selected by the model for entire mine life, 0, otherwise}
- b<sub>t,k</sub>: {1, if excavator for fleet type t purchased at year k, 0, otherwise}
- d<sub>t,k</sub>: {1, if truck for fleet type t purchased at year k, 0, otherwise}

The indices used in the model are denoted as;

- t<sub>1</sub>= Caterpillar 390F L and 773E,
- t<sub>2</sub>= Caterpillar 390F L and 772G,
- t<sub>3</sub>= Caterpillar 390F L and 770G,
- t<sub>4</sub>= Caterpillar 374F L and 773E,
- t<sub>5</sub>= Caterpillar 374F L and 772G,

t<sub>6</sub>= Caterpillar 374F L and 770G,

t<sub>7</sub>=Hitachi 490 LCH and MAN 41400

k= 1, ...,12 represents the years of remaining mine life;

k<sub>1</sub>=2023

k<sub>12</sub>=2034

i= 1, 2, 3, 4, 5 represents the locations (dump sites):

i<sub>1</sub>=Leach Pad

i<sub>2</sub>=NAG

i<sub>3</sub>=PAG

i<sub>4</sub>=Stockpile

i<sub>5</sub>=TSF

### 5.3 Constraints

The objective function is restricted by production demand, equipment compatibility, and the number of equipment constraints.

#### a) Production Demand Constraint

Production during each mining period should meet the given production schedule requirements. The production demand at each dump location is expressed in tons per hour of material flow. To meet production demand, the fleet capacities per hour was determined for each dump location at the mine site. This constraint determines the number of excavators needed in a specific dump location during a specific year in fractions.

#### b) Equipment Matching Constraint

$$\sum_{t \in T} P_{t,k,i} * f_{t,k,i} \geq D_{k,i} \quad \text{For } \forall k, i \quad (5.2)$$

A given truck can only work with a given excavator that satisfies the operational constraints for both. These constraints will be the number of passes to load a truck, the minimum dumping height of the excavator, and the capacity of each piece of equipment. The equipment was chosen by matching their capacities to each other.

$$G_{t,k,i} * h_{t,k,i} \geq P_{t,k,i} * f_{t,k,i} \quad \text{For } \forall t, k, i \quad (5.3)$$

#### c) Number of Trucks Constraints

The number of trucks that are scheduled for service can vary annually. The

requirement to purchase trucks is determined by taking the difference in the demand for trucks among subsequent years. If the difference in the number of trucks is greater than 0, more trucks need to be purchased. If the difference in the number of trucks is 0 or less, no additional trucks need to be purchased.

$$x_{t,k} \geq \sum_{i \in I} h_{t,k,i} - \sum_{i \in I} h_{t,k-1,i} \quad \text{For } \forall t, k \quad (5.4)$$

$$M * d_{t,k} \geq \sum_{i \in I} h_{t,k,i} - \sum_{i \in I} h_{t,k-1,i} \quad \text{For } \forall t, k \quad (5.5)$$

$$z_t \geq \sum_{k \in K} d_{t,k} \quad \text{For } \forall t \quad (5.6)$$

$$x_{t,k} \leq \sum_{i \in I} h_{t,k,i} - \sum_{i \in I} h_{t,k-1,i} + M(1 - z_t) + M * (1 - d_{t,k}) \quad \text{For } \forall t, k \quad (5.7)$$

d) Number of Excavators Constraints

This constraint is similar to the process of calculating the constraint associated with the number of trucks. In this constraint, the number of excavators needed to be purchased each year is the difference of the number of operational excavators and the number needed in the following year. If the difference in the number of excavators needed between two years is greater than 0, additional purchases equivalent to the amount of that difference needs to be made. If the difference in the number of excavators is 0 or less, no excavators need to be purchased.

$$y_{t,k} \geq \sum_{i \in I} f_{t,k,i} - \sum_{i \in I} f_{t,k-1,i} \quad \text{For } \forall t, k \quad (5.8)$$

$$M * b_{t,k} \geq \sum_{i \in I} f_{t,k,i} - \sum_{i \in I} f_{t,k-1,i} \quad \text{For } \forall t, k \quad (5.9)$$

$$z_t \geq \sum_{k \in K} b_{t,k} \quad \text{For } \forall t \quad (5.10)$$

$$y_{t,k} \leq \sum_{i \in I} f_{t,k,i} - \sum_{i \in I} f_{t,k-1,i} + M(1 - z_t) + M * (1 - b_{t,k}) \quad \text{For } \forall t, k \quad (5.11)$$

e) Initial Conditions Constraints

The mine owner does not have an excavator or truck fleet at the beginning of their operation. These constraints ensure that the initial amount of equipment is 0.

$$x_{t,0} = 0 \quad \text{For } \forall t \quad (5.12)$$

$$y_{t,0} = 0 \quad \text{For } \forall t \quad (5.13)$$

$$h_{t,0,i} = 0 \quad \text{For } \forall t, i \quad (5.14)$$

$$f_{t,0,i} = 0 \quad \text{For } \forall t, i \quad (5.15)$$

f) Selecting and Purchasing Same Type of Equipment each Year Constraints

These constraints force the model to purchase the same type of fleet every year. The mine owner will employ a homogeneous fleet until the end of the mine life.

$$\sum_{t \in T} z_t \leq 1 \quad \text{For } \forall t \quad (5.16)$$

$$\sum_{t \in T} d_{t,k} \leq 1 \quad \text{For } \forall k \quad (5.17)$$

$$\sum_{t \in T} b_{t,k} \leq 1 \quad \text{For } \forall k \quad (5.18)$$

g) Non-negativity Constraints

These constraints ensure the solutions of the decision variables are positive integers, rational, and binary numbers.

$$x_{t,k}, y_{t,k} \in \mathbb{Z}^+ \quad (5.19)$$

$$h_{t,k,i}, f_{t,k,i} \in \mathcal{R}^+ \quad (5.20)$$

$$z_t, b_{t,k}, d_{t,k} = 0 \text{ or } 1 \quad (5.21)$$

CHAPTER 6  
IMPLEMENTATION OF THE MILP MODEL

The mine providing the input data for this study has been operating since the beginning of 2021. The earth removal operation was contracted to a local mining company for the pre-stripping of waste material and the oxide mining operation. The equipment fleet that the contractor is utilizing at the mine site is composed of on-highway trucks and hydraulic backhoe excavators. Since the oxide project has almost completed its life and the production amount is much less than the sulfide project, the amount of equipment available in the inventory is not considered sufficient for the later stages of the project. For the sulfide project, there is no comparative solution regarding the fleet size, ownership, and operating costs. The objective of this study is the selection of the optimal truck and excavator fleets to meet the production demands over the life of the mine.

### 6.1 Production Requirements

The mine owner seeks to determine the optimal fleet type and size according to their long-term production goals. For this study, the life of the mine is 12 years from 2023 through 2034. According to the given hourly production requirements, the number of fleets required to produce each type of material is determined by dividing the hourly production demands by the hourly fleet capacity (the annual production demand that was provided by the mine owner is represented with the parameter  $D_{k,i}$ ). The production demand for PAG material in 2023 is represented with the parameter  $D_{1,1}$  which is equal to 3,040,000 tons per year.

Table 6.1 Annual Production Demand  $D_{k,i}$  (tons/year)

<b>Years</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Leach Pad</b>	<b>Stockpile</b>
<b>1</b>	3,040,000	10,260,000	5,960,000	847,000	-
<b>2</b>	3,240,000	14,060,000	5,960,000	794,000	53,000
<b>3</b>	5,680,000	6,770,000	5,960,000	308,000	1,791,000
<b>4</b>	4,280,000	9,440,000	5,960,000	55,000	1,800,000
<b>5</b>	6,350,000	11,260,000	-	40,000	1,800,000
<b>6</b>	3,710,000	14,380,000	-	23,000	1,800,000
<b>7</b>	3,250,000	11,880,000	-	-	1,800,000
<b>8</b>	3,580,000	10,110,000	-	-	1,800,000
<b>9</b>	2,970,000	4,420,000	-	-	1,800,000
<b>10</b>	2,540,000	3,560,000	-	-	1,800,000
<b>11</b>	2,670,000	3,550,000	-	-	1,720,000
<b>12</b>	1,940,000	2,590,000	-	-	873,000

## 6.2 Haul Routes and Dump Locations Information

As stated previously, there are 5 dumping locations and 5 different material types. Each type of material excavated in the mine is delivered to the appropriate location, which includes the Leach pad, Mill, PAG dump site, NAG dump site, and TSF dump site.

According to the calculated lengths of each haul segment, the total cycle time of the selected mining trucks was calculated using the equations derived in Chapter 3.

The 7 fleet types given are:

- Fleet type 1: Cat 390F L and 773E (t=1),
- Fleet type 2: Cat 390F L and 772G (t=2),
- Fleet type 3: Cat 390F L and 770G (t=3),
- Fleet type 4: Cat 374F L and 773E (t=4),
- Fleet type 5: Cat 374F L and 772G (t=5),
- Fleet type 6: Cat 374F L and 770G (t=6),
- Fleet type 7: Hitachi 490 LCH and MAN 41400 (t=7)

The estimated truck cycle times for all of the proposed equipment fleet options fluctuate in each period and route as the lengths, grades, turning radii, and maximum safe truck speeds change. The speed of truck models 773E, 772G and 770G were generated by using the rimpull and retarder charts provided by Caterpillar. As a result of the time studies carried out at the mine site and within the framework of the information provided by the mine owner, the maximum speeds of on-highway trucks were taken as 25 km/h while hauling and 35 km/h while returning empty to the mining area. The average speed calculations were also conducted for the on-highway truck fleet (The rimpull and retarder charts for on-highway trucks were not available from the manufacturer).

## 6.3 Equipment Fleet Productivity Dataset

The maximum fleet productivity rate is limited by the equipment with the lowest hourly production capacity. In most cases, the productivity of the trucks determines the fleet's overall capacity. This condition is a result of truck queuing times while waiting for other trucks to get loaded. In this study, the optimal number of trucks were determined for each haul destination for the least amount of truck queuing times. By following this approach of calculating truck queuing times, the optimal fleet productivity can be achieved by keeping all operating excavators busy.

The truck and excavator productivity rates (tons/year) are represented with the parameters  $P_{t,k,i}$  and  $G_{t,k,i}$  in the model formulation and the input data for on-highway truck and excavator fleet is represented in Table 6.2 and Table 6.3. The excavator productivity rate for fleet type 1, in year 2023 and at location PAG is represented with the parameter  $P_{1,1,1}$  which is equal to 3,136,400 tons per year.

Table 6.2 Annual Excavator Productivity Rate  $P_{t,k,i}$  (tons/year)

<b>Years</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Leach Pad</b>	<b>Stockpile</b>
1	3,136,400	3,136,400	3,136,400	3,136,400	3,685,200
2	3,136,400	3,136,400	3,136,400	3,136,400	3,685,200
3	3,136,400	3,136,400	3,136,400	3,136,400	3,685,200
4	2,797,600	2,797,600	2,797,600	2,797,600	3,287,200
5	2,797,600	2,797,600	2,797,600	2,797,600	3,287,200
6	2,797,600	2,797,600	2,797,600	2,797,600	3,287,200
7	2,478,000	2,478,000	2,478,000	2,478,000	2,911,800
8	2,478,000	2,478,000	2,478,000	2,478,000	2,911,800
9	2,478,000	2,478,000	2,478,000	2,478,000	2,911,800
10	2,178,000	2,178,000	2,178,000	2,178,000	2,559,200
11	2,178,000	2,178,000	2,178,000	2,178,000	2,559,200
12	2,178,000	2,178,000	2,178,000	2,178,000	2,559,200

Table 6.3 Annual Truck Productivity Rate  $G_{t,k,i}$  (tons/year)

<b>Years</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Leach Pad</b>	<b>Stockpile</b>
1	522,700	1,045,500	522,700	627,300	614,200
2	522,700	1,045,500	522,700	627,300	614,200
3	448,000	784,100	627,300	627,300	614,200
4	399,600	699,400	559,500	559,500	547,900
5	399,600	699,400	559,500	559,500	547,900
6	399,600	699,400	466,300	399,700	547,900
7	354,000	619,500	413,000	354,000	485,300
8	354,000	619,500	413,000	354,000	485,300
9	354,000	619,500	413,000	495,600	485,300
10	311,200	544,500	363,000	435,600	426,500
11	311,200	544,500	363,000	435,600	426,500
12	311,200	544,500	363,000	435,600	426,500

#### 6.4 Equipment Ownership and Operating Cost Dataset

The equipment ownership costs were estimated by using the ownership and operating cost estimation form from Caterpillar Performance Handbook. Equipment base prices and maintenance costs were imported from the Mine Cost Estimation Service’s website for the corresponding machine sizes and capacities.

The annual discounted truck and excavator ownership cost (\$/year) are represented with the parameters  $H_{t,k}$  and  $F_{t,k}$ , and operating costs are represented with the parameters  $N_{t,k}$  and  $V_{t,k}$ , respectively. The annual discounted truck ownership and operating costs ( $H_{t,k}$  and  $N_{t,k}$ ) and excavator ownership and operating costs ( $F_{t,k}$  and  $V_{t,k}$ ) were provided in Table 6.4 and Table 6.5 for an on-highway truck and excavator fleet ( $H_{1,1}$  represents the annual discounted ownership cost of truck type 1 in the first operating period). The annual discounted ownership cost of truck type 1 in the first operating period is represented with  $H_{1,1}$  which is equal to \$177,900 per year.

Table 6.4 Discounted Truck Ownership ( $H_{t,k}$ ) and Operating Cost ( $N_{t,k}$ )

<b>Years</b>	<b>Ownership Cost</b>	<b>Operating Cost</b>
1	177,900	312,500
2	187,600	313,900
3	185,200	315,400
4	213,000	316,800
5	230,200	318,200
6	225,100	319,700
7	280,800	321,100
8	293,700	322,600
9	306,700	324,100
10	319,900	325,500
11	333,100	327,000
12	346,496	328,500

Table 6.5 Discounted Excavator Ownership ( $F_{t,k}$ ) and Operating Cost ( $V_{t,k}$ )

Years	Ownership Cost	Operating Cost
1	203,400	573,700
2	212,900	576,400
3	209,200	579,000
4	237,500	581,600
5	254,400	584,200
6	244,700	586,900
7	303,300	589,600
8	317,300	592,200
9	331,400	594,900
10	345,600	597,600
11	359,900	600,400
12	374,300	603,100

## 6.5 Model Implementation Results

A comparison between the contractor's case and suggested off-highway fleets was made according to the net present value of ownership and the operating cost of the fleet purchased to meet the long-term production demand. The optimal result of the developed model was compared with the total and unit costs of other proposed equipment in order to see the total savings achieved when the optimal equipment choice was made. For comparison purposes, the total and unit costs to be incurred as a result of the utilization of each proposed equipment option throughout the life of the mine have been calculated one by one and compared to the optimal solution. To achieve results for the proposed equipment fleet other than the optimal case, an additional constraint should be included in the developed programming model to force solver to calculate results. For the case study presented in this study, the constraints given below should be added separately in each of the model runs. Since the optimal solution was achieved with the 7<sup>th</sup> equipment fleet, the results for the first 6 fleets should be calculated separately.

- The additional constraints are:

- $\sum_{t \in T} z_1 = 1$

- $\sum_{t \in T} z_2 = 1$

- $\sum_{t \in T} z_3 = 1$

- $\sum_{t \in T} z_4 = 1$
- $\sum_{t \in T} z_5 = 1$
- $\sum_{t \in T} z_6 = 1$

The developed programming model was solved in AMPL Gurobi solver by using the available dataset. The model is solved with 808 continuous and 98 integer variables, where 35 of them were binary variables. The model solution was achieved by 678 iterations in 0.125 seconds. First, the optimal solution was achieved for the fleet giving the minimum ownership and operating cost, number of excavators and trucks required to be purchased each year and the number of trucks and excavators that need to produce the specific type of material each year. Since no information was provided concerning the terms of the current contract, the model was run one by one for other equipment fleets to compare results.

The optimized results indicate that the mine owner should choose on-highway mining trucks and excavators on the basis of possessing the lowest overall costs between all fleets evaluated in this study.

Table 6.6 and 6.7 show the total number of trucks and excavators operating each year and provide the ownership and operating cost analysis for each set of equipment fleets.

Table 6.6 The Number of Trucks Operating for Each Equipment Fleet

<b>Number of Operating Trucks</b>							
<b>Periods</b>	<b>390FL-773E</b>	<b>390FL-772G</b>	<b>390FL-770G</b>	<b>374FL-773E</b>	<b>374FL-772G</b>	<b>374FL-770G</b>	<b>41400-490LCH</b>
<b>2023</b>	31	37	45	34	40	46	53
<b>2024</b>	34	45	49	37	45	54	61
<b>2025</b>	39	47	61	44	52	64	68
<b>2026</b>	39	45	60	42	52	63	67
<b>2027</b>	36	41	49	39	44	55	64
<b>2028</b>	34	37	43	37	38	49	51
<b>2029</b>	33	35	43	35	36	47	49
<b>2030</b>	31	33	41	33	34	44	46
<b>2031</b>	20	22	32	21	26	30	31
<b>2032</b>	19	21	31	21	26	29	31
<b>2033</b>	20	22	31	21	26	30	29
<b>2034</b>	14	14	21	14	18	20	20
<b>Truck Ownership Cost</b>	\$81.5M	\$85.2M	\$84.7M	\$87.7M	\$97.6M	\$89.2M	\$32.1M
<b>Truck Operating Cost</b>	\$109.5M	\$108.4M	\$112.2M	\$116.2M	\$118.3M	\$118.8M	\$94.2M
<b>Total Cost (\$)</b>	\$191.1M	\$193.6M	\$196.8M	\$203.9M	\$215.9M	\$208.0M	\$126.3M
<b>Unit Cost (\$/ton-material)</b>	\$1.01	\$1.03	\$1.04	\$1.08	\$1.14	\$1.10	\$0.67

Table 6.7 The Number of Excavators Operating for Each Equipment Fleet

<b>Number of Operating Excavators</b>							
<b>Periods</b>	<b>390FL-773E</b>	<b>390FL-772G</b>	<b>390FL-770G</b>	<b>374FL-773E</b>	<b>374FL-772G</b>	<b>374FL-770G</b>	<b>41400-490LCH</b>
2023	7	8	8	8	8	8	10
2024	9	9	9	9	9	10	12
2025	8	9	9	8	8	8	11
2026	8	9	9	9	9	10	11
2027	8	8	8	8	8	9	11
2028	8	8	8	8	8	9	11
2029	7	8	8	8	8	9	11
2030	7	7	7	7	7	8	10
2031	4	4	4	5	5	5	6
2032	4	4	4	4	4	5	6
2033	4	4	4	4	4	5	6
2034	3	3	3	3	3	3	4
<b>Excavator Ownership Cost</b>	\$19.4M	\$21.8M	\$21.9M	\$13.1M	\$13.1M	\$14.5M	\$10.4M
<b>Excavator Operating Cost</b>	\$43.4M	\$45.7M	\$46.8M	\$35.7M	\$35.2M	\$38.7M	\$34.9M
<b>Total Cost (\$)</b>	\$62.8M	\$67.5M	\$68.7M	\$48.8M	\$48.3M	\$53.3M	\$45.3M
<b>Unit Cost (\$/ton-material)</b>	\$0.33	\$0.36	\$0.36	\$0.26	\$0.26	\$0.28	\$0.24

Table 6.8 presents the number of excavators for the optimal fleet, which needs to excavate each material type corresponding to the mining location (in fractional numbers). Providing the number of excavators in fractional numbers ensures that each excavator can complete their operational time for other assigned tasks once they have completed the required production for the material they were initially assigned.

Table 6.8 The Number of Excavators Required (In fractions)

<b>Years</b>	<b>Oxide</b>	<b>Sulfide</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Total</b>
<b>2023</b>	0.40	0.00	1.50	5.10	3.00	10
<b>2024</b>	0.40	0.02	1.60	7.00	9.00	12
<b>2025</b>	0.15	0.70	2.80	4.20	3.00	11
<b>2026</b>	0.03	0.70	2.10	5.10	3.00	11
<b>2027</b>	0.02	0.80	3.50	6.50	0.00	11
<b>2028</b>	0.01	0.80	2.00	8.00	0.00	11
<b>2029</b>	0.00	0.90	2.00	7.50	0.00	11
<b>2030</b>	0.00	0.90	2.25	6.40	0.00	10
<b>2031</b>	0.00	0.90	1.90	2.80	0.00	6
<b>2032</b>	0.00	1.00	1.80	2.60	0.00	6
<b>2033</b>	0.00	1.00	1.90	2.50	0.00	6
<b>2034</b>	0.00	0.50	1.40	1.85	0.00	4

Similarly, by utilizing Table 6.9, the mine owner can dispatch its truck fleet between different mining locations, thereby increasing productivity and equipment efficiency.

Table 6.9 The Number of Trucks Required (In fractions)

<b>Years</b>	<b>Oxide</b>	<b>Sulfide</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Total</b>	<b>Op. Hours</b>
<b>2023</b>	2.10	0.00	9.00	20.40	20.70	53	266,600
<b>2024</b>	2.00	0.20	9.70	28.00	20.70	61	308,700
<b>2025</b>	0.80	5.00	19.70	16.80	20.70	68	344,000
<b>2026</b>	0.10	5.00	14.90	23.40	20.70	66	337,200
<b>2027</b>	0.10	5.60	24.70	31.30	0	63	322,300
<b>2028</b>	0.10	6.50	12.40	32.00	0	51	260,000
<b>2029</b>	0	6.40	12.30	29.90	0	49	247,300
<b>2030</b>	0	6.40	13.50	25.40	0	45	231,000
<b>2031</b>	0	6.40	13.00	11.10	0	31	155,900
<b>2032</b>	0	7.20	12.70	10.20	0	30	154,900
<b>2033</b>	0	6.90	11.50	10.20	0	29	145,600
<b>2034</b>	0	3.50	8.30	7.40	0	19	98,100

The number of trucks presented in Table 6.9 represents the total number of trucks that are working 5100 hours in each operating year . However, the truck allocation in each mining

location was done according to the optimal number of trucks assigned that is given in Table 6.10. Therefore, by keeping the total operational hours and the total number of trucks the same in each year, the truck scheduling can be performed again by following the calculation steps below.

Table 6.10 Optimal Number of Trucks for Optimal Mining Fleet

<b>Years</b>	<b>Oxide</b>	<b>Sulfide</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>
<b>2023</b>	5	8	6	4	7
<b>2024</b>	5	8	6	4	7
<b>2025</b>	5	7	7	5	7
<b>2026</b>	5	7	7	5	7
<b>2027</b>	5	7	7	5	7
<b>2028</b>	5	8	6	4	7
<b>2029</b>	5	7	6	4	7
<b>2030</b>	5	7	6	4	7
<b>2031</b>	5	7	7	4	7
<b>2032</b>	5	7	7	4	7
<b>2033</b>	5	7	6	4	7
<b>2034</b>	5	7	6	4	7

Truck Scheduling Calculation for PAG in 2023:

- Number of Excavators Assigned by the Model (Table 6.13) = 1.50 (2 Excavators)
- Number of Trucks Assigned to the Excavators at PAG (Table 6.14) = 1.50 Excavators \* 6 Trucks/Excavator = 9 trucks
- Optimal Number of Trucks Assigned for each Excavator (Table 6.15) = 6 Trucks/Excavator
- Total Required Optimal Number of Trucks = 2 Excavators \* 6 Trucks = 12 Trucks
- Maximum Operating Hours Assigned for the Trucks by the Model = 9 \* 5100 = 45,900 hours
- Total Operating Hours of Optimal Number of Trucks = 6 \* 1 \* 5100 + 6 \* 0.5 \* 5100 = 45,900 hours

These calculations show that the total operating hours of the trucks assigned by the model and the required number of optimal trucks are the same. Following the same methodology, the optimal truck allocation is presented in Table 6.11.

Table 6.11 Optimal Truck Allocation for Optimal Mining Fleet

Years	Oxide	Sulfide	PAG	NAG	TSF	Op. Hours
2023	5	0	12	24	21	266,600
2024	5	8	12	28	21	308,700
2025	5	7	21	20	21	344,000
2026	5	7	21	25	21	337,200
2027	5	7	28	35	0	322,300
2028	5	8	18	36	0	260,000
2029	0	7	18	32	0	247,300
2030	0	7	18	28	0	231,000
2031	0	7	14	12	0	155,900
2032	0	14	14	12	0	154,900
2033	0	7	12	12	0	145,600
2034	0	7	12	8	0	98,100

Figure 6.1 represents the number of trucks operating in each mining location, as well as the total number of operating hours required to meet the production schedule provided by the mine owner.

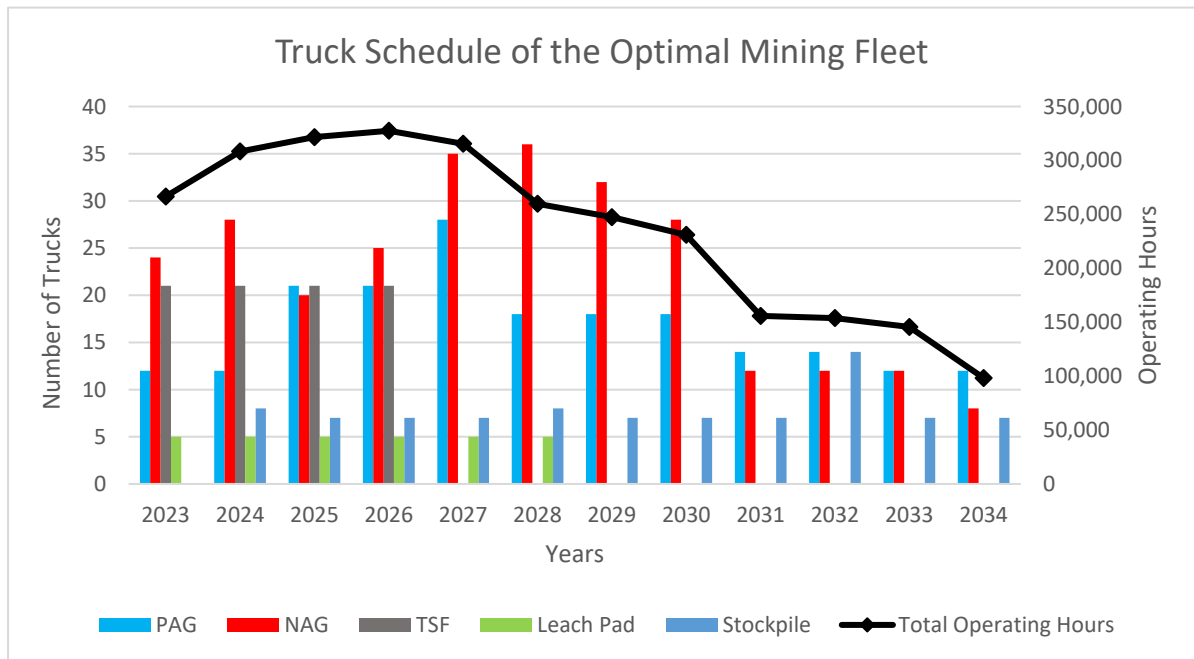


Figure 6.1 Optimal Truck Fleet Schedule

Tables 6.12 and 6.13 show the required number of trucks and excavators needs to be purchased each year in integer numbers and Tables 6.14 and 6.15 show the number of trucks and excavators operationally needed to meet annual production demands in fractional numbers, respectively.

Table 6.12 The Number of Trucks Need to be Purchased ( $x_{t,k,i}$ )

Period\Fleet	1	2	3	4	5	6	7
1	31	36	44	33	40	45	53
2	3	8	4	3	5	8	8
3	5	2	12	7	7	10	7
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0

Table 6.13 The Number of Excavators Need to be Purchased ( $y_{t,k,i}$ )

Period\Fleet	1	2	3	4	5	6	7
1	7	7	8	8	8	8	10
2	1	2	1	1	1	2	2
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0

Table 6.14 The Number of Trucks Operating at Location PAG ( $h_{t,k,i}$ )

Period\Fleet	1	2	3	4	5	6	7
1	5.80	7.20	8.50	6.70	7.60	9.30	9.00
2	7.50	8.50	9.10	7.10	10.30	9.90	9.70
3	12.90	15.40	24.20	12.50	24.00	24.70	19.70
4	10.70	13.00	16.80	10.50	15.30	16.50	14.90
5	15.90	19.30	20.00	15.60	20.20	24.50	24.70
6	9.30	11.30	11.70	9.10	10.30	12.70	12.40
7	9.20	11.10	11.50	9.00	10.20	12.60	12.30
8	10.10	12.30	12.70	10.00	11.30	13.90	13.50
9	8.40	10.20	13.20	8.30	10.70	12.90	13.10
10	8.20	9.90	12.80	8.00	10.70	12.60	12.70
11	8.60	10.40	13.50	8.40	10.90	13.20	11.50
12	6.20	6.00	9.80	6.10	7.90	9.60	8.30

Table 6.15 The Number of Excavators Operating at Location PAG ( $f_{t,k,i}$ )

<b>Period\Fleet</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	1.00	1.00	1.10	1.10	1.10	1.20	1.50
<b>2</b>	1.25	1.20	1.10	1.20	1.50	1.20	1.60
<b>3</b>	1.80	1.90	2.40	2.10	3.00	2.75	2.80
<b>4</b>	1.50	1.60	1.70	1.80	1.70	1.80	2.10
<b>5</b>	2.30	2.40	2.50	2.60	2.50	2.70	3.50
<b>6</b>	1.30	1.40	1.50	1.50	1.50	1.60	2.10
<b>7</b>	1.30	1.40	1.40	1.50	1.50	1.60	2.00
<b>8</b>	1.40	1.50	1.60	1.70	1.60	1.70	2.25
<b>9</b>	1.20	1.30	1.30	1.40	1.30	1.40	1.90
<b>10</b>	1.20	1.20	1.30	1.30	1.30	1.40	1.80
<b>11</b>	1.20	1.30	1.35	1.40	1.40	1.50	1.90
<b>12</b>	0.90	0.80	1.00	1.00	1.00	1.10	1.40

### 6.5.1 Equipment Rebuilding Schedule

Based on the equipment's operational life, a rebuilding schedule was developed to meet the needs of the mine owner. Since the amount of equipment in operation will decrease due to the low stripping ratios towards the end of the mine life, the spare equipment fleet will be comprised of haul trucks that have achieved or are about to reach their operational life. The considerations and assumptions that were considered in the development of the rebuilding schedule are:

- The units that complete their 30,600 hours of operational life will either be rebuilt, salvaged, or spared according to the equipment requirements in the following mining period,
- If an equipment is not going to be utilized in the next operating period before completing its service life, it was decided to put that equipment as a spare unit for utilization in equipment breakdowns,
- The decision on the number of equipment to be rebuilt or salvaged remains with the mine owner and is subject to change according to the needs of the upcoming mining period,
- The equipment that is not operationally needed in the following years after a major rebuild can also be spared or salvaged by the mine owner,

- The operational costs of equipment sitting idle were not calculated in the total operating costs by the developed MILP model. Therefore, only the rebuilding or salvaging costs will be deducted from the total ownership and operating costs.
- It is assumed that spared equipment will be either utilized for spare parts or stored in case of additional unit requirements during the mining operation. Therefore, their remaining book value is assumed to be zero at the end of the mine life.

Each period of mining operation was given a number and a letter to reflect the purchasing period and the age of equipment. The equipment that was purchased in the first operating period is represented with “1-a”. The developed equipment rebuilding schedule is provided in Table 6.16.

Table 6.16 Truck rebuilding Schedule for Optimal Mining Fleet

Period	Required	Available	Additional	Number of Trucks at Corresponding Age						Rebuild	Spared	Salvaged
				1	2	3	4	5	6			
<b>1-a</b>	53	0	53	53	0	0	0	0	0	0	0	0
<b>2-b</b>	61	53	8	8	53	0	0	0	0	0	0	0
<b>3-c</b>	68	61	7	7	8	53	0	0	0	0	0	0
<b>4-d</b>	66	68	0	0	7	8	51	0	0	0	0	0
<b>5-e</b>	63	66	0	0	0	7	8	48	0	0	3a	0
<b>6-f</b>	51	63	0	0	0	0	7	8	36	34a	3a+12a	2a
<b>7-g</b>	49	15	34	34	0	0	0	7	8	4b	3a+12a	4b
<b>8-h</b>	45	41	4	4	34	0	0	0	7	0	3a+12a	7c
<b>9-i</b>	31	38	0	0	4	27	0	0	0	0	3a+12a	7g
<b>10-j</b>	30	31	0	0	0	4	26	0	0	0	3a+12a	1g
<b>11-k</b>	29	30	0	0	0	0	4	25	0	0	3a+12a	10g
<b>12-l</b>	19	29	0	0	0	0	0	4	15	0	3a+12a	4h+15g

Predicated on the age of the equipment, the remaining book values and the cost of rebuilding trucks can be deductible from the overall ownership and operating cost of the proposed mining fleets. Since the developed MILP does not include the operating cost of idle equipment, it is not going to be deducted. By referring to the ownership and operating cost calculations given in Chapter 3, total deductible rebuild costs and book values for each piece of equipment were subtracted. The number of units that were either salvaged, rebuilt, or spared, and the total deductible costs (rebuilding and salvaging) are given in Table 6.17.

Table 6.17 Deductible Cost Savings Achieved

<b>Equipment</b>	<b>Used Hours</b>	<b>Years Used</b>	<b>Deductible Rebuilding Costs (*1,000\$)</b>	<b>Deductible Salvage Costs (*1,000\$)</b>
3a	20,400	4	\$163	\$0
12a	25,500	5	\$597	\$0
2a	30,600	6	\$108	\$0
4b	30,600	6	\$200	\$0
7c	30,600	6	\$161	\$0
7g	10,200	2	\$0	\$462
1g	20,400	4	\$0	\$35
10g	25,500	5	\$0	\$71
4h	25,500	5	\$0	\$40
15g	30,600	6	\$0	\$0
<b>Total Cost Saving</b>			\$1,270	\$641

According to the given results in Table 6.17, a total of \$1.9M can be saved by applying the truck rebuilding and salvaging schedule. By following the same steps as the truck rebuilding schedule, a \$0.8M savings can also be achieved with excavator rebuilding schedule, for a total savings of \$2.7M.

### 6.5.2 Cost Comparison Between Each Set of Equipment Fleet

The discounted operating cost of a material handling fleet in each period was calculated by dividing the total discounted operating cost of the mining excavators and trucks by the amount of material handled in each period. Figure 6.2 and 6.3 show the results of annual discounted operating cost analysis for 7 different equipment fleets. The financial evaluation of the equipment fleets was performed by using a 10% discount rate.

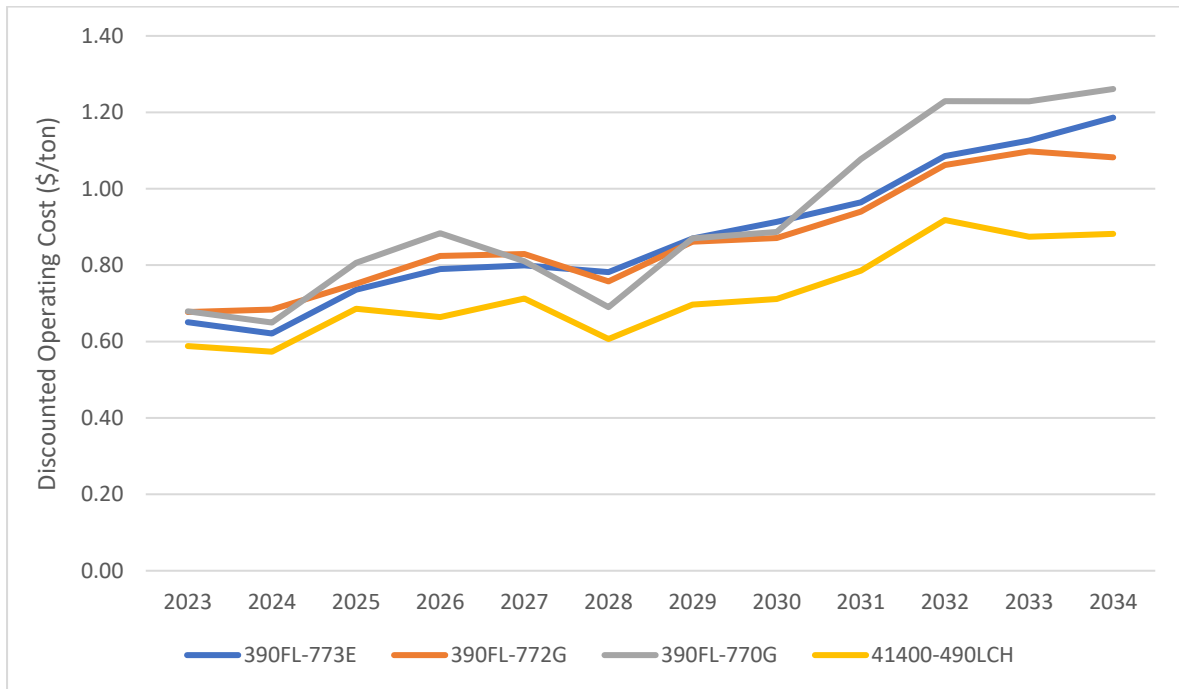


Figure 6.2 Discounted Operating Costs for the fleets of Caterpillar 390F L

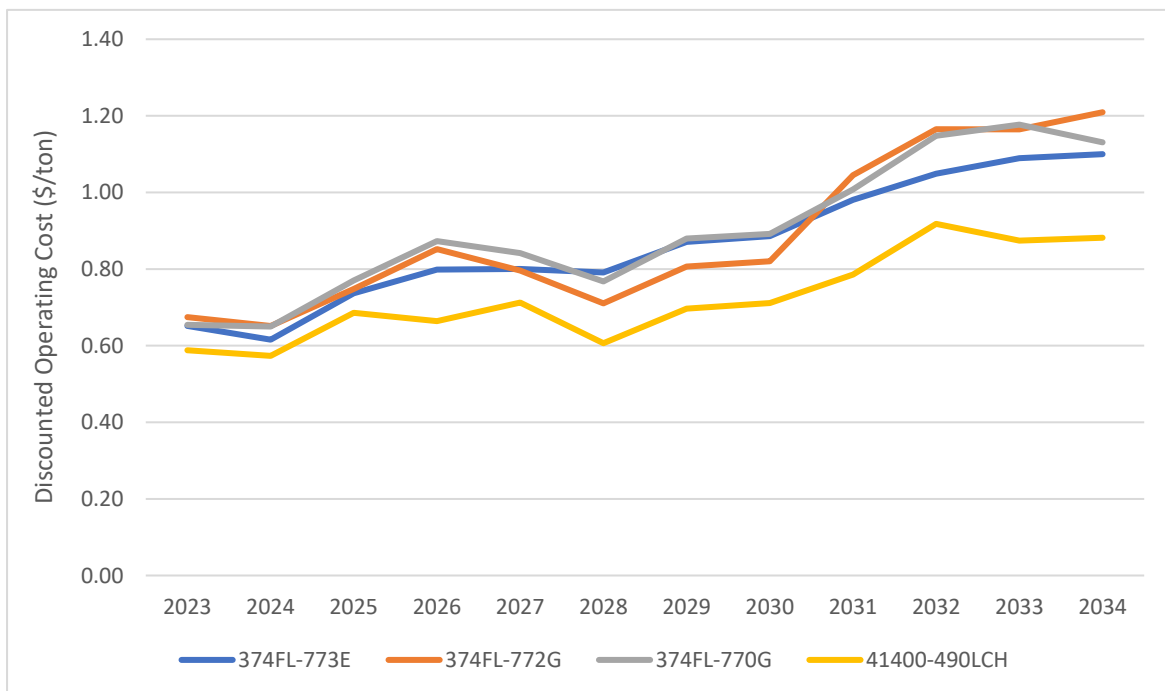


Figure 6.3 Discounted Operating Costs for the fleets of Caterpillar 374F L

Table 6.18 shows the results of developed MILP model in terms of total cost of each proposed equipment fleet and the total savings achieved with the utilization of equipment rebuilding schedule. The results indicate that the lowest cost option is the on-highway trucks

and excavators. In addition, the larger capacity off-highway equipment offers lower overall mining costs although they have higher ownership and operating costs per unit.

Table 6.18 Total Costs of Mining Fleets Utilized in MILP Model

<b>Fleet Costs</b>	<b>390FL-773E</b>	<b>390FL-772G</b>	<b>390FL-770G</b>	<b>374FL-773E</b>	<b>374FL-772G</b>	<b>374FL-770G</b>	<b>41400-490LCH</b>
<b>Truck Ow. Cost</b>	\$81M	\$85M	\$85M	\$90M	\$99M	\$89M	\$32M
<b>Truck Op. Cost</b>	\$109M	\$108M	\$112M	\$116M	\$118M	\$119M	\$94M
<b>Excav. Ow. Cost</b>	\$19M	\$23M	\$23M	\$14M	\$14M	\$15M	\$10M
<b>Excav. Op. Cost</b>	\$43M	\$46M	\$47M	\$36M	\$35M	\$39M	\$35M
<b>Total Cost</b>	\$252M	\$262M	\$267M	\$256M	\$266M	\$262M	\$171M
<b>Total Savings</b>	\$13.9M	\$16.7M	\$12.3M	\$12.1M	\$14.5M	\$11M	\$2.7M
<b>Total Cost (\$/ton)</b>	\$1.27	\$1.30	\$1.35	\$1.28	\$1.32	\$1.32	\$0.89

### 6.5.3 Sensitivity Analysis

A sensitivity analysis on 4 different parameters was conducted to observe the effect of uncertainty on the dependent variables. The results of the sensitivity analysis will be used to forecast the effects of fluctuating inflation rate, discount rate, operating hours, and equipment availability. Initially, the optimal solution of the presented MILP model was achieved by minimizing the Net Present Value to \$171M with the assumed rates of parameters. In order to measure the sensitivity of the objective value against the change in the values of the parameters, 10% and 20% incremental variations in the rates of parameters were applied one by one. It was observed that the model was highly sensitive to the changes in the equipment availability rates. Conversely, a variation of 10% and 20% in the inflation and discount rates had an insignificant effect on the total NPV of the selected mining fleet. Table 6.19 shows the changes in the objective value against different variation rates in parameters.

Table 6.19 The Effects of the Incremental Variations on the Objective Value

<b>Parameters</b>	<b>-20%</b>	<b>-10%</b>	<b>0%</b>	<b>10%</b>	<b>20%</b>
<b>Availability (%)</b>	\$222M	\$197M	\$171M	\$146M	\$121M
<b>Operating Hours</b>	\$198M	\$185M	\$171M	\$159M	\$145M
<b>Inflation Rate (%)</b>	\$160M	\$166M	\$171M	\$177M	\$183M
<b>Discount Rate (%)</b>	\$184M	\$178M	\$171M	\$166M	\$160M

In Figure 6.4, the changes in the amount of the NPV given in Table 6.19 were converted to the percentages. As can be seen from the figure, a 20% incremental change in the rate of equipment availability creates an approximately \$50M variation on the NPV of the project.

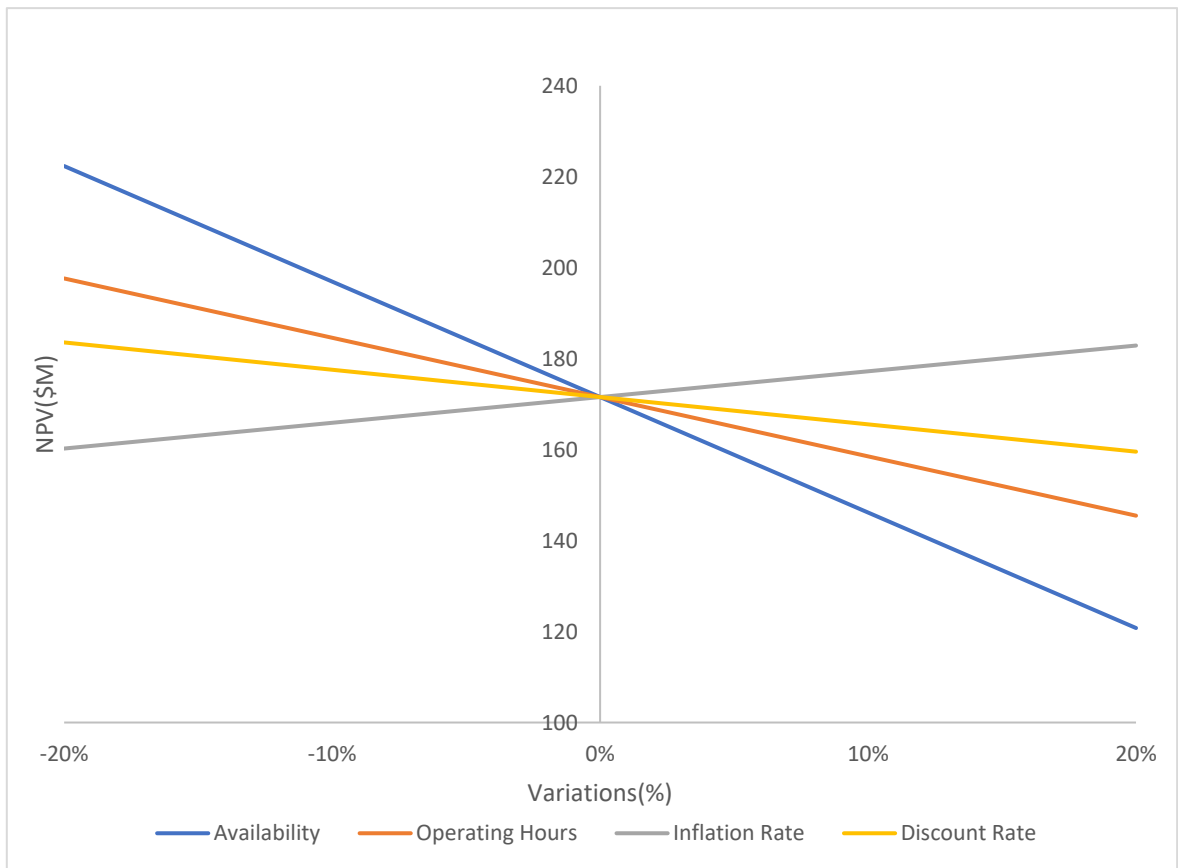


Figure 6.4 Sensitivity Analysis Results

## CHAPTER 7

### CONCLUSIONS AND RECOMMENDATIONS

The objective of the equipment selection models in the literature is primarily focused on maximizing the overall productivity of the equipment fleet and minimizing the total amount of equipment to be purchased to meet mine planning requirements. The research studies focused on the equipment selection problem are generally deterministic in nature to decrease complexities resulting from stochastic modelling. Therefore, most of the solution approaches available in the literature for equipment selection consider multiple periods, multiple commodity flows, and multiple location requirements of mining operations separately.

In this study, a mixed integer linear programming approach was developed to provide an optimal solution to the existing equipment selection problem. This is to prevent unnecessary expenditure due to the lack of preliminary analysis covering all aspects of material handling operations. The constraints in the developed model satisfy the long-term production plan, compatibility of purchased trucks and excavators, meet the production requirements with the most economical fleet, and consider the unavailability of a pre-existing equipment fleet.

The developed model was applied for an open pit polymetallic gold mine, including the by-production of base metals, such as Copper and Zinc. The mine plan is expected to be completed in five phases by the end of 2034 for three different material types: oxide, sulfide, and waste. A certain portion of the waste material will be utilized in constructing the Tailings Storage Facility (TSF) until the end of 2026. The production operation for the sulfide project is estimated to begin in the first half of 2024. The total production demand shows a substantial increase two years after the beginning of the operation. After computing the equipment cycle times and the productivities, a compatibility analysis was conducted for the optimal matching of excavators and trucks, and an input dataset was created for the application of the developed model by using the methodologies presented in Chapter 3.

The optimum solution to the problem was achieved by minimizing the total net present cost of a twelve-year production plan to \$171 million with the purchase of on-highway equipment fleets. After running the model separately for each proposed equipment fleet for comparison purposes, it was observed that an overall savings of between \$80 to \$90 million were achieved with the utilization of on-highway trucks and excavators as compared to other proposed off-highway equipment alternatives.

Table 6.6 and 6.7 demonstrate the overall performance of different equipment matches in terms of unit operating cost during the life of the mine. In each mining period, equipment efficiencies, haul road conditions, and production requirements experience significant changes. These changes cause variances on the total productivity of each proposed material handling fleet during successive mining periods. Therefore, the discounted unit operating costs of selected equipment fleets show varying results.

Application of appropriate rebuilding schedules also showed that spared and salvaged equipment throughout the life of the mine will reduce additional costs. The mine owner can make changes in its salvaging and rebuilding policies according to the requirements of the current mining period and the conditions of available equipment. These policies eliminate the need for purchasing additional equipment during the initial years of the project and therefore lower capital requirements.

## **7.1 Recommendations**

The following can be considered for further studies in the improvement of the equipment selection problem by utilizing the mixed integer linear programming approach:

- I. Uncertainties in the fleet productivity rates as a result of the dynamic truck and excavator cycle times.
- II. The stochastic nature of equipment breakdowns and cycle times.
- III. Application of equipment rebuilding and replacement schedule that considers the interactions of heterogeneous equipment fleets.
- IV. The compatibility of heterogeneous truck and excavator fleets where the bench geometry and the geology of excavated material are different.

The consideration of the recommendations given above will ensure an optimal result even when the number of uncertainties are more than the presented case study. The optimal result for the equipment selection problems can also be achieved by stochastic modelling approaches. The uncertainties in the fleet productivity rates are a result of variations in the truck and excavator cycle times and other operational delays such as equipment breakdowns. By applying relevant simulation techniques on the fleet productivity rates or on other fixed parameters, the model can be solved as a stochastic model and the distribution of the optimal solution can be achieved.

A linear programming approach that considers the compatibility of different sets of equipment fleets should also consider the different operating conditions and requirements of these fleets. As such, the maintenance and rebuilding schedules, operational capacities, operator experience, and the requirements for additional infrastructure and different equipment should be included in the developed model to achieve realistic results.

Another important factor affecting the extent of the study is the lack of access to sufficient information by equipment manufacturers and contractor companies. In such cases, it is very important to conduct field studies and closely examine different operations in order to collect required data sets. In addition, different mining operations utilizing equipment of the same capacity can be examined to compare the results.

It is well-known that the mining industry adapts to technological developments at a comparatively slower rate than other industries. The main reason for this situation is the well-established traditional mining approach. To improve productivity and increase health and safety standards, automation solutions can be utilized in material handling operations. In further studies, autonomous mining solutions can also be included to observe the cost benefit of these systems versus the traditional mining approaches.

Finally, necessary modifications can be made to apply this developed programming model to underground mining. In these studies, the utilized underground mining technique should also be considered to adjust operational requirements. In addition, autonomous underground mining solutions can be considered to reduce the delays and safety hazards resulting from drilling and blasting operations.

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APPENDIX A  
PHASE DESIGNS AND PRODUCTIVITY CALCULATIONS

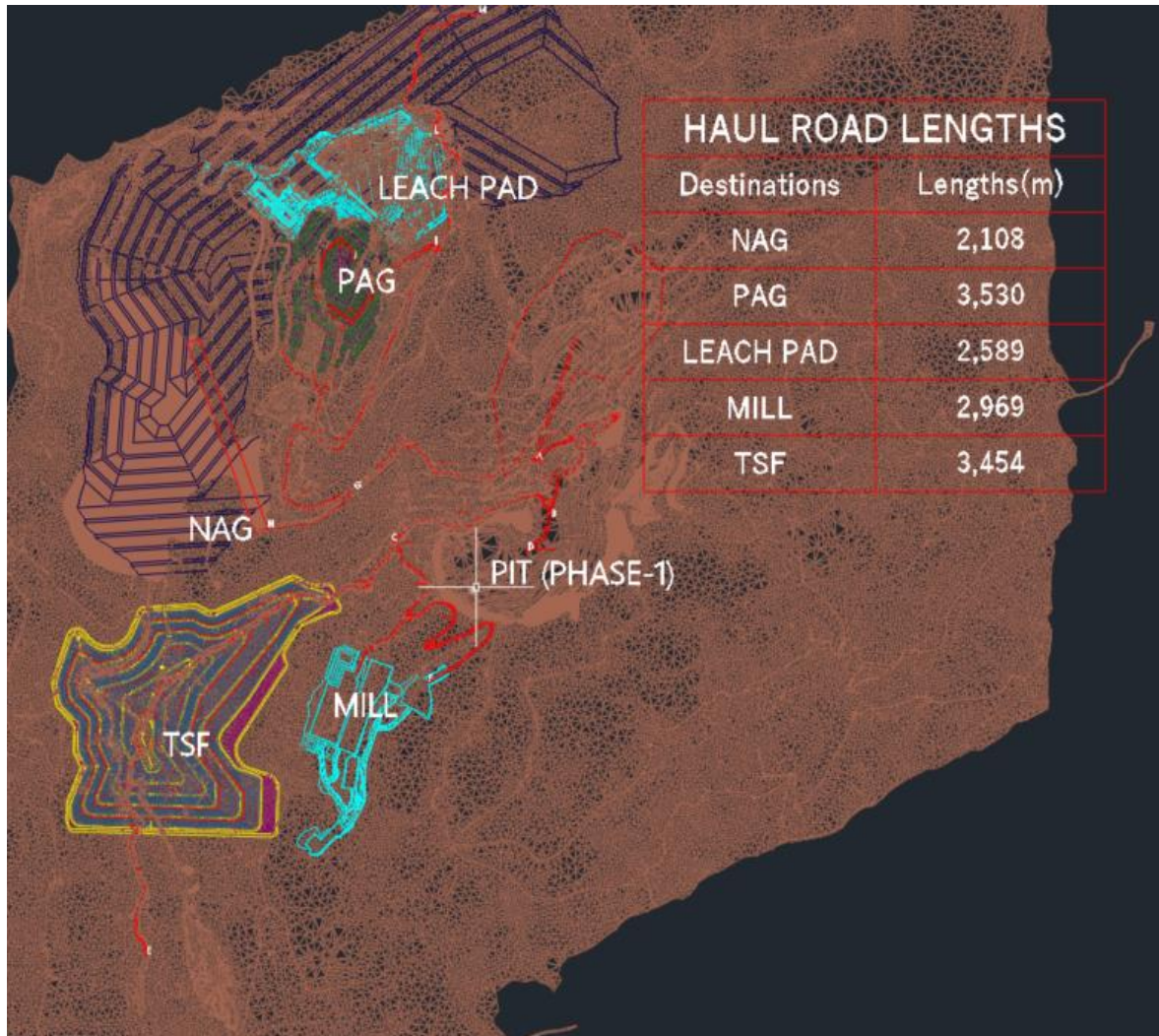


Figure A.1 Topography Merged with Phase Design-1

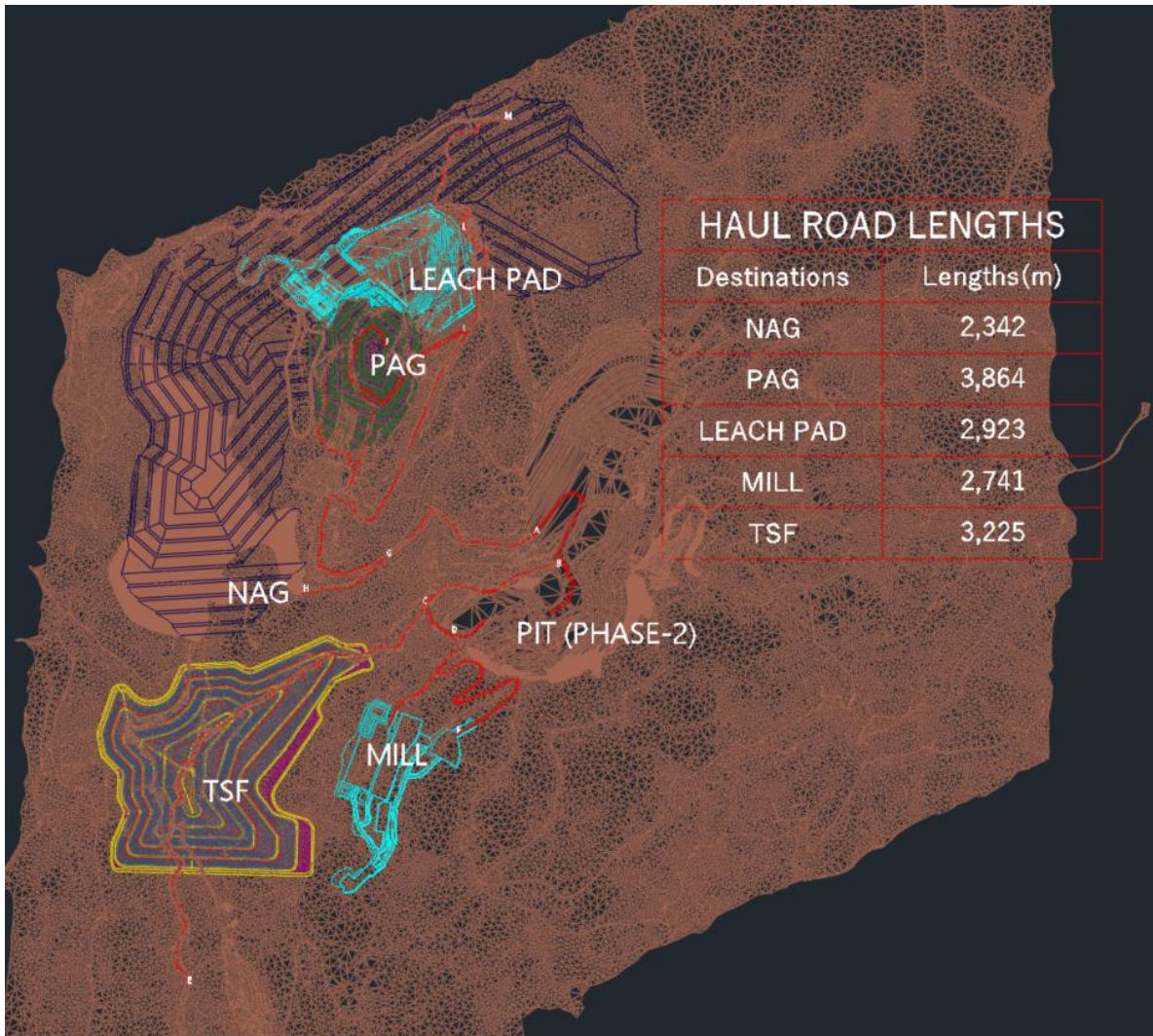


Figure A.2 Topography Merged with Phase Design-2

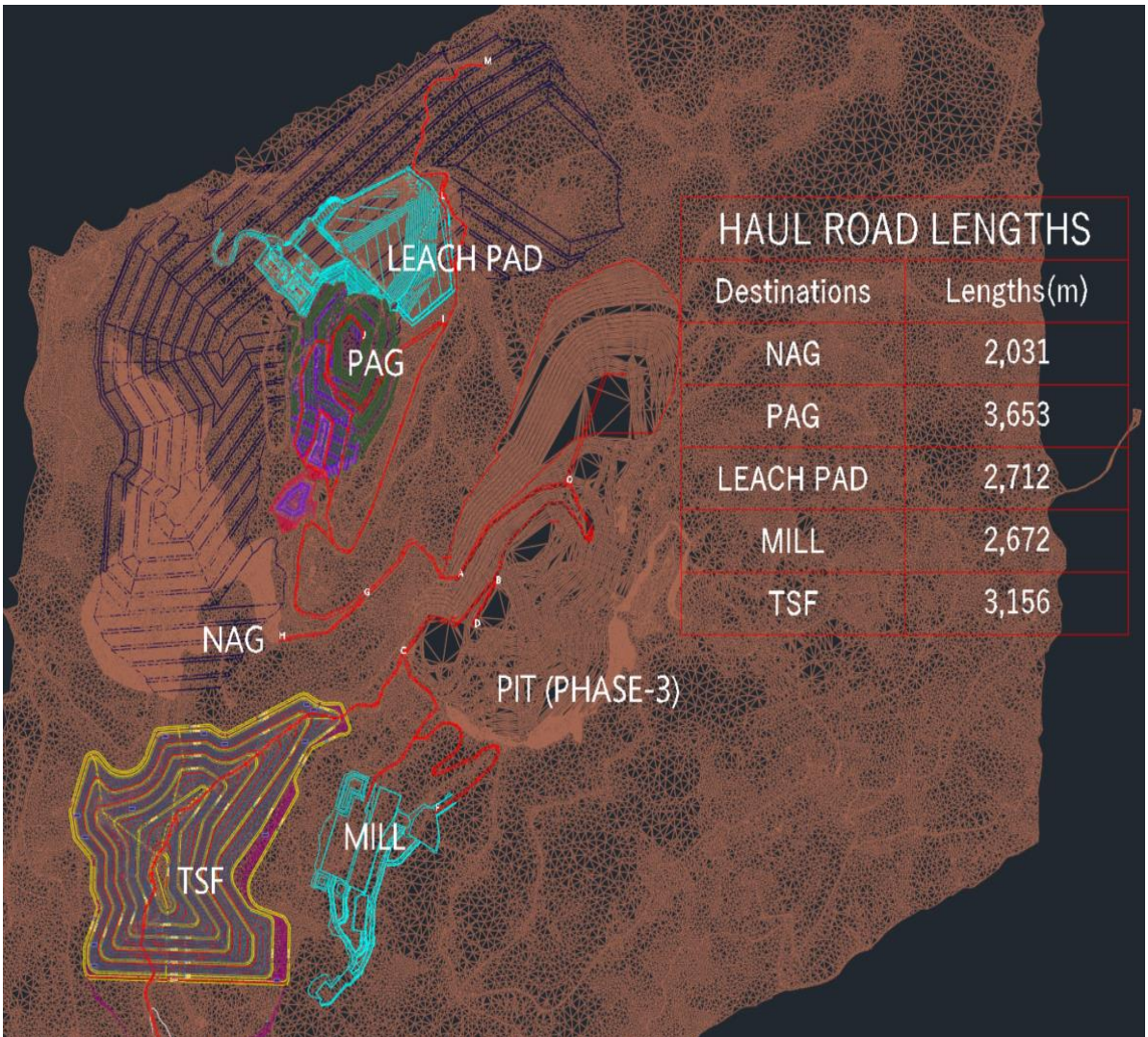


Figure A.3 Topography Merged with Phase Design-3

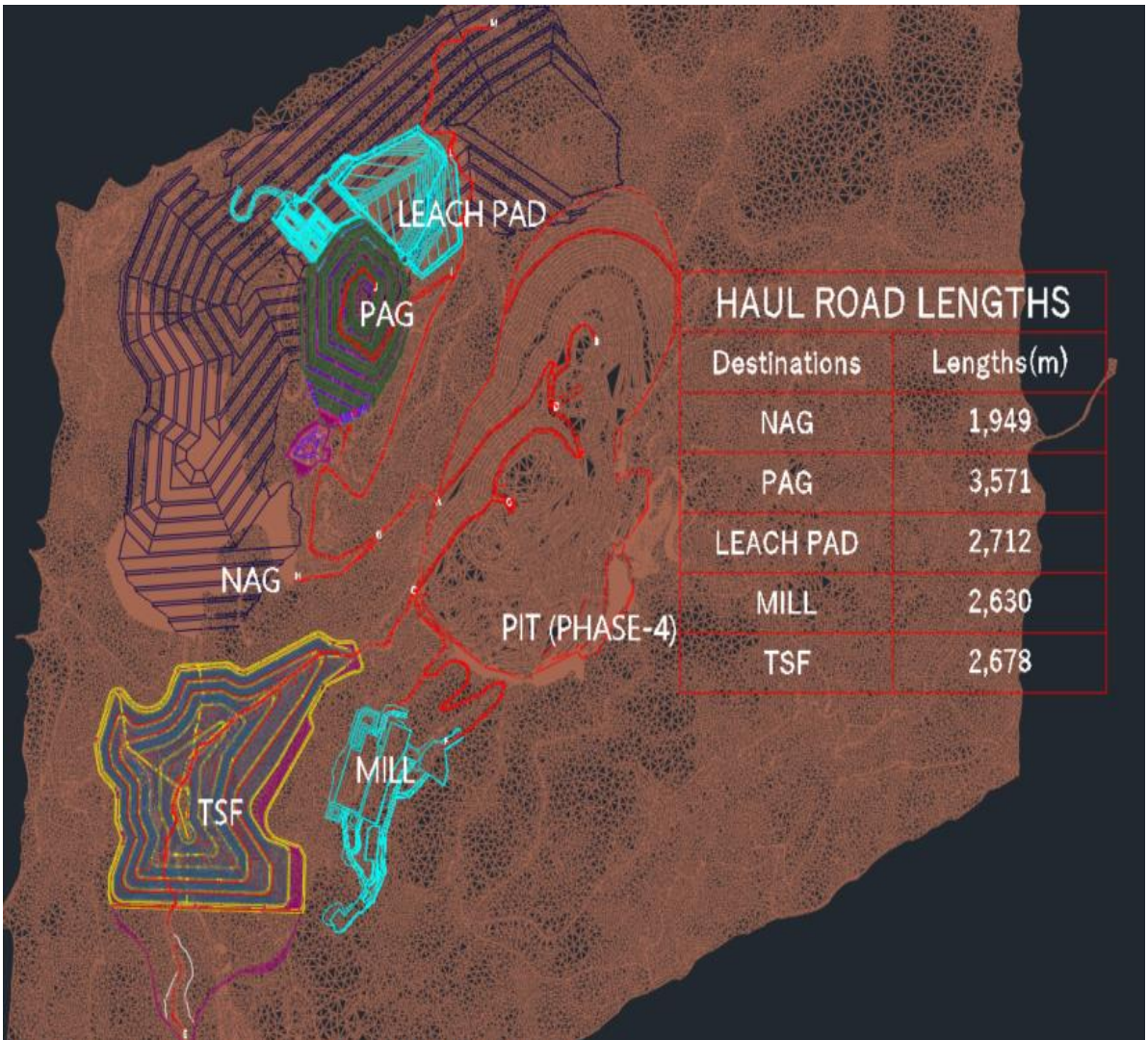


Figure A.4 Topography Merged with Phase Design-4

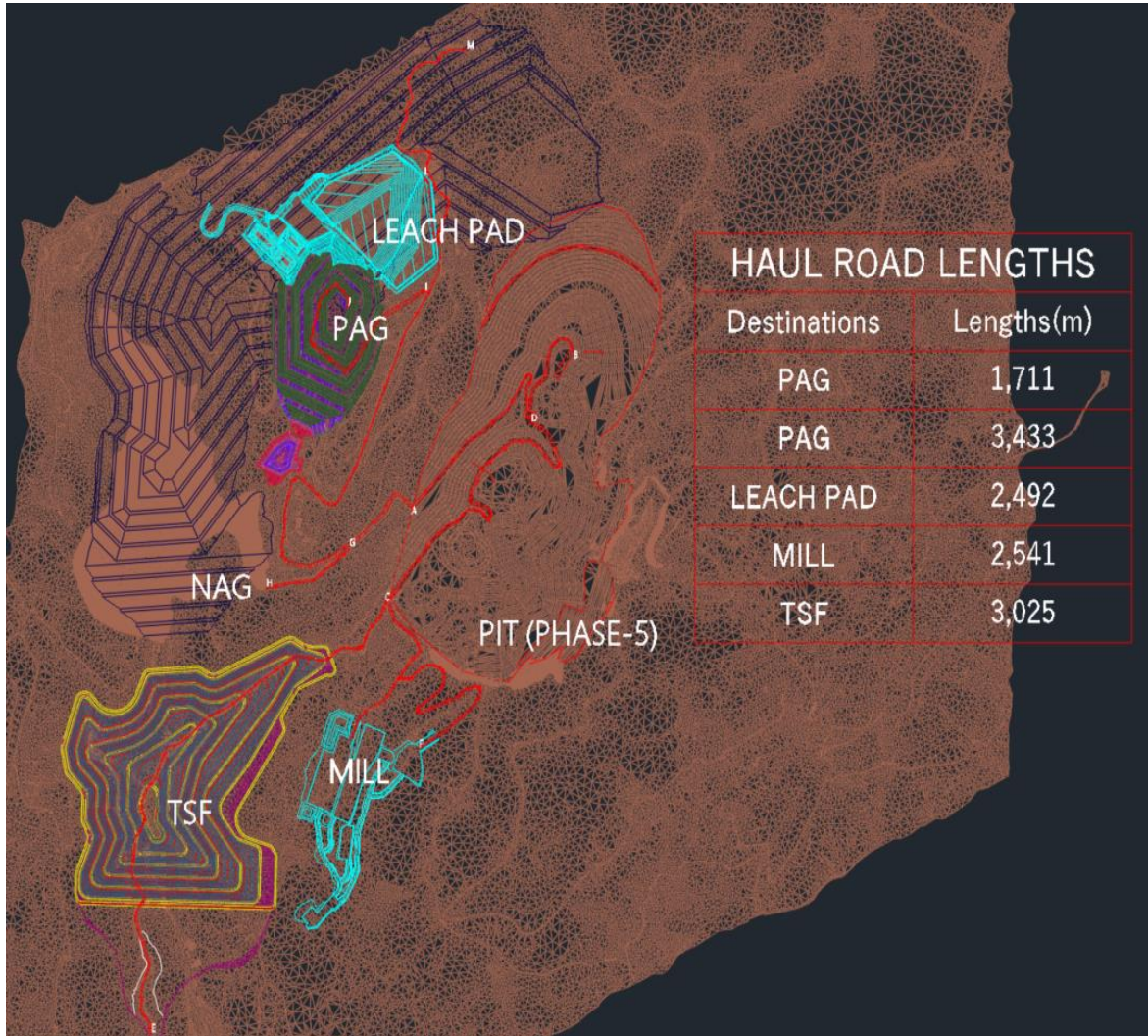


Figure A.5 Topography Merged with Phase Design-5

Table A.1 Truck Cycle Time Calculation for Caterpillar 773E

FACE TO LEACH PAD								
Segment	Up or Flat	Down	Max. Speed(km/h)	Speed Multiplier	Adjusted Speed	Max Safe Speed	Grade	Haul Time(min)
Face - A	416	-	78.7	0.661	52	40	0%	0.624
1-A	58.88	-	46.4	1	46.4	40	2%	0.088
2	59.69	-	46.4	1	46.4	40	1%	0.09
3	62.29	-	46.4	1	46.4	40	2%	0.048
4	42.61	-	35.3	1	35.3	40	3%	0.072
5	62.95	-	28.4	1	28.4	40	4%	0.133
6	42.45	-	35.3	1	35.3	40	3%	0.072
7	48.59	-	23.8	1	24.3	40	5%	0.12
8	73.31	-	18.4	1	18.6	40	7%	0.043
9	44.05	-	35.3	1	28.9	40	3%	0.091
10	-	147.7	78.4	0.64	50.2	40	-1%	0.057
11	54.38	-	46.4	1	23	40	1%	0.142
12	-	158.67	78.4	0.64	23	40	-3%	0.057
13	52.92	-	35.3	1	23	40	3%	0.138
14	93.32	-	23.8	1	23.8	40	5%	0.235
15-G	49.64	-	35.3	1	28.2	40	3%	0.105
16	73.97	-	28.4	1	28.4	40	4%	0.156
17	73.9	-	28.4	1	28.4	40	4%	0.093
18	56.45	-	28.4	1	28.4	40	4%	0.119
19	79.33	-	18.4	1	18.4	30	7%	0.259
20	91.42	-	14.2	1	14.2	30	10%	0.133
21	82.26	-	10.7	1	10.7	30	13%	0.181
22	61.44	-	15.3	1	15.3	30	9%	0.241
23	151	-	14.2	1	14.2	30	10%	0.638
24	73.42	-	12.1	1	12.1	30	11%	0.116
25	60.28	-	12.1	1	12.1	30	11%	0.249
26	73.92	-	16.1	1	16.1	30	8%	0.275
27	93.6	-	12.1	1	12.1	30	11%	0.167
28	62.52	-	8.2	1	8.2	30	14%	0.165
29	105.2	-	14.2	1	14.2	30	10%	0.445
30	87.43	-	16.1	1	16.1	30	8%	0.139
31	139	-	15.3	1	15.3	30	9%	0.545
32	227.8	-	15.3	1	15.3	30	9%	0.893
33	71.18	-	14.2	1	14.2	30	10%	0.301
34-I	144.3	-	14.2	1	14.2	30	10%	0.61
<b>Total</b>								<b>7.841</b>

Table A.2 Equipment Matching results for Caterpillar 390F L

CAT 390F L						
Truck Models	PAG-NAG-TSF-OXIDE			SULFIDE		
	NC	L	TL	NC	L	TL
770G	4	35.18	2.75	3	35.18	2.17
772G	5	44.169	3.33	4	44.169	2.75
773E	6	55.068	3.92	5	55.068	3.33

Table A.3 Equipment Matching results for Caterpillar 374F L

<b>CAT 374F L</b>						
<b>Truck Models</b>	<b>PAG-NAG-TSF-OXIDE</b>			<b>SULFIDE</b>		
	<b>NC</b>	<b>L</b>	<b>TL</b>	<b>NC</b>	<b>L</b>	<b>TL</b>
770G	5	35.18	3	4	35.18	2.50
772G*	6	44.169	3.50	5	44.169	3.00
773E	8	55.068	4.50	6	55.068	3.50

Table A.4 Productivity Calculation for Fleet 390F L-772G for NAG

<b>NAG</b>				
<b>NT</b>	<b>TW</b>	<b>Tw/W</b>	<b>TC</b>	<b>P</b>
1	-7.48	10.8	12	179
2	-4.15	10.8	12	357
3	-0.81	10.8	12	536
4	2.52	13.3	14.8	580
5	5.85	16.7	18.5	580
6	9.19	20	22.2	580
7	12.52	23.3	25.9	580
8	15.85	26.7	29.6	580

Table A.5 Productivity Calculation for Fleet 390F L-772G for PAG

<b>PAG</b>				
<b>NT</b>	<b>TW</b>	<b>Tw/W</b>	<b>TC</b>	<b>P</b>
1	-18.7	22	24.5	88
2	-15.4	22	24.5	175
3	-12	22	24.5	263
4	-8.69	22	24.5	351
5	-5.36	22	24.5	439
6	-2.02	22	24.5	526
7	1.31	23.3	25.9	580
8	4.64	26.7	29.6	580

Table A.6 Productivity Calculation for Fleet 390F L-772G for TSF

<b>TSF</b>				
<b>NT</b>	<b>TW</b>	<b>Tw/W</b>	<b>TC</b>	<b>P</b>
1	-15.6	18.9	21.1	102
2	-12.3	18.9	21.1	204
3	-8.94	18.9	21.1	306
4	-5.61	18.9	21.1	408
5	-2.28	18.9	21.1	510
6	1.06	20	22.2	580
7	4.39	23.3	25.9	580
8	7.72	26.7	29.6	580

Table A.7 Productivity Calculation for Fleet 390F L-772G for Oxide

<b>OXIDE</b>				
<b>NT</b>	<b>TW</b>	<b>Tw/W</b>	<b>TC</b>	<b>P</b>
1	-13.1	16.4	18.3	118
2	-9.76	16.4	18.3	235
3	-6.43	16.4	18.3	353
4	-3.09	16.4	18.3	470
5	0.24	16.7	18.5	580
6	3.57	20	22.2	580
7	6.91	23.3	25.9	580
8	10.24	26.7	29.6	580

Table A.8 Productivity Calculation for Fleet 390F L-772G for Sulfide

<b>SULFIDE</b>				
<b>NT</b>	<b>TW</b>	<b>Tw/W</b>	<b>TC</b>	<b>P</b>
1	-15.3	18.1	20.1	107
2	-12.6	18.1	20.1	214
3	-9.84	18.1	20.1	320
4	-7.09	18.1	20.1	427
5	-4.34	18.1	20.1	534
6	-1.59	18.1	20.1	641
7	1.16	19.3	21.4	703
8	3.91	22	24.4	703

APPENDIX B  
OWNERSHIP AND OPERATING COST CALCULATIONS

HOURLY OWNING AND OPERATING COST ESTIMATE						Estimate(\$/Hour)
Machine Designation						390F L
Estimated Ownership Period(Years)				N		6
Estimated Usage(Hours/Year)						5100
Ownership Usage (Total Hours)(B*C)						30600
<b>OWNING COSTS</b>						<b>Estimate</b>
Delivered Price(P), to the Customer(including attachments and VAT 18%)				P		1,259,760.0
Less Tire Replacement Cost if desired						-
Delivered Proce Less Tires						-
Gross Selling Price		300000				-
Less Residual Value at Replacement(S)				S		-
Net Value to be recovered through work						1,259,760
Cost Per Hour: =Net Value /Total Hours						41.17
Interest Costs (efektif faiz orani)						
= $\left( \frac{P * (N + 1) + S * (N - 1)}{2N} \right) * \frac{Interest Rate\%}{Hours/Year}$				10.5%		15.13
Insurance:						
= $\left( \frac{P * (N + 1) + S * (N - 1)}{2N} \right) * \frac{Insurance Rate\%}{Hours/Year}$				1%		1.44
(Optional Method when insurance cost per year is known)						
Ins.\$		Per Yr.÷		Hours/Yr.=		
Property Tax:						
= $\left( \frac{P * (N + 1) + S * (N - 1)}{2N} \right) * \frac{Tax Rate \%}{Hours/Year}$				0.10%		0.14
(Optional Method when Property Tax cost per year is known)						
Property T.\$		Per Yr.÷		Hours/Yr.=		
<b>TOTAL HOURLY OWNING COST(add lines 3b, 4, 5 and 6)</b>						<b>57.88</b>

Figure B.1 Ownership Cost Calculation for Caterpillar 390F L

HOURLY OWNING AND OPERATING COST ESTIMATE						Estimate(\$/Hour)
Machine Designation						390F L
Estimated Ownership Period(Years)				N		6
Estimated Usage(Hours/Year)						5100
Ownership Usage (Total Hours)(B*C)						30600
<b>OWNING COSTS</b>						<b>Estimate</b>
Delivered Price(P), to the Customer(including attachments and VAT 18%)				P		1,037,693.8
Less Tire Replacement Cost if desired						-
Delivered Proce Less Tires						-
Gross Selling Price		300000				-
Less Residual Value at Replacement(S)				S		-
Net Value to be recovered through work						1,037,694
Cost Per Hour: =Net Value /Total Hours						33.91
Interest Costs (efektif faiz orani)						
= $\left( \frac{P * (N + 1) + S * (N - 1)}{2N} \right) * \frac{Interest Rate\%}{Hours/Year}$				10.5%		
Insurance:						
= $\left( \frac{P * (N + 1) + S * (N - 1)}{2N} \right) * \frac{Insurance Rate\%}{Hours/Year}$				1%		1.19
(Optional Method when insurance cost per year is known)						
Ins.\$		Per Yr. ÷		Hours/Yr.=		
Property Tax:						
= $\left( \frac{P * (N + 1) + S * (N - 1)}{2N} \right) * \frac{Tax Rate \%}{Hours/Year}$				0.10%		0.12
(Optional Method when Property Tax cost per year is known)						
Property T.\$		Per Yr. ÷		Hours/Yr.=		
<b>TOTAL HOURLY OWNING COST(add lines 3b, 4, 5 and 6)</b>						<b>35.22</b>

Figure B.2 Ownership Cost Calculation for Caterpillar 773E

OPERATING COSTS				Estimate(\$)
Fuel:	Unit Price(\$/l) *	Consumption(l/hr)	37.8-48.4	
	1	*	43.1	43.10
Planned Maintenance (PM)-Lube Oils, Grease, Labor				12.68
Tires: Replacement Cost ÷ Life in Hours				-
Undercarriage: (Impact+Abrasiveness+Z Factor)*Basic Factor				8.16
Repair Cost (Labor and Parts)				25.08
Special Wear Items: Cost÷Life				20.88
<b>TOTAL OPERATING COSTS(add lines 8,9, 10a (or 10b), 11 and 12)</b>				<b>109.90</b>
<b>MACHINE OWNING PLUS OPERATING(add lines 7 and 13)</b>				<b>167.78</b>
<b>OPERATOR'S HOURLY WAGE(include fringes)</b>				<b>2.60</b>
<b>TOTAL OWNING AND OPERATING COST</b>				<b>170.38</b>

Figure B.3 Operating Cost Calculation for Caterpillar 390F L

Table B.1 Rebuilding and Operating Cost Calculation for Caterpillar 390F L

Years	Equipment Base Price	Rebuild Cost	Operating Cost
2023	\$1,049,800	\$629,880	\$573,744
2024	\$1,160,029	\$696,017	\$633,987
2025	\$1,281,832	\$769,099	\$700,555
2026	\$1,416,424	\$849,855	\$774,114
2027	\$1,565,149	\$939,089	\$855,396
2028	\$1,729,490	\$1,037,694	\$945,212
2029	\$1,911,086	\$1,146,652	\$1,044,459
2030	\$2,111,750	\$1,267,050	\$1,154,128
2031	\$2,333,484	\$1,400,090	\$1,275,311
2032	\$2,578,500	\$1,547,100	\$1,409,219
2033	\$2,849,242	\$1,709,545	\$1,557,187
2034	\$3,148,412	\$1,889,047	\$1,720,691

Table B.2 Depreciation and Rebuilding Schedule of 390FL in 2023

<b>Years</b>	<b>Book Value First</b>	<b>Depreciation</b>	<b>Book Value Remaining</b>
2023	\$1,259,760	\$209,960	\$1,049,800
2024	\$1,049,800	\$209,960	\$839,840
2025	\$839,840	\$209,960	\$629,880
2026	\$629,880	\$209,960	\$419,920
2027	\$419,920	\$209,960	\$209,960
2028(rebuild)	\$209,960	\$209,960	\$0
2029	\$1,037,694	\$172,949	\$864,745
2030	\$864,745	\$172,949	\$691,796
2031	\$691,796	\$172,949	\$518,847
2032	\$518,847	\$172,949	\$345,898
2033	\$345,898	\$172,949	\$172,949
2034	\$172,949	\$172,949	\$0

APPENDIX C  
MODEL IMPLEMENTATION RESULTS

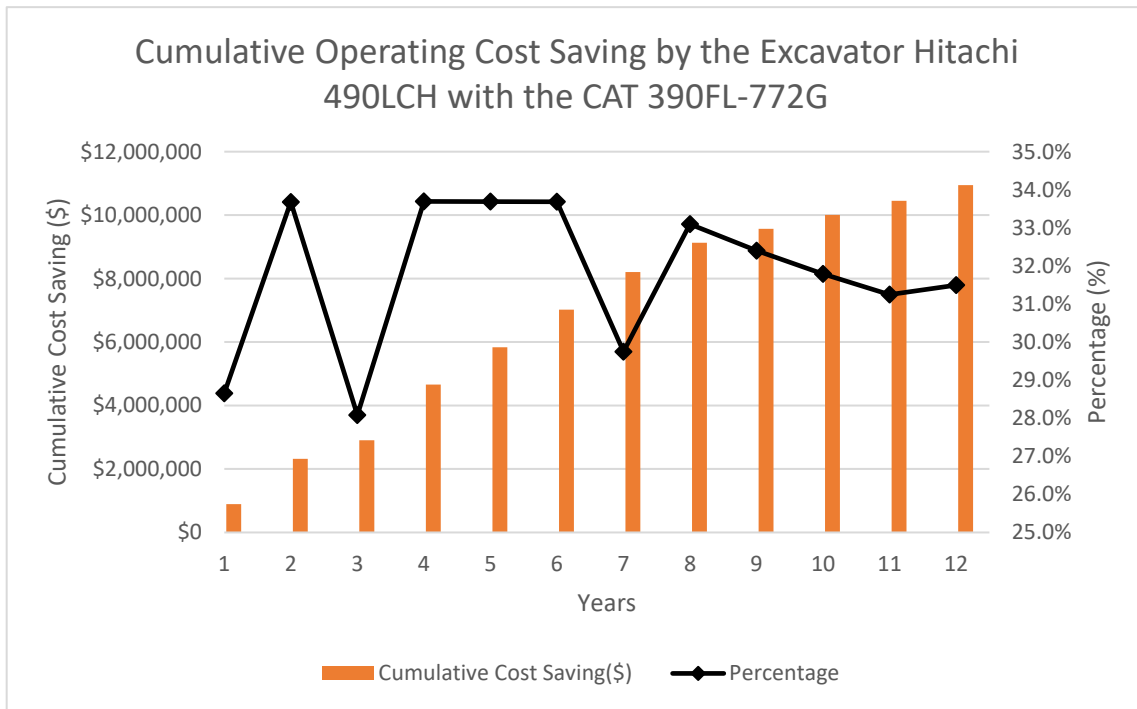


Figure C.1 Cumulative Savings Achieved with 490LCH Against 390FL-772G

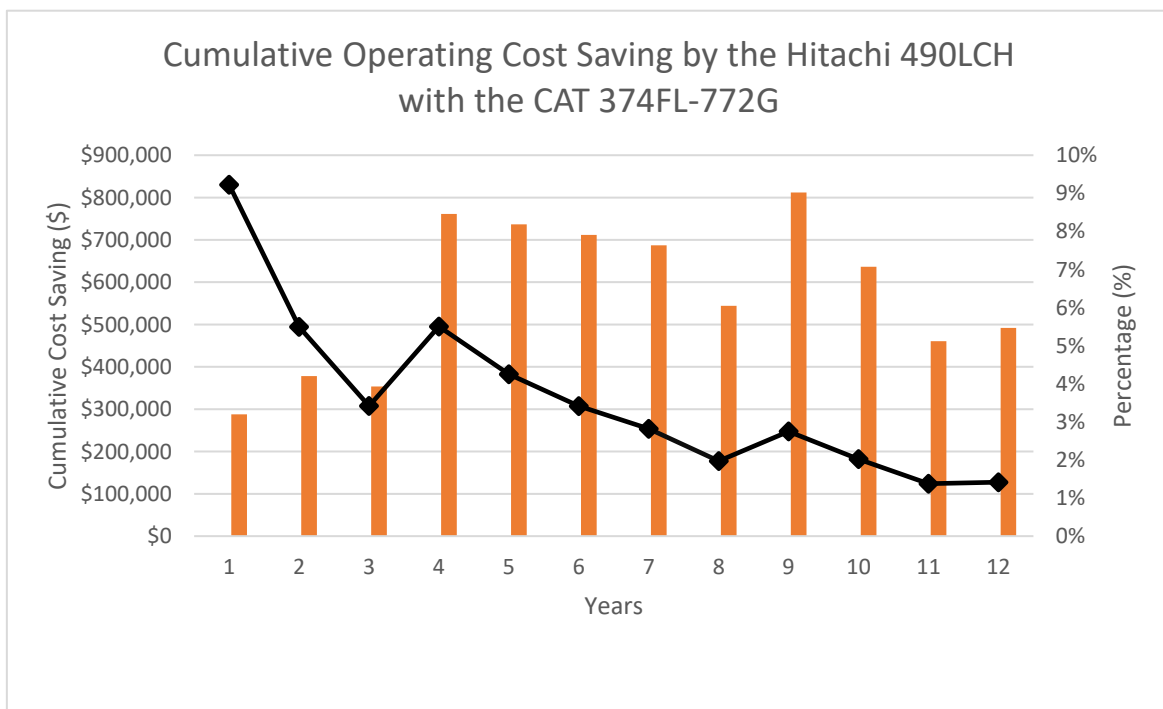


Figure C.2 Cumulative Savings Achieved with 490LCH Against 374FL-772G

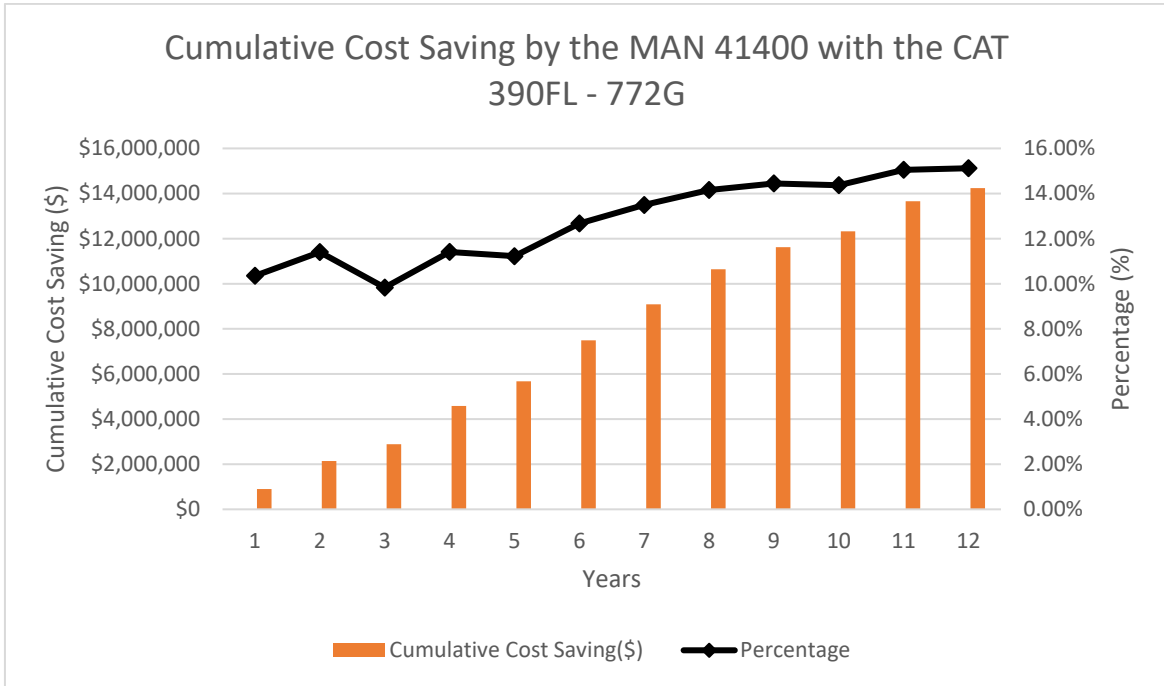


Figure C.3 Cumulative Savings Achieved with 41400 Against 390FL-772G

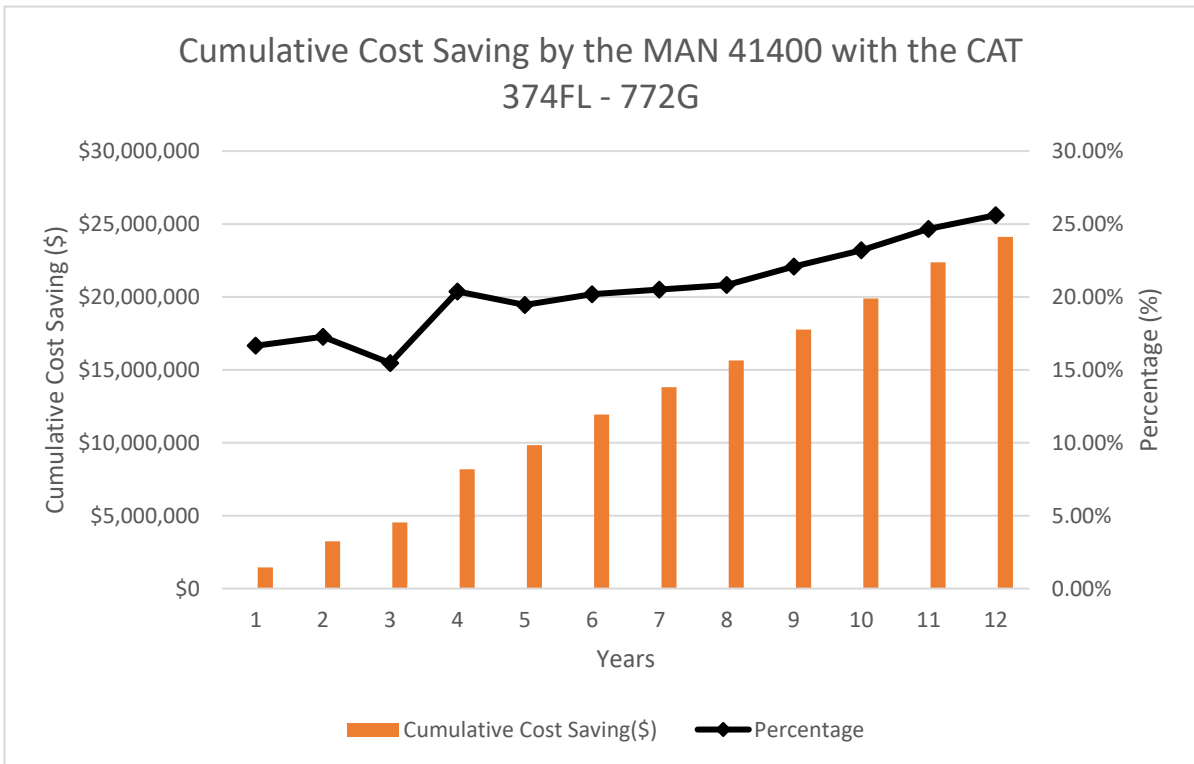


Figure C.4 Cumulative Savings Achieved with 41400 Against 374FL-772G

Table C.1 Proposed Excavator and Truck Models and Their Specifications

<b>Parameters</b>	<b>Resources</b>			
	<b>Trucks</b>			
Truck Models	Cat 773E	Cat 772G	Cat 770G	Man 41400
Truck Capacity (tons)	55	44.2	35	41
Truck Capacity (Loose m <sup>3</sup> )	35.2	31.3	25.9	20
	<b>Excavators</b>			
Excavator Models	Cat 390FL	Cat 374FL	Hitachi 490LCH	
Bucket Capacity (Loose m <sup>3</sup> )	4.6	3.8	2.3	
Cycle Time (seconds)	35	30	26.6	

Table C.2 Truck Allocation Result for the Fleet 390FL-772G

<b>CAT 772G-390FL (Fraction of Trucks)</b>						
<b>Years</b>	<b>Oxide</b>	<b>Sulfide</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Total</b>
2023	1.43	0.00	7.20	13.88	12.10	35
2024	1.34	0.10	7.67	19.03	12.10	41
2025	0.63	3.50	15.37	9.16	12.10	41
2026	0.13	3.94	12.99	14.32	13.56	45
2027	0.09	3.94	19.27	17.08	0.00	41
2028	0.06	2.99	11.26	21.82	0.00	37
2029	0.00	3.38	11.13	20.35	0.00	35
2030	0.00	3.38	12.26	17.32	0.00	33
2031	0.00	3.29	10.17	7.57	0.00	22
2032	0.00	3.74	9.90	6.94	0.00	21
2033	0.00	3.88	10.41	6.92	0.00	22
2034	0.00	2.46	6.06	5.05	0.00	14

Table C.3 Excavator Allocation Result for the Fleet 390FL-772G

<b>CAT 390FL-772G (Fraction of Excavators)</b>						
<b>Years</b>	<b>Oxide</b>	<b>Sulfide</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Total</b>
2023	0.29	0	1.03	3.47	2.02	7
2024	0.27	0.01	1.1	4.76	2.02	9
2025	0.1	0.5	1.92	2.29	2.02	7
2026	0.02	0.56	1.62	3.58	2.26	9
2027	0.02	0.56	2.41	4.27	0	8
2028	0.01	0.5	1.41	5.45	0	8
2029	0	0.56	1.39	5.09	0	8
2030	0	0.56	1.53	4.33	0	7
2031	0	0.55	1.27	1.89	0	4
2032	0	0.62	1.24	1.73	0	4
2033	0	0.55	1.3	1.73	0	4
2034	0	0.35	0.76	1.26	0	3

Table C.4 Productivity for Caterpillar 772G Matched with 390F L

<b>Productivity For Caterpillar 772G (tons/year) Matched With 390FL</b>					
<b>Years</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Leach Pad</b>	<b>Stockpile</b>
<b>1</b>	422,270	738,972	492,648	591,177	511,842
<b>2</b>	422,270	738,972	492,648	591,177	511,842
<b>3</b>	369,486	738,972	492,648	492,648	511,842
<b>4</b>	329,572	659,144	439,430	439,430	456,550
<b>5</b>	329,572	659,144	439,430	439,430	456,550
<b>6</b>	329,572	659,144	439,430	376,654	601,521
<b>7</b>	291,939	583,879	389,253	333,645	532,835
<b>8</b>	291,939	583,879	389,253	333,645	532,835
<b>9</b>	291,939	583,879	389,253	389,253	547,094
<b>10</b>	256,587	513,175	342,117	426,536	480,844
<b>11</b>	256,587	513,175	342,117	426,536	443,154
<b>12</b>	319,902	513,175	342,117	342,117	355,446

Table C.5 Productivity for Caterpillar 772G Matched with 374F L

<b>Productivity For Caterpillar 772G (tons/year) Matched With 374FL</b>					
<b>Years</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Leach Pad</b>	<b>Stockpile</b>
1	402,161	703,783	469,188	563,026	469,188
2	402,161	703,783	469,188	563,026	373,702
3	351,891	703,783	469,188	469,188	469,188
4	279,003	627,757	358,718	418,504	418,504
5	313,878	627,757	358,718	418,504	418,504
6	358,718	627,757	358,718	358,718	488,255
7	317,757	556,075	317,757	317,757	432,503
8	317,757	556,075	317,757	317,757	432,503
9	278,038	444,860	370,717	370,717	370,717
10	244,369	390,990	325,825	325,825	325,825
11	244,369	390,990	279,279	325,825	325,825
12	244,369	390,990	279,279	325,825	325,825

Table C.6 Productivity for Caterpillar 390FL Matched with 772G

<b>Productivity For Caterpillar 390 FL (tons/year) Matched With 772G</b>					
<b>Years</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Leach Pad</b>	<b>Stockpile</b>
1	2,955,887	2,955,887	2,955,887	2,955,887	3,582,893
2	2,955,887	2,955,887	2,955,887	2,955,887	3,582,893
3	2,955,887	2,955,887	2,955,887	2,955,887	3,582,893
4	2,636,578	2,636,578	2,636,578	2,636,578	3,195,852
5	2,636,578	2,636,578	2,636,578	2,636,578	3,195,852
6	2,636,578	2,636,578	2,636,578	2,636,578	3,609,127
7	2,335,515	2,335,515	2,335,515	2,335,515	3,197,013
8	2,335,515	2,335,515	2,335,515	2,335,515	3,197,013
9	2,335,515	2,335,515	2,335,515	2,335,515	3,282,561
10	2,052,699	2,052,699	2,052,699	2,559,216	2,885,064
11	2,052,699	2,052,699	2,052,699	2,559,216	3,102,081
12	2,559,216	2,052,699	2,052,699	2,052,699	2,488,120

Table C.7 Productivity for Caterpillar 374FL Matched with 772G

<b>Productivity For Caterpillar 374FL (tons/year) Matched With 772G</b>					
<b>Years</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Leach Pad</b>	<b>Stockpile</b>
<b>1</b>	2,815,130	2,815,130	2,815,130	2,815,130	3,284,319
<b>2</b>	2,815,130	2,815,130	2,815,130	2,815,130	2,615,914
<b>3</b>	2,815,130	2,815,130	2,815,130	2,815,130	3,284,319
<b>4</b>	2,511,027	2,511,027	2,511,027	2,511,027	2,929,531
<b>5</b>	2,511,027	2,511,027	2,511,027	2,511,027	2,929,531
<b>6</b>	2,511,027	2,511,027	2,511,027	2,511,027	2,929,531
<b>7</b>	2,224,300	2,224,300	2,224,300	2,224,300	2,595,017
<b>8</b>	2,224,300	2,224,300	2,224,300	2,224,300	2,595,017
<b>9</b>	2,224,300	2,224,300	2,224,300	2,224,300	2,595,017
<b>10</b>	1,954,951	1,954,951	1,954,951	1,954,951	2,280,777
<b>11</b>	1,954,951	1,954,951	1,954,951	1,954,951	2,280,777
<b>12</b>	1,954,951	1,954,951	1,954,951	1,954,951	2,280,777

APPENDIX D  
MODEL INPUT DATASET

Table D.1 Annual Excavator Productivity Rate  $P_{1,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
1	3,136,401	3,136,401	3,136,401	3,136,401	3,685,272
2	3,136,401	3,136,401	3,136,401	3,136,401	3,685,272
3	3,136,401	3,136,401	3,136,401	3,136,401	3,685,272
4	2,797,593	2,797,593	2,797,593	2,797,593	3,287,171
5	2,797,593	2,797,593	2,797,593	2,797,593	3,287,171
6	2,797,593	2,797,593	2,797,593	2,797,593	3,287,171
7	2,478,144	2,478,144	2,478,144	2,478,144	2,911,820
8	2,478,144	2,478,144	2,478,144	2,478,144	2,911,820
9	2,478,144	2,478,144	2,478,144	2,478,144	2,911,820
10	2,178,057	2,178,057	2,178,057	2,178,057	2,559,216
11	2,178,057	2,178,057	2,178,057	2,178,057	2,559,216
12	2,178,057	2,178,057	2,178,057	2,178,057	2,559,216

Table D.2 Annual Excavator Productivity Rate  $P_{2,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
1	2,955,887	2,955,887	2,955,887	2,955,887	3,582,893
2	2,955,887	2,955,887	2,955,887	2,955,887	3,582,893
3	2,955,887	2,955,887	2,955,887	2,955,887	3,582,893
4	2,636,578	2,636,578	2,636,578	2,636,578	3,195,852
5	2,636,578	2,636,578	2,636,578	2,636,578	3,195,852
6	2,636,578	2,636,578	2,636,578	2,636,578	3,609,127
7	2,335,515	2,335,515	2,335,515	2,335,515	3,197,013
8	2,335,515	2,335,515	2,335,515	2,335,515	3,197,013
9	2,335,515	2,335,515	2,335,515	2,335,515	3,282,561
10	2,052,699	2,052,699	2,052,699	2,559,216	2,885,064
11	2,052,699	2,052,699	2,052,699	2,559,216	3,102,081
12	2,559,216	2,052,699	2,052,699	2,052,699	2,488,120

Table D.3 Annual Excavator Productivity Rate  $P_{3,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
1	2,853,725	2,853,725	2,853,725	2,853,725	3,622,035
2	2,853,725	2,853,725	2,853,725	2,853,725	3,622,035
3	2,853,725	2,853,725	2,853,725	2,853,725	3,622,035
4	2,545,452	2,545,452	2,545,452	2,545,452	3,230,766
5	2,545,452	2,545,452	2,545,452	2,545,452	3,230,766
6	2,545,452	2,545,452	2,545,452	2,545,452	3,230,766
7	2,254,795	2,254,795	2,254,795	2,254,795	2,861,855
8	2,254,795	2,254,795	2,254,795	2,254,795	2,861,855
9	2,254,795	2,254,795	2,254,795	2,254,795	2,861,855
10	1,981,753	1,981,753	1,981,753	1,981,753	2,515,302
11	1,981,753	1,981,753	1,981,753	1,981,753	2,515,302
12	1,981,753	1,981,753	1,981,753	1,981,753	2,515,302

Table D.4 Annual Excavator Productivity Rate  $P_{4,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
1	2,729,831	2,729,831	2,729,831	2,729,831	3,509,783
2	2,729,831	2,729,831	2,729,831	2,729,831	3,509,783
3	2,729,831	2,729,831	2,729,831	2,729,831	3,509,783
4	2,434,942	2,434,942	2,434,942	2,434,942	3,130,639
5	2,434,942	2,434,942	2,434,942	2,434,942	3,130,639
6	2,434,942	2,434,942	2,434,942	2,434,942	3,130,639
7	2,156,903	2,156,903	2,156,903	2,156,903	2,773,162
8	2,156,903	2,156,903	2,156,903	2,156,903	2,773,162
9	2,156,903	2,156,903	2,156,903	2,156,903	2,773,162
10	1,895,716	1,895,716	1,895,716	1,895,716	2,437,349
11	1,895,716	1,895,716	1,895,716	1,895,716	2,437,349
12	1,895,716	1,895,716	1,895,716	1,895,716	2,437,349

Table D.5 Annual Excavator Productivity Rate  $P_{5,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
<b>1</b>	2,815,130	2,815,130	2,815,130	2,815,130	3,284,319
<b>2</b>	2,815,130	2,815,130	2,815,130	2,815,130	2,615,914
<b>3</b>	2,815,130	2,815,130	2,815,130	2,815,130	3,284,319
<b>4</b>	2,511,027	2,511,027	2,511,027	2,511,027	2,929,531
<b>5</b>	2,511,027	2,511,027	2,511,027	2,511,027	2,929,531
<b>6</b>	2,511,027	2,511,027	2,511,027	2,511,027	2,929,531
<b>7</b>	2,224,300	2,224,300	2,224,300	2,224,300	2,595,017
<b>8</b>	2,224,300	2,224,300	2,224,300	2,224,300	2,595,017
<b>9</b>	2,224,300	2,224,300	2,224,300	2,224,300	2,595,017
<b>10</b>	1,954,951	1,954,951	1,954,951	1,954,951	2,280,777
<b>11</b>	1,954,951	1,954,951	1,954,951	1,954,951	2,280,777
<b>12</b>	1,954,951	1,954,951	1,954,951	1,954,951	2,280,777

Table D.6 Annual Excavator Productivity Rate  $P_{6,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
<b>1</b>	2,615,914	2,615,914	2,615,914	2,615,914	3,139,097
<b>2</b>	2,615,914	2,615,914	2,615,914	2,615,914	3,139,097
<b>3</b>	2,615,914	2,615,914	2,615,914	2,615,914	3,139,097
<b>4</b>	2,333,331	2,333,331	2,333,331	2,333,331	2,799,997
<b>5</b>	2,333,331	2,333,331	2,333,331	2,333,331	2,799,997
<b>6</b>	2,333,331	2,333,331	2,333,331	2,333,331	2,799,997
<b>7</b>	2,066,895	2,066,895	2,066,895	2,066,895	2,480,274
<b>8</b>	2,066,895	2,066,895	2,066,895	2,066,895	2,480,274
<b>9</b>	2,066,895	2,066,895	2,066,895	2,066,895	2,480,274
<b>10</b>	1,816,607	1,816,607	1,816,607	1,816,607	2,179,929
<b>11</b>	1,816,607	1,816,607	1,816,607	1,816,607	2,179,929
<b>12</b>	1,816,607	1,816,607	1,816,607	1,816,607	2,179,929

Table D.7 Annual Excavator Productivity Rate  $P_{7,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
<b>1</b>	2,013,362	2,013,362	2,013,362	2,013,362	2,500,966
<b>2</b>	2,013,362	2,013,362	2,013,362	2,013,362	2,500,966
<b>3</b>	2,013,362	2,013,362	2,013,362	2,013,362	2,500,966
<b>4</b>	2,013,362	2,013,362	2,013,362	2,013,362	2,500,966
<b>5</b>	1,795,869	1,795,869	1,795,869	1,795,869	2,230,800
<b>6</b>	1,795,869	1,795,869	1,795,869	1,795,869	2,230,800
<b>7</b>	1,590,805	1,590,805	1,590,805	1,590,805	1,976,072
<b>8</b>	1,590,805	1,590,805	1,590,805	1,590,805	1,976,072
<b>9</b>	1,590,805	1,590,805	1,590,805	1,590,805	1,976,072
<b>10</b>	1,398,168	1,398,168	1,398,168	1,398,168	1,736,782
<b>11</b>	1,398,168	1,398,168	1,398,168	1,398,168	1,736,782
<b>12</b>	1,398,168	1,398,168	1,398,168	1,398,168	1,736,782

Table D.8 Annual Truck Productivity Rate  $G_{1,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
<b>1</b>	522,734	1,045,467	522,734	627,280	614,212
<b>2</b>	522,734	1,045,467	522,734	627,280	614,212
<b>3</b>	448,057	784,100	627,280	627,280	614,212
<b>4</b>	399,656	699,398	559,519	559,519	547,862
<b>5</b>	399,656	699,398	559,519	559,519	547,862
<b>6</b>	399,656	699,398	466,265	399,656	547,862
<b>7</b>	354,021	619,536	413,024	354,021	485,303
<b>8</b>	354,021	619,536	413,024	354,021	485,303
<b>9</b>	354,021	619,536	413,024	495,629	485,303
<b>10</b>	311,151	544,514	363,009	435,611	426,536
<b>11</b>	311,151	544,514	363,009	435,611	426,536
<b>12</b>	311,151	544,514	363,009	435,611	426,536

Table D.9 Annual Truck Productivity Rate  $G_{2,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
<b>1</b>	422,270	738,972	492,648	591,177	511,842
<b>2</b>	422,270	738,972	492,648	591,177	511,842
<b>3</b>	369,486	738,972	492,648	492,648	511,842
<b>4</b>	329,572	659,144	439,430	439,430	456,550
<b>5</b>	329,572	659,144	439,430	439,430	456,550
<b>6</b>	329,572	659,144	439,430	376,654	601,521
<b>7</b>	291,939	583,879	389,253	333,645	532,835
<b>8</b>	291,939	583,879	389,253	333,645	532,835
<b>9</b>	291,939	583,879	389,253	389,253	547,094
<b>10</b>	256,587	513,175	342,117	426,536	480,844
<b>11</b>	256,587	513,175	342,117	426,536	443,154
<b>12</b>	319,902	513,175	342,117	342,117	355,446

Table D.10 Annual Truck Productivity Rate  $G_{3,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
<b>1</b>	356,716	713,431	407,675	475,621	517,434
<b>2</b>	356,716	713,431	407,675	475,621	517,434
<b>3</b>	285,372	570,745	407,675	407,675	402,448
<b>4</b>	254,545	509,090	318,182	363,636	358,974
<b>5</b>	318,182	509,090	318,182	363,636	358,974
<b>6</b>	318,182	636,363	318,182	363,636	403,846
<b>7</b>	281,849	450,959	281,849	250,533	357,732
<b>8</b>	281,849	450,959	281,849	250,533	357,732
<b>9</b>	225,479	375,799	281,849	281,849	286,186
<b>10</b>	198,175	330,292	247,719	247,719	251,530
<b>11</b>	198,175	330,292	247,719	283,108	279,478
<b>12</b>	198,175	330,292	247,719	283,108	279,478

Table D.11 Annual Truck Productivity Rate  $G_{4,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
<b>1</b>	454,972	909,944	545,966	682,458	584,964
<b>2</b>	454,972	909,944	545,966	682,458	584,964
<b>3</b>	454,972	682,458	545,966	545,966	584,964
<b>4</b>	405,824	608,735	486,988	486,988	521,773
<b>5</b>	405,824	608,735	486,988	486,988	521,773
<b>6</b>	405,824	608,735	486,988	405,824	521,773
<b>7</b>	359,484	539,226	431,381	359,484	462,194
<b>8</b>	359,484	539,226	431,381	359,484	462,194
<b>9</b>	359,484	539,226	431,381	431,381	462,194
<b>10</b>	315,953	473,929	379,143	379,143	406,225
<b>11</b>	315,953	473,929	379,143	379,143	406,225
<b>12</b>	315,953	473,929	379,143	379,143	406,225

Table D.12 Annual Truck Productivity Rate  $G_{5,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
<b>1</b>	2,815,130	2,815,130	2,815,130	2,815,130	3,284,319
<b>2</b>	2,815,130	2,815,130	2,815,130	2,815,130	2,615,914
<b>3</b>	2,815,130	2,815,130	2,815,130	2,815,130	3,284,319
<b>4</b>	2,511,027	2,511,027	2,511,027	2,511,027	2,929,531
<b>5</b>	2,511,027	2,511,027	2,511,027	2,511,027	2,929,531
<b>6</b>	2,511,027	2,511,027	2,511,027	2,511,027	2,929,531
<b>7</b>	2,224,300	2,224,300	2,224,300	2,224,300	2,595,017
<b>8</b>	2,224,300	2,224,300	2,224,300	2,224,300	2,595,017
<b>9</b>	2,224,300	2,224,300	2,224,300	2,224,300	2,595,017
<b>10</b>	1,954,951	1,954,951	1,954,951	1,954,951	2,280,777
<b>11</b>	1,954,951	1,954,951	1,954,951	1,954,951	2,280,777
<b>12</b>	1,954,951	1,954,951	1,954,951	1,954,951	2,280,777

Table D.13 Annual Truck Productivity Rate  $G_{6,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
<b>1</b>	2,615,914	2,615,914	2,615,914	2,615,914	3,139,097
<b>2</b>	2,615,914	2,615,914	2,615,914	2,615,914	3,139,097
<b>3</b>	2,615,914	2,615,914	2,615,914	2,615,914	3,139,097
<b>4</b>	2,333,331	2,333,331	2,333,331	2,333,331	2,799,997
<b>5</b>	2,333,331	2,333,331	2,333,331	2,333,331	2,799,997
<b>6</b>	2,333,331	2,333,331	2,333,331	2,333,331	2,799,997
<b>7</b>	2,066,895	2,066,895	2,066,895	2,066,895	2,480,274
<b>8</b>	2,066,895	2,066,895	2,066,895	2,066,895	2,480,274
<b>9</b>	2,066,895	2,066,895	2,066,895	2,066,895	2,480,274
<b>10</b>	1,816,607	1,816,607	1,816,607	1,816,607	2,179,929
<b>11</b>	1,816,607	1,816,607	1,816,607	1,816,607	2,179,929
<b>12</b>	1,816,607	1,816,607	1,816,607	1,816,607	2,179,929

Table D.14 Annual Truck Productivity Rate  $G_{7,k,i}$  (tons/year)

<b>Periods</b>	<b>PAG</b>	<b>NAG</b>	<b>TSF</b>	<b>Oxide</b>	<b>Sulfide</b>
<b>1</b>	2,013,362	2,013,362	2,013,362	2,013,362	2,500,966
<b>2</b>	2,013,362	2,013,362	2,013,362	2,013,362	2,500,966
<b>3</b>	2,013,362	2,013,362	2,013,362	2,013,362	2,500,966
<b>4</b>	2,013,362	2,013,362	2,013,362	2,013,362	2,500,966
<b>5</b>	1,795,869	1,795,869	1,795,869	1,795,869	2,230,800
<b>6</b>	1,795,869	1,795,869	1,795,869	1,795,869	2,230,800
<b>7</b>	1,590,805	1,590,805	1,590,805	1,590,805	1,976,072
<b>8</b>	1,590,805	1,590,805	1,590,805	1,590,805	1,976,072
<b>9</b>	1,590,805	1,590,805	1,590,805	1,590,805	1,976,072
<b>10</b>	1,398,168	1,398,168	1,398,168	1,398,168	1,736,782
<b>11</b>	1,398,168	1,398,168	1,398,168	1,398,168	1,736,782
<b>12</b>	1,398,168	1,398,168	1,398,168	1,398,168	1,736,782

Table D.15 Annual Discounted Excavator Ownership Cost  $F_{i,k,i}$  (\$/year)

<b>Fleet\Period(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>
<b>1</b>	203,363	212,944	209,185	237,503	254,448	244,734	303,347	317,296	331,366	345,557	359,871	374,307
<b>2</b>	203,363	212,944	209,185	237,503	254,448	244,734	303,347	317,296	331,366	345,557	359,871	374,307
<b>3</b>	203,363	212,944	209,185	237,503	254,448	244,734	303,347	317,296	331,366	345,557	359,871	374,307
<b>4</b>	122,157	127,913	125,655	142,831	152,843	147,008	182,216	190,595	199,047	207,571	216,169	224,841
<b>5</b>	122,157	127,913	125,655	142,831	152,843	147,008	182,216	190,595	199,047	207,571	216,169	224,841
<b>6</b>	122,157	127,913	125,655	142,831	152,843	147,008	182,216	190,595	199,047	207,571	216,169	224,841
<b>7</b>	73,631	77,100	75,739	86,093	92,128	88,611	109,832	114,883	119,977	125,116	130,298	135,525

Table D.16 Annual Discounted Truck Ownership Cost  $H_{t,k,i}$  (\$/year)

<b>Fleet\Period(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>
<b>1</b>	177,929	187,645	185,220	213,026	230,175	225,128	280,808	293,721	306,746	319,882	333,132	346,496
<b>2</b>	159,950	168,683	166,504	191,500	206,916	202,379	252,433	264,041	275,749	287,558	299,469	311,483
<b>3</b>	121,262	127,883	126,231	145,181	157,132	153,429	191,376	200,176	209,053	218,006	227,036	236,144
<b>4</b>	177,929	187,645	185,220	213,026	230,175	225,128	280,808	293,721	306,746	319,882	333,132	346,496
<b>5</b>	159,950	168,683	166,504	191,500	206,916	202,379	252,433	264,041	275,749	287,558	299,469	311,483
<b>6</b>	121,262	127,883	126,231	145,181	157,132	153,429	191,376	200,176	209,053	218,006	227,036	236,144
<b>7</b>	41,514	44,321	44,106	51,723	56,765	56,988	71,762	75,062	78,391	81,748	85,134	88,549

Table D.17 Annual Discounted Excavator Operating Cost  $V_{t,k}$  (\$/year)

<b>Fleet\Period(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>
<b>1</b>	573,744	576,352	578,971	581,603	584,247	586,902	589,570	592,250	594,942	597,646	600,363	603,092
<b>2</b>	573,744	576,352	578,971	581,603	584,247	586,902	589,570	592,250	594,942	597,646	600,363	603,092
<b>3</b>	573,744	576,352	578,971	581,603	584,247	586,902	589,570	592,250	594,942	597,646	600,363	603,092
<b>4</b>	426,201	428,138	430,084	432,039	434,003	435,975	437,957	439,948	441,948	443,957	445,974	448,002
<b>5</b>	426,201	428,138	430,084	432,039	434,003	435,975	437,957	439,948	441,948	443,957	445,974	448,002
<b>6</b>	426,201	428,138	430,084	432,039	434,003	435,975	437,957	439,948	441,948	443,957	445,974	448,002
<b>7</b>	312,165	313,584	315,009	316,441	317,879	319,324	320,776	322,234	323,698	325,170	326,648	328,132

Table D.18 Annual Discounted Truck Operating Cost  $N_{t,k}$  (\$/year)

<b>Fleet\Period(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>
<b>1</b>	312,522	313,942	315,369	316,803	318,243	319,689	321,142	322,602	324,069	325,542	327,021	328,508
<b>2</b>	274,323	275,570	276,822	278,080	279,344	280,614	281,890	283,171	284,458	285,751	287,050	288,355
<b>3</b>	226,689	227,719	228,754	229,794	230,838	231,888	232,942	234,001	235,064	236,133	237,206	238,284
<b>4</b>	312,522	313,942	315,369	316,803	318,243	319,689	321,142	322,602	324,069	325,542	327,021	328,508
<b>5</b>	274,323	275,570	276,822	278,080	279,344	280,614	281,890	283,171	284,458	285,751	287,050	288,355
<b>6</b>	226,689	227,719	228,754	229,794	230,838	231,888	232,942	234,001	235,064	236,133	237,206	238,284
<b>7</b>	164,163	164,909	165,658	166,411	167,168	167,928	168,691	169,458	170,228	171,002	171,779	172,560

APPENDIX E  
MODEL OUTPUT DATASET

Table E.1 Number of Trucks for Fleet type t Purchased at Year k ( $x_{t,k}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	31	36	44	33	40	45	53
<b>2</b>	3	8	4	3	5	8	8
<b>3</b>	5	2	12	7	7	10	7
<b>4</b>	0	0	0	0	0	0	0
<b>5</b>	0	0	0	0	0	0	0
<b>6</b>	0	0	0	0	0	0	0
<b>7</b>	0	0	0	0	0	0	0
<b>8</b>	0	0	0	0	0	0	0
<b>9</b>	0	0	0	0	0	0	0
<b>10</b>	0	0	0	0	0	0	0
<b>11</b>	0	0	0	0	0	0	0
<b>12</b>	0	0	0	0	0	0	0

Table E.2 Number of Excavators for Fleet type t Purchased at Year k ( $y_{t,k}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	7	7	8	8	8	8	10
<b>2</b>	1	2	1	1	1	2	2
<b>3</b>	0	0	0	0	0	0	0
<b>4</b>	0	0	0	0	0	0	0
<b>5</b>	0	0	0	0	0	0	0
<b>6</b>	0	0	0	0	0	0	0
<b>7</b>	0	0	0	0	0	0	0
<b>8</b>	0	0	0	0	0	0	0
<b>9</b>	0	0	0	0	0	0	0
<b>10</b>	0	0	0	0	0	0	0
<b>11</b>	0	0	0	0	0	0	0
<b>12</b>	0	0	0	0	0	0	0

Table E.3 Number of Trucks Working in Location PAG ( $h_{t,k,1}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	5.81	7.2	8.52	6.68	7.56	9.3	9.06
<b>2</b>	7.49	8.53	9.08	7.12	10.32	9.91	9.66
<b>3</b>	12.86	15.37	24.16	12.48	24.03	24.73	19.75
<b>4</b>	10.7	12.99	16.81	10.55	15.34	16.51	14.88
<b>5</b>	15.88	19.27	19.96	15.65	20.23	24.49	24.75
<b>6</b>	9.28	11.26	11.66	9.14	10.34	12.72	12.4
<b>7</b>	9.18	11.13	11.53	9.04	10.23	12.58	12.26
<b>8</b>	10.11	12.26	12.7	9.96	11.27	13.86	13.5
<b>9</b>	8.38	10.17	13.17	8.26	10.68	12.93	13.07
<b>10</b>	8.16	9.9	12.82	8.04	10.66	12.58	12.72
<b>11</b>	8.58	10.41	13.47	8.45	10.93	13.23	11.46
<b>12</b>	6.23	6.06	9.79	6.14	7.94	9.61	8.33

Table E.4 Number of Trucks Working in Location NAG ( $h_{t,k,2}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	10.73	13.88	18.2	12.2	17.71	17.81	20.38
<b>2</b>	13.74	21.93	22.53	16.71	20.43	25.19	28.06
<b>3</b>	13.22	14.41	16.02	15.97	10.79	16.93	21.21
<b>4</b>	13.49	14.32	18.54	15.51	15.04	20.23	25.3
<b>5</b>	16.76	17.53	23.03	19.26	18.67	25.12	32.64
<b>6</b>	20.56	21.82	22.6	23.62	22.91	30.81	32.03
<b>7</b>	19.17	20.35	26.34	22.03	21.36	28.74	29.87
<b>8</b>	16.31	17.32	22.42	18.75	18.18	24.46	25.42
<b>9</b>	7.13	7.57	11.76	8.2	9.94	10.69	11.11
<b>10</b>	6.53	6.94	10.95	7.51	9.11	9.8	10.34
<b>11</b>	6.52	6.92	10.75	7.49	9.08	9.77	10.16
<b>12</b>	4.76	5.05	7.84	5.46	6.62	7.13	7.41

Table E.5 Number of Trucks Working in Location TSF ( $h_{t,k,3}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	11.4	12.1	14.62	10.92	12.7	15.95	21.45
<b>2</b>	11.4	12.1	14.62	10.92	12.7	15.95	20.72
<b>3</b>	9.5	12.1	14.62	10.92	12.7	15.95	20.72
<b>4</b>	10.65	13.56	18.73	12.24	16.61	20.43	20.72
<b>5</b>	0	0	0	0	0	0	0
<b>6</b>	0	0	0	0	0	0	0
<b>7</b>	0	0	0	0	0	0	0
<b>8</b>	0	0	0	0	0	0	0
<b>9</b>	0	0	0	0	0	0	0
<b>10</b>	0	0	0	0	0	0	0
<b>11</b>	0	0	0	0	0	0	0
<b>12</b>	0	0	0	0	0	0	0

Table E.6 Number of Trucks Working in Location Leach Pad ( $h_{t,k,4}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	1.35	1.43	2.66	1.24	1.5	1.94	2.1
<b>2</b>	1.26	1.34	1.67	1.16	1.41	1.82	1.97
<b>3</b>	0.49	0.63	0.76	0.56	0.66	0.82	0.76
<b>4</b>	0.01	0.13	0.15	0.11	0.13	0.17	0.14
<b>5</b>	0.07	0.09	0.11	0.08	0.1	0.12	0.11
<b>6</b>	0.06	0.06	4.19	0.06	0.06	0.08	0.06
<b>7</b>	0	0	0	0	0	0	0
<b>8</b>	0	0	0	0	0	0	0
<b>9</b>	0	0	0	0	0	0	0
<b>10</b>	0	0	0	0	0	0	0
<b>11</b>	0	0	0	0	0	0	0
<b>12</b>	0	0	0	0	0	0	0

Table E.7 Number of Trucks Working in Location Sulfide ( $h_{t,k,5}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	1.7	1.38	0	1.96	0.53	0	0
<b>2</b>	0.09	0.1	0.1	0.09	0.14	0.14	0.59
<b>3</b>	2.92	3.5	4.45	3.06	3.82	4.56	5.55
<b>4</b>	3.29	3.94	5.01	3.45	4.3	5.14	5.04
<b>5</b>	3.29	3.94	5.01	3.45	4.3	5.14	5.65
<b>6</b>	3.29	2.99	4.46	3.45	3.69	4.5	6.46
<b>7</b>	3.71	3.38	5.03	3.89	4.16	5.08	6.38
<b>8</b>	3.71	3.38	5.03	3.89	4.16	5.08	6.38
<b>9</b>	3.71	3.46	6.29	3.89	4.86	5.81	6.38
<b>10</b>	4.22	3.74	7.16	4.47	5.52	6.61	7.25
<b>11</b>	4.03	3.88	6.15	4.23	5.28	6.31	6.93
<b>12</b>	2.05	2.46	3.12	2.15	2.68	3.2	3.52

Table E.8 Number of Excavators Working in Location PAG ( $f_{t,k,1}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	0.97	1.03	1.07	1.11	1.08	1.16	1.51
<b>2</b>	1.25	1.22	1.14	1.19	1.47	1.24	1.61
<b>3</b>	1.81	1.92	2.42	2.08	3	2.75	2.82
<b>4</b>	1.53	1.62	1.68	1.76	1.7	1.83	2.13
<b>5</b>	2.27	2.41	2.49	2.61	2.53	2.72	3.54
<b>6</b>	1.33	1.41	1.46	1.52	1.48	1.59	2.07
<b>7</b>	1.31	1.39	1.44	1.51	1.46	1.57	2.04
<b>8</b>	1.44	1.53	1.59	1.66	1.61	1.73	2.25
<b>9</b>	1.2	1.27	1.32	1.38	1.34	1.44	1.87
<b>10</b>	1.17	1.24	1.28	1.34	1.33	1.4	1.82
<b>11</b>	1.23	1.3	1.35	1.41	1.37	1.47	1.91
<b>12</b>	0.89	0.76	0.98	1.02	0.99	1.07	1.39

Table E.9 Number of Excavators Working in Location NAG ( $f_{i,k,2}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	3.58	3.47	4.55	4.07	4.43	4.24	5.1
<b>2</b>	4.58	5.48	5.48	5.32	5.11	6.16	7.01
<b>3</b>	3.31	3.51	3.2	3.79	2.7	3.39	4.24
<b>4</b>	3.37	3.58	3.71	3.88	3.76	4.05	5.06
<b>5</b>	4.19	4.38	4.61	4.81	4.67	5.02	6.53
<b>6</b>	5.14	5.45	5.65	5.91	5.73	6.16	8.01
<b>7</b>	4.79	5.09	5.27	5.51	5.34	5.75	7.47
<b>8</b>	4.08	4.33	4.48	4.69	4.55	4.89	6.36
<b>9</b>	1.78	1.89	1.96	2.05	1.99	2.14	2.78
<b>10</b>	1.63	1.73	1.83	1.88	1.82	1.96	2.59
<b>11</b>	1.63	1.73	1.79	1.87	1.82	1.95	2.54
<b>12</b>	1.19	1.26	1.31	1.37	1.32	1.43	1.85

Table E.10 Number of Excavators Working in Location TSF ( $f_{i,k,3}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	1.9	2.02	2.08	2.18	2.12	2.28	2.97
<b>2</b>	1.9	2.02	2.08	2.18	2.12	2.28	2.96
<b>3</b>	1.9	2.02	2.08	2.18	2.12	2.28	2.96
<b>4</b>	2.13	2.26	2.34	2.44	2.37	2.55	2.96
<b>5</b>	0	0	0	0	0	0	0
<b>6</b>	0	0	0	0	0	0	0
<b>7</b>	0	0	0	0	0	0	0
<b>8</b>	0	0	0	0	0	0	0
<b>9</b>	0	0	0	0	0	0	0
<b>10</b>	0	0	0	0	0	0	0
<b>11</b>	0	0	0	0	0	0	0
<b>12</b>	0	0	0	0	0	0	0

Table E.11 Number of Excavators Working in Location Leach Pad ( $f_{t,k,4}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	0.27	0.29	0.3	0.31	0.3	0.32	0.42
<b>2</b>	0.25	0.27	0.28	0.29	0.28	0.3	0.39
<b>3</b>	0.1	0.1	0.11	0.11	0.11	0.12	0.15
<b>4</b>	0.02	0.02	0.02	0.02	0.02	0.02	0.03
<b>5</b>	0.01	0.02	0.02	0.02	0.02	0.02	0.02
<b>6</b>	0.01	0.01	0.01	0.01	0.01	0.01	0.01
<b>7</b>	0	0	0	0	0	0	0
<b>8</b>	0	0	0	0	0	0	0
<b>9</b>	0	0	0	0	0	0	0
<b>10</b>	0	0	0	0	0	0	0
<b>11</b>	0	0	0	0	0	0	0
<b>12</b>	0	0	0	0	0	0	0

Table E.12 Number of Excavators Working in Location Sulfide ( $f_{t,k,5}$ )

<b>Period\Fleet(t\k)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>1</b>	0.28	0.2	0	0.33	0.08	0	0
<b>2</b>	0.01	0.01	0.01	0.02	0.02	0.02	0.02
<b>3</b>	0.49	0.5	0.49	0.51	0.55	0.57	0.72
<b>4</b>	0.55	0.56	0.56	0.57	0.61	0.64	0.72
<b>5</b>	0.55	0.56	0.56	0.57	0.61	0.64	0.81
<b>6</b>	0.55	0.5	0.56	0.57	0.61	0.64	0.81
<b>7</b>	0.62	0.56	0.63	0.65	0.69	0.73	0.91
<b>8</b>	0.62	0.56	0.63	0.65	0.69	0.73	0.91
<b>9</b>	0.62	0.55	0.63	0.65	0.69	0.73	0.91
<b>10</b>	0.7	0.62	0.72	0.74	0.79	0.83	1.04
<b>11</b>	0.67	0.55	0.68	0.71	0.75	0.79	0.99
<b>12</b>	0.34	0.35	0.35	0.36	0.38	0.4	0.5