A MIXED INTEGER LINEAR PROGRAMMING MODEL FOR TRUCK-SHOVEL SCHEDULING TO MINIMIZE FUEL CONSUMPTION

by

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SUMMARY

A MIXED INTEGER LINEAR PROGRAMMING MODEL FOR TRUCK-SHOVEL SCHEDULING TO MINIMIZE FUEL CONSUMPTION

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In the mining industry, methods to reduce the fuel consumed in the haulage operations are largely sought as a result of the growing energy demand, fuel cost increases and adverse environmental impacts due to the emission of greenhouse gases. Fuel consumption reduction in the open-pit mine operations can be achieved by improving the performance efficiency, technology efficiency, equipment efficiency and operation efficiency of trucks, shovels and the truck-shovel dispatching system. The study conducted in this work lies within the operational strategies that seek to improve the operational efficiency of the truck-shovel dispatching system.

A mixed integer linear programming model (MILP) for the truck-shovel dispatching system is developed. This optimization model minimizes the fuel consumption of dump trucks and shovels, meets the handling demand of dump sites and determines the optimal number of trips that each truck should realize on each route of the mine. The developed model is built using an m-truck-for-n shovels strategy so that a truck could be allocated to different shovels during a shift. A case study of an under-trucked mine is considered for optimization and simulation of the developed model. To illustrate the effectiveness of the MILP model, its performance is compared to a fixed dispatch method. The results show

that the MILP model decreases the average fuel consumption per ton for the fleet of trucks, shovels and for the truck-shovel system. Therefore, a saving of fuel is achieved by the MILP model.

Two other possible applications of the MILP model are also illustrated in this study. The first application shows how this model can be used in the case of a heterogeneous fleet of shovels to determine the best allocation of shovels that can lead to minimum fuel consumption in the haulage operations. The second application shows how the MILP model can be used to identify the best fleet in terms of fuel consumption and litres per ton between different fleets having different match factors.

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LIST OF SYMBOLS

i, β	Unloading point indexes
j, γ	Shovel indexes
e	Subscript that indicates an empty truck
lo	Subscript that indicates a loaded truck
k	Number of type of shovels
S	Number of shovels
N	Fleet size of trucks
y	Truck index $y = 1, 2, ..., N$
U	Number of unloading points
C_y	Capacity of truck y [*ton*]
D_i	The hourly handling demand of the unloading point i [*ton/hour*]
C_j	The hourly loading capacity of the shovel j [*ton/hour*]
S_{C_j}	Number of shovels of capacity C_j in the fleet, $j = 1, 2...k$
C_b	The bucket capacity
sh	shift duration [*hour*]
x_j^y	Number of time that the truck y has been loaded by the j-th shovel during a shift. It is equal to the number of cycles for which a truck y has been loaded by the shovel j during a shift
$t_{l,j}^y$	The loading time of a truck y when loaded by the shovel j [*hour*]
$t_{e,ij}^y$	Travel time of an empty truck y from an unloading point i to a shovel j [*hour*]
$t_{lo,ji}^y$	Travel time of a loaded truck y from a shovel j to an unloading point i [*hour*]
t_u^y	The unloading time of truck y [*hour*]
$t_{cycle,ij\beta}^y$	Cycle time of a dump truck y [*hour*]
$t_{cl,j}$	The loading cycle of a shovel j [*hour*]
Ut_j	The utilization time of the shovel j during a shift [*hour*]
I_j	The idle time of a shovel j during a shift [*hour*]
d_{ij}	Distance from an unloading point i to a shovel j [*km*]
d^y	The total distance that a truck y has travelled during a shift [*km*]
$v_{e,ij}^y$	The driving speed of an empty truck y [*km/h*]
$v_{lo,ji}^y$	The driving speed of a loaded truck y [*km/h*]
$f_{j,idle}$	Fuel consumption by the shovel j during idling time [*litres/hour*]

f_{idle}^{y}	Fuel consumption of truck y during engine idling [*litres/hour*]
$f_{e,ij}^{y}$	Fuel consumption of an empty truck y moving from an unloading point i to a shovel j [*litres/hour*]
f^{y}	The rate of fuel consumption of a dump truck y [*litres/ton*]
f_j	Fuel consumption of a shovel during the time it used to load a truck [*litres/hour*]
$f_{lo,ji}^{y}$	Fuel consumption of a loaded truck y moving from a shovel j to an unloading point i [*litres/hour*]
t_{cycle}	The average cycle time for all tucks in the shift period
$Z_{e,ij}^{y}$	Number of journeys that the y truck has traveled from the i-th unloading point to the j-th shovel during a shift.
$Z_{lo,ji}^{y}$	Number of journeys that the y truck has traveled from the j-th shovel to the i-th unloading point during a shift.
$F_{ij\beta}^{y}$	The fuel consumption of a dump truck per single cycle [*litres*]
Ft_j^{y}	The fuel consumed by the truck y for x_j^{y} cycles that this truck has realized to a j-th shovel during a shift [*litres*]
Ft	The total amount of fuel consumed by trucks [*litres*]
$F_{idle,j}$	The fuel consumed by the j-th shovel during its idling period for the entire shift [*litres*]
$Fs_{u,j}$	For a complete shift, the fuel consumed by the j-th shovel during its utilization time [*litres*]
F_j	The fuel consumed by the j-th shovel during a shift [*litres*]
Fs	The total fuel consumed by shovels for the whole shift [*litres*]
F	The total fuel consumed for the whole haulage operation during a shift [*litres*]
LTt^{y}	Litres per ton moved for a truck y [*litres/ton*]
LTs_j	Litres per ton for a shovel j [*litres/ton*]
$LTts$	Litres per ton moved for trucks and shovels [*litres/ton*]
LTt	Litres per ton moved for trucks [*litres/ton*]
$LTkm^{y}$	Litres per ton-kilometre of a truck y [*litres/tkm*]
LF	Load factor
MF	Match factor
P^{y}	The engine power of truck y [kW]
R	The Rimpull
v_{max}	The maximum speed at which a truck operates with a best performance
P_j	Total number of possibilities to allocate the shovels in different loading point

TR	Total rolling resistance
GR	Grade resistance
RR	Rolling resistance
RRF	Rolling resistance coefficient [kg/t]
GRF	Grade resistance factor [kg/t]
GVW	Gross vehicle weight [kg]
WE	Weight of an empty truck [kg]
PW	Payload of a truck [kg]

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CHAPTER 1 INTRODUCTION

1.1 CHAPTER OVERVIEW

In this section, the study is introduced. The context of the problem is highlighted, and the research questions are put forward. In addition, the hypothesis and approach of the study are presented. The research goals as well as the research contribution are also indicated.

1.2 PROBLEM STATEMENT

1.2.1 Context of the problem

Shovels and dump trucks are commonly used in open-pit mines for ore loading and transportation because of their flexibility and ability to transport material over long distances. According to [1], haulage has the highest operating cost of all the operations performed in open-pit mines. Transportation costs of materials in open-pit mines can represent up to 60% of the total mining costs [2, 3]. The largest contributor to the transportation cost in open-pit mining operations is the energy consumption of the haul trucks and shovels. This energy is essentially constituted by the diesel fuel. [4] pointed out that the energy consumed by haul trucks represents 32% of the total energy input in mines. The main part of this energy can be saved by improving the technology of equipment and the energy efficiency of the haulage operations [5, 6]. Improving the energy efficiency of the haulage operations is encouraged in the mining industry because it results in a lower operating cost.

There is an overwhelming body of evidence that human activities have induced and increased greenhouse gas emissions. As a consequence, global temperatures have risen. In all industrial sectors, measures have been taken to reduce emissions of greenhouse gases. Given that fuel is one of the most important sources of greenhouse gases emissions in surface mines, any strategy to reduce its consumption in the haulage operations will result in a significant decrease of greenhouse gases emissions and will contribute to the improvement of air quality and energy efficiency of the haulage operations.

It should be noted that mining operations are governed by environmental laws concerning the quality of air, water, exploration activities, historic sites, and endangered species. Hence, in the mining industry, project managers are continuously looking for methods that can decrease air pollution due to the mining operations.

1.3 RESEARCH OBJECTIVE AND QUESTIONS

The objective of this research is to develop an optimization model for truck-shovel dispatching system in open-pit mines. The developed optimization model will intend to minimize the fuel consumption of both trucks and shovels with respect to the handling demand of each unloading point. It must consider in its formulation the technical specifications of equipment so that it could be used in both cases, homogeneous or heterogeneous fleet. Differences in the payloads of trucks and the loading capacities of shovels imply different powers, traction of trucks and lead to the inter-trucks time variation. In the case of an under-trucked mine, the inter-truck time variation influences the utilization and waiting time of shovels, hence, their fuel consumption. Besides this, the loading time of a truck depends directly on its capacity and the shovel capacity. For a specific truck, the smaller capacity shovel implies a longer loading time and the larger capacity shovel implies a shorter loading time. The quantity of fuel consumed by a truck during loading is proportional to its loading time. Therefore, it depends on the shovel capacity. For this reason, in the case of a heterogeneous fleet, technical specifications of equipment must be taken into account for the optimization problem of haulage operations in open-pit mines.

The following research questions are put forward:

- For a given fleet of trucks, what is the optimum number of trips that each truck must realize on each haul route of the mine so that the handling demand for each unloading point is met with minimum litres of fuel consumed per ton moved?

- In a large open-pit mine having several loading points with a heterogeneous fleet of shovels one question arises:"what is the best allocation of shovels which can lead to minimum litres of fuel consumed per ton moved for the entire haulage operations?"

- Between different fleets of equipment having different match factors, how can we choose the fleet that can lead to minimum fuel consumption?

- For a given production, can the match factor be used as the unique criteria for determining the best fleet of equipment to use in the haulage operations?

1.4 HYPOTHESES AND APPROACH

It is hypothesized that the fuel consumption in open-pit mines can be minimized through optimization of the energy performance of the truck-shovel dispatching system.

In order to attain the goals aforementioned, the approach followed in this research work will include the following:

- A literature study on the theory related to the truck-shovel dispatching system and to the estimation of the fuel consumption of trucks and shovels.

- Developing a mathematical model that can characterize the truck-shovel dispatching system and optimize the overall fuel consumption of trucks and shovels.

- Finding and implementing the appropriate mathematical algorithm capable of solving the optimization model developed previously.

- Verifying the effectiveness of the developed model by means of a case study.

- Discussing the results and drawing conclusions.

1.5 RESEARCH GOALS

Two goals are pursued in this study. Firstly, to present an operational strategy for assigning trucks to shovels. This strategy will intend to minimize fuel consumption of both trucks and shovels while the handling demand of each unloading point is met. Secondly, in a mine with a heterogeneous fleet of shovels, to develop an optimization model which can be used to find the best allocation of shovels that can lead to lower fuel consumption in the haulage operations.

1.6 RESEARCH CONTRIBUTION

This work contributes the following:

- For an operational open-pit mine with certain topography and resources, the litres per ton obtained from the proposed MILP model can be used as a reference for evaluating the efficiency of his truck-shovel dispatching system.

- During the planning of a new open-pit mine, the proposed modelling frame work can be used to determine the expected litres of fuel consumed per ton moved. This can help the decision maker to justify the budget allocated to the haulage operations.

- For a mine with several pits and a heterogeneous fleet of shovels, the MILP model developed in this research may be a powerful tool which can be used to optimally allocate shovels. Indeed, in this study, it will be demonstrated that the best allocation of shovels can contribute to decreasing the fuel consumed in the haulage operations.

CHAPTER 2 LITERATURE REVIEW

2.1 CHAPTER OVERVIEW

This chapter presents a literature survey, which includes a description of open-pit mining, an overview of truck dispatching systems, the solution approaches of the truck dispatching problem in the open-pit mining industry, the energy efficiency opportunities in mining and the research gap of this study.

2.2 OPEN-PIT MINING

Figure 2.1. Open-pit mining

Open-pit mining is a cone shaped excavation that is used when the ore reserve is found near the surface. We generally opt for an open-pit mining when the overburden is relatively thin and there is no need of tunnelling for extracting the deposits of commercially useful minerals. Before the extraction operation starts, the overburden must be removed. In this mining method, truck and shovels are used in the haulage because of their flexibility in operating and their ability to transport material for a long distance. One of the major drawbacks of this type of mining is its higher operating costs. Despite its higher operating costs, surface mining is more productive than an underground mining [7]. Based on the ore mined, we distinguish shallow mines or queries from which sand and gravels are extracted; and deeper or strip mines from which minerals such as coal and copper are extracted. Figure 2.1 displays a typical deeper open-pit mining.

2.3 OVERVIEW OF TRUCK DISPATCHING SYSTEMS

The truck-shovel operation is a popular material handling system in surface mines because of its flexibility in removing a large volume of earth material [8]. Two strategies are used for allocating trucks to shovels, namely the fixed dispatching policy and the flexible dispatching policy [9]. From a managerial point of view, given the production target, truck allocation models are useful for determining and justifying an adequate allocated budget for truck resources [10]

2.3.1 Fixed dispatching policy

The fixed dispatch method consists of allocating a truck to a specified shovel. Each truck is assigned to follow a particular route and this assignation will remain unchanged until the end of the shift. Thus, the number of trucks assigned to a shovel is fixed and does not change throughout the shift. Numerous research conducted in this field have indicated that this method is not efficient in the case of a large mine [9].

2.3.2 Flexible dispatching policy

In this method, trucks are not allocated to a specific shovel during the shift. They are assigned to a needed shovel at a specific time based on the production target and the current condition of the dispatching system. This way of allocating trucks to shovels or pits can increase the fleet productivity, reduce the number of equipment needed for a certain level of production and decrease the queuing time. In short, allocation and dispatching of trucks according to the flexible dispatching policy can significantly improve the capacity of loading and transportation of the truck-shovel system [9].

2.4 SOLUTION APPROACHES OF THE TRUCK DISPATCHING PROBLEM IN THE OPEN-PIT MINING INDUSTRY

In the mining industry, improving the efficiency of the truck-shovel dispatching system in an open-pit mine is largely sought as a result of the growing energy demand and increasing fuel costs. To this end, several heuristic methods have been presented in the literature. Below, a summary of existing studies that have modelled and optimized the truck-shovel dispatching system is presented.

Using a transportation algorithm, [11] investigated the real-time dispatching of trucks. In [11], trucks are dispatched to a needy shovel so that the waiting time of trucks and the truck travelling are minimized while the ore quality is kept between the prescribed upper and lower limits. Needy shovels are determined by minimizing the deviation of the cumulative production of each route from its targets. The application of the transportation algorithm to a real-time truck dispatching results in a significant increase in production over fixed dispatching. However, the model considers only a homogeneous fleet of trucks, but it does not consider the equipment specifications.

A genetic algorithm was used in [12] to optimize the fleet size of trucks and minimize the cost of the truck transportation system. The results showed an improvement of the economic efficiency of the truck dispatching system due to a better scheduling program and a minimized maintenance cost achieved by the genetic algorithm. However, the proposed genetic algorithm considered only the homogeneous fleets of trucks. A mathematical framework that maximizes the overall productivity of the fleet in open-pit mines was developed in [13]. The developed mathematical model optimizes the expected productivity of truck-shovel systems considering the availability of each equipment. It assigns trucks to a route based on their operating performance. The results of the proposed model, when applied to a real case study, demonstrated the need for accounting of equipment reliability, availability and maintainability characteristics.

A study conducted in [14] addresses the operational planning problem in surface mines in the case of dynamic truck allocation. In [14] a mathematical model which minimizes the fleet size of trucks with the goal of optimizing mineral extraction, meeting the production target and the ore quality required has been developed. In that model, a penalty cost has been applied at all deviation from the production target and the ore quality. The number of trucks needed for achieving a given production rate has also been minimized in [10] using a linear integer program for truck allocation. In [10], a probabilistic approach based on the theory of finite source queues has been used for incorporating the truck congestion into the optimization model.

A benchmarking energy consumption for dump trucks in mines has been done in [4] using a generic model. Based on mine equipment, engine characteristics and vehicle dynamics, the optimization model developed in [4] minimizes the specific fuel consumption of dump trucks in open-pit mines. From the same model, the authors of [4] investigated the influence of certain operating parameters like the payload of trucks, material handling rate, vehicle speed, distance, mine gradient, wind speed and the rolling resistance on the specific fuel consumption of dump trucks. The results show that for a typical mine with the proposed generic model, a fuel savings of 17% could be achieved. The study conducted in [4] does not consider the impact of a heterogeneous fleet of shovels on the total fuel consumption of the entire haulage operation. It will be shown in this study that in the case of a heterogeneous fleet of shovels, the best allocation of shovels in different pits can improve the efficiency of the truck-shovel system and lead to less litres of fuel consumed per ton moved.

Following the most recent literature review on truck dispatch systems, three strategies are used for assigning a truck to a right shovel: the 1-*truck-for-n-shovels, the m-trucks-for-1-shovel* and the *m-trucks-for-n-shovels* strategies [15]. The first strategy considers *n-shovels* for a truck which is ready and waits for an assignment; the system determines the cost of assigning that truck to any shovel and assigns it to a shovel which gives the lowest cost. In the second strategy, the truck-dispatching decisions are made by considering one shovel at a time and the m next trucks to be assigned in the near future. Firstly, shovels are ranked based on their delay with respect to their production targets. Secondly, considering each shovel in that order, trucks are assigned with the goal of minimizing their production delays. In the last strategy, the m trucks which have to be dispatched in the near future are assigned to n shovels using combinatorial optimization methods.

In this study, the *m-trucks-for-n-shovels* dispatching strategy is formulated as a mixed-integer linear programming (MILP) model which optimizes the route choice of dump trucks and minimizes the fuel consumption of both the trucks and shovels with respect to the production goal in the case of an *under-trucked mine*. No waiting time of trucks is considered in the development of the proposed MILP model. Indeed, in the mining industry, a smaller trucking fleet may be interested as it is usually correlated to a lower operating cost of the fleet [16].

The major challenge facing in the haulage operations in open-pit mining industry consists of determining where a truck should be sent after dumping its load? To answer this question, based on specified objectives, the dispatcher has to determine the best destination where he should send the truck. In order to dispatch trucks to different shovels, various criteria are used in the haulage operations. These criteria seek to directly or indirectly maximize the production and minimize the equipment inactivity [15]. [17] and [18] are studies that have provided a good description of these criteria, and have examined their mathematical formulation in detail and have identified their strengths and weaknesses. A brief description of these criteria is given bellow.

2.4.1 Minimizing truck waiting time

An empty truck at an unloading point is sent to a shovel so that the time it will wait before being loaded by that shovel is short. This criterion is only applicable in the case of an over-trucked mine in which no specific shovel production target and ore quality are required. In the case of an under-trucked mine, as the number of trucks in the system is small and trucks do not wait at shovels very often, the application of this rule leads to an underutilization of certain shovels.

2.4.2 Minimizing shovel idle time

An empty truck at an unloading point is dispatched to the shovel which has been waiting for a truck for a long time or is expected to be idle in the near future. This policy aims to maximize the utilization of shovels by minimizing their idle time. It is recommended in a mine in which specific ore quality is required. This rule tends to optimally utilise the shovels but it does not maximize the overall production. The overall production decreases with this criterion because of the long cycle time required to reach the furthest shovel.

2.4.3 Minimizing truck cycle time

An empty truck at an unloading point is dispatched to a shovel so that the expected cycle time for this truck is minimal. This policy aims to maximize the overall production of the haulage by maximizing the number of truck cycles during the shift. As a consequence, it prioritizes the shovels that are closer to the unloading point by assigning more trucks to these shovels.

2.4.4 Minimizing shovel saturation

An empty truck at an unloading point is dispatched to the shovel which has at that time the least degree of saturation among the available shovels. The degree of saturation for a shovel is the ratio between the number of trucks that have been sent and the number of trucks that should have been allocated to the considered shovel. This rule aims to dispatch trucks to shovels at an equal time interval and avoids the queue of trucks at shovels. This would be desirable in a mine which has a sufficient number of trucks that can meet the shovel requirements.

2.5 ENERGY EFFICIENCY OPPORTUNITIES IN MINING

Improving energy efficiency is encouraged in mining sectors, as it usually results in a lower operating cost and can constitute an opportunity to reduce the environmental impact due to the mining operations. [19, 20] and [21] point out that this can be achieved at four levels: performance efficiency, operation efficiency, equipment efficiency and technology efficiency (POET). According to [19, 21] the POET concept is described as follows.

2.5.1 Performance efficiency

The performance efficiency of an industrial energy system is a measure of its energy efficiency. There are many performance indicators that can be used to evaluate the performance of an industrial energy system. They can be compiled into two groups: engineering indices (EI) and social and environmental indices (SEI). The fuel consumption is one of the common engineering indices used in the mining industry to evaluate the performance efficiency of the mining operations such as the haulage operations.

It is easy to calculate and express in litres per bank cubic meter (BCM) [1] or litres per ton of material moved.

Downer EDI Mining Pty Ltd (DEDIM) has developed an energy and greenhouse performance indicator called Downer Energy and Emission Measure (DEEM). The DEEM performance indicator considers the provenance and destination of the material transported, the quantity of material moved and the fuel consumed to transport the material. Two indicators are used in the DEDIM's approach, the GJ/ton-km for the haulage equipment such as trucks, road trains, scrapers, and graders, and the GJ/ton of material moved for equipment such as excavators, shovels and dozers. At the final stage in the DEEM approach, the litres of fuel consumed is converted to units of energy (GJ) and greenhouse gas emissions (tons CO_2-e) [22].

The other indicator used in the mining industry is the equivalent flat haul (EFH). The EFH parameter describes the characteristics of the haul road travelled. This parameter takes into account the distance from the source to the destination and the elevation change from the source to the destination. The aim of the EFH is to normalize the elevation change and the distance travelled in order to allow the comparison of the energy consumed and tonnage transported during the haulage operations [22].

2.5.2 Operation efficiency

The operation efficiency of an energy system can be achieved by optimally coordinating, sizing and matching all components of the system [19, 20, 21, 23]. In this regard, to operate efficiently a system such as the truck-shovel dispatching system three steps are followed. These steps are described bellow.

- The first step consists of optimally sizing and matching the fleet of equipment (number and capacity). According to [24] the optimal fleet size can be determined based on the production target and the productivity of each equipment. The productivity of a truck is determined based on its effective payload and estimated cycle time. Based on the determined productivity, the number of trucks that is needed in the haulage operations is then determined by dividing the hourly tonnage required by the tons per truck per hour. This method gives a rough estimation

[1] A bank cubic meter is the contents of the cubic meter of rock in place, before it is drilled and blasted []

of the number of trucks needed to meet the production target [25] and assumes that the fleet of trucks is homogeneous. It does not accurately provide a dispatching model of the truck-shovel system. In order to accurately determine the fleet size, several methods that involve stochastic simulation such as the Monte Carlo, computer simulation programs such as the Talpac and the application of the queuing theory to the haul cycle have been proposed. More information about these methods can be found in [26, 25, 27].

- The second step consists of optimally controlling the dispatch of the truck while the given performance index is optimized. This is achieved by each time determining the best destination of each truck. The best destination can be determined manually through human intervention or by means of an automatic system.

- The last step consists of improving the skills of truck, shovel and dispatch operators. Indeed, human decisions and judgement are important factors in achieving operation efficiency of an industrial energy system. This is valid for the manual and the most automated dispatching system. Human behaviour and operator proficiency highly affect the performance of an industrial energy system [28, 29].

2.5.3 Equipment efficiency

The equipment efficiency of an industrial energy system during its operation is evaluated by comparing its energy output to that which this system can provide under ideal and controlled conditions. It can be ameliorated by improving the efficiency of each component of the energy system in relation to the technology design specifications [19, 21]. To illustrate this definition, let us consider the truck-shovel dispatching system. A proper maintenance plan of trucks and shovels can minimize the deviation of their performances from the design specifications and then improve the overall energy efficiency of the truck-shovel dispatching system. Equipment efficiency of the truck-shovel dispatching system can also be improved by retrofitting more efficient trucks and shovels. This action must be well timed to avoid losses due to the use of old equipment.

2.5.4 Technology efficiency

According to [19, 21], technology efficiency of an energy system can be achieved with replacing old technologies by new and more efficient technologies. This can also be achieved by introducing new efficient technologies to the existing system. In the mining industry, the replacement of the human driver by the computer driver has improved the fuel efficiency of trucks and contributed to greenhouse gas emission reduction. This has also resulted in increasing the productivity of trucks because of the truck availability improvement [30]. Another significant example of technology efficiency improvement is the substitution of the manual dispatching systems by the automated dispatching systems. Research showed that this decreased the number of trucks needed and the haulage costs between 5 and 35 percent [31].

In order to avoid the negative effects of truck and shovel break down on production; nowadays, trucks and shovels are equipped with vital sign monitors to allow the detection of potential mechanical failures. The use of vital sign monitors aboard shovels in conjunction with the GPS and a geological description of the face allow for the identification of the material property dug by the shovel. This information is vital when material quality is required. Indeed, when having this information, it is possible to know the quality of material transported by each truck and then control the quality of materials dumped at unloading points [15].

2.6 RESEARCH GAP

It has been shown that there is a large amount of studies focused on the energy efficiency improvement of the truck-shovel dispatching system. However, in the case of heterogeneous fleets of trucks and shovels, the work done so far does not present a complete mathematical model that can minimize the fuel consumed for all haulage operations and allocate trucks to shovels in an optimal manner in the case of heterogeneous fleets of trucks and shovels. Heterogeneous fleets of equipment are common because of pre-existing equipment and optimal fleet selection that minimizes the cost of the project [32]. In this study, a mathematical programming model to minimize the fuel consumed during the haulage operations is built. This model is applicable to both cases, (homogeneous and heterogeneous) fleets of equipment. It optimally determines the routes of each truck and the number of trips that each truck should realize empty or loaded on those routes. Optimization of route results in vehicle emission reduction which contributes to the improvement of air quality.

CHAPTER 3 THEORETICAL MODELING OF A TRUCK-SHOVEL DISPATCHING SYSTEM

3.1 CHAPTER OVERVIEW

In this chapter, a mixed integer linear programming model (MILP) is developed to minimize the fuel consumed in the haulage operations in open-pit mines. To develop this mathematical model, factors that influence the efficiency of the load, transport, and dump process are identified and modelled. The characteristics of haul roads that influence the fuel consumption of dump trucks are considered in the estimation model of the fuel consumption of dump trucks. The performance indicators that will be used in the evaluation process of the energy efficiency of the MILP model are modelled. The solution procedure followed in order to solve the MILP model is also presented in this chapter. To evaluate the energy performance of the MILP model, its energy indicators are compared to those obtained with the fixed dispatch model. The fixed dispatch model uses as a benchmark model which also aims to minimize the fuel consumed in the haulage operations. This benchmark model is also developed in this chapter.

3.2 TRUCK-SHOVEL DISPATCHING PROBLEM

Dump trucks are usually used for ore haulage in open pit mines. Figure 3.1 displays a generic open pit mine which has U unloading points, S shovels and $U \times S$ transport routes. During each shift, empty trucks located at unloading points are assigned to shovels and those who were loaded by shovels return back to unloading points to complete their cycles. Shovels consume fuel during their working and

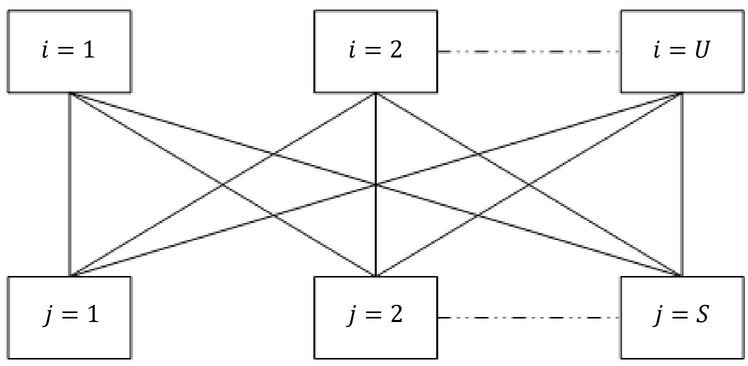


Figure 3.1. Transport routes of trucking $S \times U$

idling periods and dump trucks consume fuel during their waiting, loading, unloading and travelling periods. The fuel consumption of each equipment (truck and shovel) depends on its size, type, operating time, operating conditions and technical specifications.

The purpose of this study is to present an operational strategy for assigning trucks to shovels. The strategy will intend to minimize fuel consumption of both trucks and shovels while the handling demand of each unloading point is met. Another aspect of this research is to develop a truck-shovel dispatching model which could be used as a reference for evaluating the efficiency of a truck-shovel dispatching system for an operational open-pit mine.

3.3 BASIC ASSUMPTION

In this work, the following assumptions are made in the modelling for the truck-shovel dispatching system:

- Firstly, in haulage operations, depending on the mine topography, truck engine specifications and payload capacity, each truck is driven at its optimum speed that leads to the most efficient fuel consumption.

- Secondly, all unloading points are wide enough, so that loaded trucks could dump their loads at the same time. Therefore, no queuing of trucks can happen at a dumping point.

- Thirdly, in the case of an under-trucked mine, no waiting time of trucks at a shovel can happen.

- Fourthly, the haul routes of the mine allow for two-way traffic of trucks.

- Fifthly, a shovel can load only one truck at a time.

- Sixthly, during a shift an empty dump truck can be assigned to any shovel. A loaded truck can dump its load at any unloading point. consequently, no truck is assigned to a particular route during a shift.

- Lastly, all the trucks start their operation at the parking spaces near to the unloading points. At the end of a shift, trucks end their operation after dumping their loads at unloading points.

3.4 FACTORS OF PRODUCTION

In the haulage operations, there are a large number of factors that influence the efficiency of the load, transport and dump process. Among which, the truck payload, truck cycle time, shovel cycle time and operators proficiency of both trucks and shovels are decisive factors of the production. These factors are described below.

3.4.1 Truck payload

The truck payload is defined as the capacity of transportation of the considered truck. Its maximal value is generally given in the manufacturer's catalogue. But, during the haulage operations, the parameters such as particle size distribution, swell factors, material density and fill factor can cause the payload of a truck to vary [33, 34, 35, 36]. The payload variance has an impact on the production and on the fuel consumption. The research in [33]shows that for a Caterpillar truck 793D when the payload variance increases, the fuel consumption, rate of greenhouse gas emission and their cost linearly increase. A large payload variance makes the predictability of equipment wear and tear less accurate, which decreases the accuracy of the maintenance plan [37], and can result in a maintenance cost increase. For this reason, a minimum payload variance is always desirable. In mining operations, to minimize the payload variance, trucks are equipped with an on-board payload measurement system and an online fleet monitoring, the variation of the particle size distribution, swell factor, material density and fill factor is minimized [33].

3.4.2 Travel time

The travel time $t^y_{e,ij}$ of a truck y from the $i-th$ unloading point to the $j-th$ shovel and return trip $t^y_{lo,j\beta}$ are respectively calculated by equations 3.1 and 3.2. They depend on the operating speed of the dump truck.

$$t^y_{e,ij} = \frac{d_{ij}}{v^y_{e,ij}} \quad (i = 1,2,...,U; \quad j = 1,2,...,S), \tag{3.1}$$

$$t^y_{lo,j\beta} = \frac{d_{j\beta}}{v^y_{lo,j\beta}} \quad (\beta = 1,2,...,U; \quad j = 1,2,...,S). \tag{3.2}$$

Where the subscript e and lo denote an empty truck and a loaded truck, y is the truck index, d_{ij} is the distance between the i-th unloading point to the j-th shovel, $d_{j\beta}$ is the distance between the j-th shovel to the β-th unloading point, $v^y_{e,ij}$ is the speed at which the empty truck y travels from an unloading point i to a shovel j, $v^y_{lo,j\beta}$ is the speed at which the loaded truck y travels from the shovel j to an unloading point β, U is the number of unloading points and S is the number of shovels.

3.4.3 Loading time

The loading time of truck y is the time required to fill this truck by a shovel. It depends on the shovel capacity and the capacity of the truck its self. The greater the capacity of a shovel, the fewer the number of passes that are required for it to fill a truck. Thus, the loading time of a dump truck is inversely proportional to the shovel capacity. It is given by the following equation:

$$t^y_{l,j} = \frac{C_y}{C_j} \tag{3.3}$$

With: C_y, the capacity of the truck y and C_j , the hourly loading capacity of the shovel j .

3.4.4 Truck cycle time

The duration of a single cycle of a dump truck y is the time required for that truck to travel from an unloading point i to a shovel j, to be loaded by this shovel, to travel from this shovel to an unloading point β and to dump its load. It is calculated as:

$$t^y_{cycle,ij\beta} = t^y_{e,ij} + t^y_{lo,j\beta} + t^y_{l,j} + t^y_u. \tag{3.4}$$

Where t^y_u is the unloading time of the truck y. Note that $i = \beta$ implies that the truck returns to the original unloading point where it started its cycle.

This definition of the cycle time implies that a truck y can be dynamically assigned to different shovels during its operating time and can dump its load at different unloading points. Therefore, a truck y can start a cycle at an unloading point i and end it at the same or another unloading point.

If we denote by $Z^y_{e,ij}$ the number of journeys that the y truck has travelled from the i-th unloading point to the j-th shovel during a shift and by $Z^y_{lo,j\beta}$ the number of journeys that the y truck has travelled from the j-th shovel to the β-th unloading point during a shift. Then, the number of times x^y_j that this truck y has been loaded by a particular j-th shovel during a shift can be determined as:

$$x^y_j = \sum_{i=1}^{U} Z^y_{e,ij} \quad or \quad x^y_j = \sum_{i=1}^{U} Z^y_{lo,j\beta} \tag{3.5}$$

And the sum of cycle times of all cycles performed by a truck y during the all shift is calculated as:

$$\sum_{\beta=1}^{S} \sum_{i=1}^{U} \left[Z^y_{e,ij} t^y_{e,ij} + Z^y_{lo,j\beta} t^y_{lo,j\beta} + Z^y_{lo,j\beta} \left(t^y_{l,j} + t^y_u \right) \right] \tag{3.6}$$

For multiple dump trucks working between multiple shovels and unloading points, the average cycle time for all trucks is calculated as:

$$t_{cycle} = \frac{\sum_{i=1}^{U} \sum_{\beta=1}^{U} \sum_{j=1}^{S} \sum_{y=1}^{N} t^y_{cycle,ij\beta}}{2USN}, \tag{3.7}$$

where N is the number of trucks.

3.4.5 Shovel cycle, utilisation and idle time

The loading cycle is the time required for the shovel to fill the bucket, swing loaded to the dumping point (or truck), dump, swing empty to the loading point and position the bucket for filling [37]. It depends on the machine size, job conditions, and operator ability. The harder the loading conditions, the longer it takes for a shovel to complete one cycle. Improving the job conditions and operator average ability can decrease the loading cycle time [38]. The loading cycle $t_{cl,j}$ of a shovel j is related to its hourly capacity as follows [37]:

$$t_{cl,j} = \frac{C_b \times \eta}{C_j} \tag{3.8}$$

With: C_b , the bucket capacity and η is a coefficient. It is the product of the fill factor of the bucket (the percentage of the shovel's bucket that is actually filled with the material), swell factor (ratio of BCM/LCM[1]), operating efficiency of the shovel and the propel time factor.

The utilization time Ut_j of the shovel j during a shift is the total time during which this shovel has been used to load trucks. It is calculated as follows:

$$Ut_j = \sum_{y=1}^{N} x_j^y t_{l,j}^y \tag{3.9}$$

Or:

$$Ut_j = \sum_{y=1}^{N} \sum_{i=1}^{U} Z_{lo,j\beta}^y t_{l,j}^y \tag{3.10}$$

The idle time I_j of the shovel j during a shift is the total time that this shovel has waited for trucks. This time is calculated as:

$$I_j = sh - \sum_{y=1}^{N} x_j^y t_{l,j}^y \tag{3.11}$$

or:

$$I_j = sh - \sum_{y=1}^{N} \sum_{i=1}^{U} Z_{lo,j\beta}^y t_{l,j}^y. \tag{3.12}$$

Where sh is the shift duration.

3.5 HAUL ROAD CHARACTERISTICS

3.5.1 Total resistance

One of the major characteristics of haul roads that influence the fuel consumption of dump trucks is the total resistance. Total resistance or total effective grade represents the resisting force that the usable rimpull must overcome before the equipment can move [39]. For a truck moving in the opposite direction of the sloping road, it is the sum of the grade resistance GR and rolling resistance RR. The

[1]LCM = loose cubic meter

total resistance is calculated by equation (3.13) [40] as:

$$TR = GR + RR. \tag{3.13}$$

For a truck moving in the same direction of the sloping road, the total resistance is calculated by equation (3.14) as:

$$TR = RR - GR. \tag{3.14}$$

3.5.2 Rolling resistance

The rolling resistance is defined as the force that must to be overcome to pull the wheel over the ground. It is acting in the opposite direction of the motion of the truck. The rolling resistance depends on the wheels and the gross weight of the truck. It is characterized by a rolling resistance coefficient RRF and is calculated as follows:

$$RR = RRF \times GVW. \tag{3.15}$$

Where GVW is the gross vehicle weight. It is the sum of the payload PW and the weight WE of the empty truck [38, 41]. It is determined by equation (3.16).

$$GVW = WE + PW. \tag{3.16}$$

3.5.3 Grade resistance/assistance *GR*

The grade resistance is defined as the gravitational force that must be overcome to propel a truck climbing a hill. For a truck moving downhill, this force is called grade assistance as it assists the truck movement. It is proportional to the gross vehicle weight and slope of the road. The greater the slope of the road and gross vehicle weight, the greater the grade resistance/assistance. Parameters that influence the GR are shown on Figure 3.2. The grade resistance/assistance is determined by equation (3.17) [39] as:

$$GR = GRF \times GVW. \tag{3.17}$$

Where GRF is the grade resistance factor expresses in kg/t.

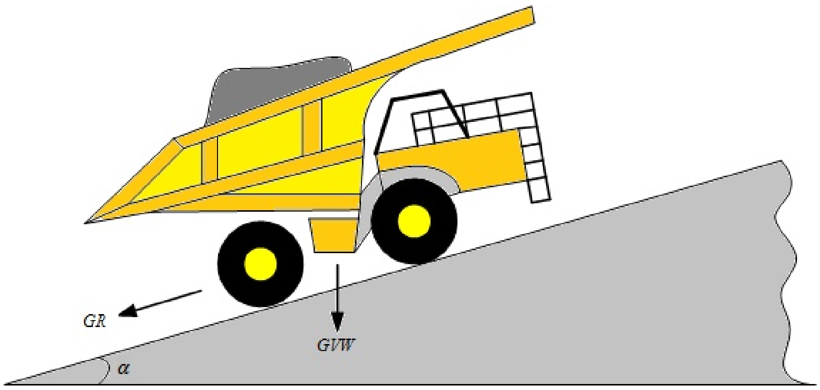


Figure 3.2. Parameters that influence the grade resistance/assistance

3.6 FUEL CONSUMPTION OF DUMP TRUCKS

In surface mining operations trucks and shovels consume diesel fuel [42]. Factors such as truck payloads, mine gradient, rolling resistance, speed, acceleration, aerodynamic, weather, operator's driving style and maintenance plan influence the fuel consumption of dump trucks. An appropriate management technique of these factors can decrease their influence on the fuel consumption of dump trucks and thus contribute to a cost reduction of the haulage operations. The energy consumption of a truck can be determined from its operating data in an actual mine. For estimation purposes it can be formulated as a function of the speeds of the truck, the power requirements, mine characteristics and the gross vehicle weight of the considered truck [41]. In this formulation, the maximum speed v_{max} attainable, the rimpull R and the gear range are determined using the Rimpull-Speed-Gradeability curve or the retarder curve when the weight of the truck and the total resistance are known. These characteristic curves are generally given in the manufacturer's catalogue. An illustrative Rimpull-Speed-Gradeability curve of trucks is displayed by the Figure 3.3. The Rimpull-Speed-Gradeability curve is used to determine the maximum speed and the rimpull when the truck is moving uphill. The calculated maximum speed and rimpull are then used to estimate the power required for maintaining that specific speed. At this gradeability performance the power required is determined by equation (3.18) [33] as:

$$grade\ P^y = R \times v_{max}. \tag{3.18}$$

Where R is the rimpull. It expresses the amount of effort available between the tires and the ground to propel the truck. Note that v_{max} represents the maximum speed at which the truck operates with its best performance.

The *grade* P^y can also be estimated by this empirical formula (3.19) [41, 43] as:

$$grade\ P^y = \left(\frac{GVW.TR.v_{max}}{273.75}\right)0.7457 \tag{3.19}$$

Similarly, the retarder curve is used to determine the maximum speed and the rimpull when the truck is moving downhill. The retarding power required to maintain that specific speed without using the brake system at this retarder performance is determined by equation (3.20) or (3.21) as:

$$retarder\ P^y = R \times v_{max}, \tag{3.20}$$

or

$$retarder\ P^y = \left(\frac{GVW.TR.v_{max}}{273.75}\right)0.7457 \tag{3.21}$$

The rate of a dump truck fuel consumption can therefore be estimated by equation (3.22) when the engine load factor of the truck in question is known [44]. The load factor is the portion of the full power required by the truck. The usual load factors for dump trucks are generally given in the manufacturer's catalogue. For indication, Table 3.1 gives the usual load factors for Caterpillar trucks. In this study, to determine the fuel consumption of dump trucks, the following values of load factor are considered: 35% for a loaded truck (normal load), 20% for an empty truck and 10% for an idling truck [45].

$$f^y = 0.3 \times P^y \times LF \quad [L/h]. \tag{3.22}$$

Where P^y , 0.3 and LF represent the maximal engine power (kW), the unit conversion factor (L/kW/hr) and the engine load factor respectively. For a truck moving uphill P^y is given by equation (3.23) and for a truck moving downhill it is given by equation (3.24).

$$P^y = grade\ P^y \tag{3.23}$$

$$P^y = retarder\ P^y \tag{3.24}$$

The fuel consumed by a dump truck y per single cycle $F^y_{ij\beta}$ can then be estimated by equation (3.25) as:

$$F^y_{ij\beta} = f^y_{e,ij}t^y_{e,ij} + f^y_{lo,j\beta}t^y_{lo,j\beta} + f^y_{idle}(t^y_{l,j} + t^y_u). \tag{3.25}$$

Where $f^y_{e,ij}$ is the fuel consumption of the empty truck y moving from the unloading point i to the shovel j, $f^y_{lo,j\beta}$ is the fuel consumption of the loaded truck y moving from the shovel j to the unloading point β and f^y_{idle} is the fuel consumption of the truck y during the engine idling time.

For x_j^y cycles that a y truck has accomplished to a particular shovel j during a shift, the amount of fuel Ft_j^y consumed by this truck to accomplish these cycles is calculated as:

$$Ft_j^y = \sum_{i=1}^{U} Z_{e,ij}^y f_{e,ij}^y t_{e,ij}^y + \sum_{\beta=1}^{U} Z_{lo,j\beta}^y f_{lo,j\beta}^y t_{lo,j\beta}^y + \sum_{\beta=1}^{U} Z_{lo,j\beta}^y f_{idle}^y \left(t_{l,j}^y + t_u^y \right) \tag{3.26}$$

From the above equation, for a given shift, the total amount of fuel Ft consumed by all trucks during a shift is calculated as:

$$Ft = \sum_{j=1}^{S} \sum_{y=1}^{N} Ft_j^y \tag{3.27}$$

Table 3.1. Load factors for Caterpillar

Load factors		
20%-30%	Low	Large amount of idling. Short to medium hauls on well maintained level haul roads. Minimum total resistance
30%-40%	Medium	Normal load and haul time. Varying load and haul road conditions. Some adverse grades. Some high rolling resistance.
40%-50%	High	Long haul time with frequent adverse grades. Continuous use on very poorly maintained haul roads with high rolling resistance.

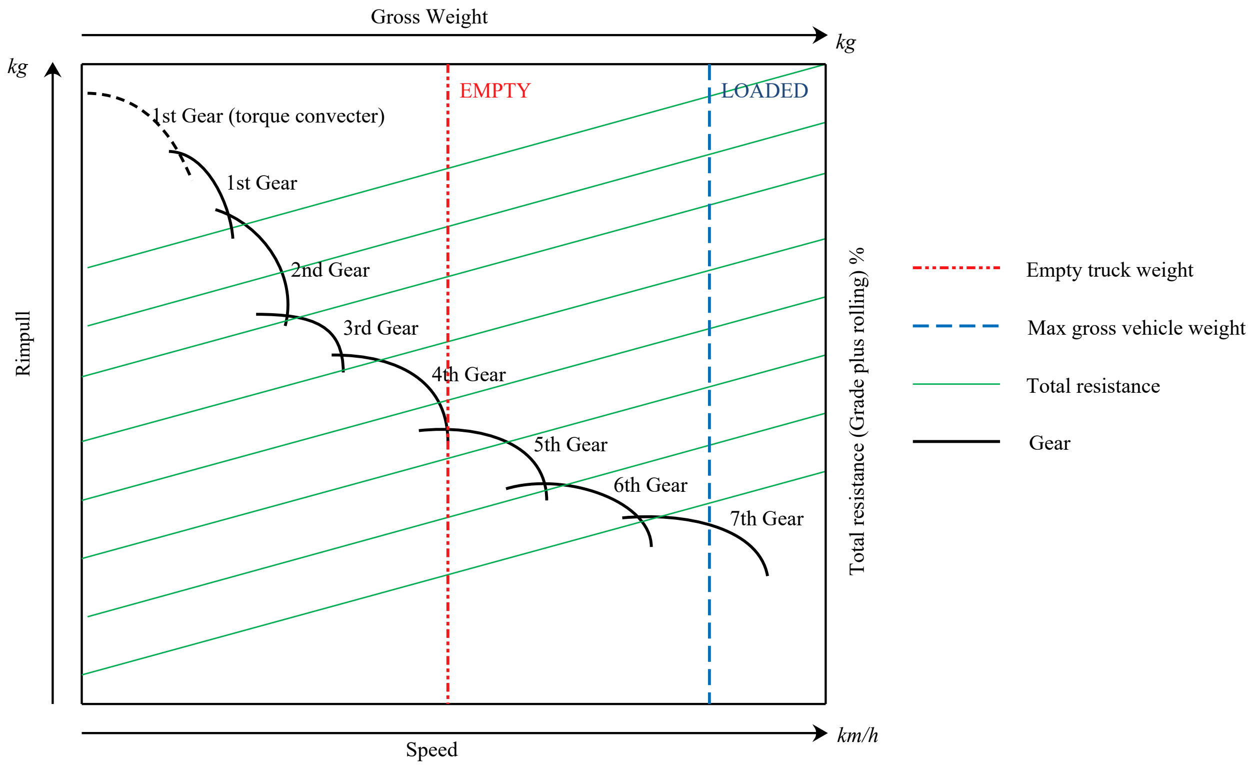


Figure 3.3. Rimpull-Speed-Gradeability curve

3.7 FUEL CONSUMPTION OF SHOVELS

Similarly, the fuel consumption of shovels can be estimated knowing their applications. Indeed, the engine fuel is controlled by the engine load factor, which depends on the application of the shovel. Table 3.2 and Table 3.3 respectively display the engine load factors and the hourly fuel consumption for caterpillar front shovels [38].

In this study, the rate of fuel consumption f_j of shovels during working times will be estimated by assuming that shovels are working with high load factors. The hourly fuel consumption $f_{j,idle}$ of shovels during idle times will be assumed to be 10% of the hourly fuel consumption of those shovels when they work with low load factors.

Table 3.2. Load factors for Caterpillar front shovels

	Load factor guide
Low	Light easy work. Considerable idling.
Medium	Steady cycling with frequent periods at idle.
High	Steady cycling in hard to dig material

Table 3.3. Hourly fuel consumption for Caterpillar front shovels

	Litres per hour		
Model	Low	Medium	High
5080	36-42	46-53	62-74
5130B	91-95	110-114	129-132
5230	163-193	193-204	208-227

For a complete shift the fuel consumed by the j-th shovel during its idling period is given as:

$$Fs_{idle,j} = I_j . f_{j,idle} \tag{3.28}$$

For a complete shift the fuel consumed by the j-th shovel during periods where it has been used to load trucks is calculated as:

$$Fs_{u,j} = f_j \sum_{y=1}^{N} \sum_{\beta=1}^{U} Z_{lo,j\beta}^{y} t_{l,j}^{y} \tag{3.29}$$

The total fuel consumed by the j-th shovel during a shift duration is determined as:

$$Fs_j = Fs_{idle,j} + Fs_{u,j} \tag{3.30}$$

The total fuel consumed by shovels for the whole shift is given as:

$$Fs = \sum_{j=1}^{S} Fs_j \tag{3.31}$$

3.8 PERFORMANCE INDICATORS

In this study, two performance indicators are used to evaluate the energy efficiency for the truck-shovel dispatching system, the litres per ton and the litres per ton-kilometres. The litres of fuel per ton moved at the end of a shift for trucks (LTt), for shovels (LTs) and for both trucks and shovels ($LTts$) are evaluated by equations (3.32), (3.33) and 3.34 respectively:

$$LTt = \frac{Ft}{\sum_{y=1}^{N}\sum_{\beta=1}^{U}\sum_{j=1}^{S} Z_{lo,j\beta}^{y} C_y} \tag{3.32}$$

$$LTs = \frac{Fs}{\sum_{y=1}^{N}\sum_{\beta=1}^{U}\sum_{j=1}^{S} Z_{lo,j\beta}^{y} C_y} \tag{3.33}$$

$$LTts = \frac{F}{\sum_{y=1}^{N}\sum_{i=1}^{U}\sum_{j=1}^{S} Z_{lo,j\beta}^{y} C_y} \tag{3.34}$$

Where F is the sum of the fuel consumed by shovels and trucks during the entire shift duration. It is calculated as follows:

$$F = Ft + Fs \tag{3.35}$$

With: Ft and Fs, being the fuel consumed by trucks and shovels respectively during the whole shift. The litres per ton of a truck y and for a shovel j at the end of a shift are calculated by equation (3.36) and (3.37) respectively:

$$LTt^{y} = \frac{\sum_{j=1}^{S} Ft_j^{y}}{\sum_{\beta=1}^{U}\sum_{j=1}^{S} Z_{lo,j\beta}^{y} C_y} \tag{3.36}$$

$$LTs_j = \frac{Fs_j}{\sum_{y=1}^{N}\sum_{\beta=1}^{U} Z_{lo,j\beta}^{y} C_y} \tag{3.37}$$

The litres per ton-kilometre $LTkm^{y}$ of a truck y is calculated as:

$$LTkm^{y} = \frac{\sum_{j=1}^{S} Ft_j^{y}}{\left(\sum_{i=1}^{U}\sum_{j=1}^{S} Z_{e,ij}^{y} d_{ij} + \sum_{\beta=1}^{U}\sum_{j=1}^{S} Z_{lo,j\beta}^{y} d_{j\beta}\right)\sum_{\beta=1}^{U}\sum_{j=1}^{S} Z_{lo,j\beta}^{y} C_y} \tag{3.38}$$

3.9 MILP MODEL FOR FUEL MINIMIZATION

As previously mentioned, the objective of this study is to minimize the fuel consumption of both trucks and shovels. The model is built in such a way that all the requirements of dump sites are met and the optimal number of trips of each truck on each route of the pit is determined. The technical specifications, such as payload of trucks, loaded capacity of shovels, and fuel consumption in function of the operating conditions of equipment are directly considered in the mathematical model. The objective function is given by the following:

$$\min F \tag{3.39}$$

In the mining industry, there is no interest to minimize the utilization of shovels because a high production is always required. On the other hand, there is an interest to minimize the fuel consumption of shovels during their idling periods. Considering this fact, a more realistic objective function is given in (3.40).

$$\min\left(Ft+\sum_{j=1}^{S}F_{idle,j}\right) \tag{3.40}$$

The operating constraints of the problem include the following:

- Material transported from all shovels should be greater than the handling demand of each unloading point. This constraint ensures that trucks are dispatched so that the production target at the mine is satisfied. The way this requirement is taken into account is shown in equation (3.41):

$$\sum_{y=1}^{N}\sum_{j=1}^{S} Z^{y}_{lo,j\beta}C_{y} \geq D_{\beta}sh, \quad \forall\beta. \tag{3.41}$$

With D_i, being the hourly handling demand of the unloading point i and sh, the shift duration.

- Material transported by trucks during the shift duration from each loading point is less than the shovel capacity allocated to that pit.

$$\sum_{y=1}^{N}\sum_{\beta=1}^{U} Z^{y}_{lo,j\beta}C_{y} \leq C_{j}sh, \quad \forall j. \tag{3.42}$$

- For the sh-th shift, the utilization time of each shovel is less or equal to the shift duration. This constraint is written as follows:

$$\sum_{y=1}^{N} x^{y}_{j}t^{y}_{l,j} \leq \ sh, \quad \forall j. \tag{3.43}$$

From equation (3.5), the constraint (3.43) can also be written as:

$$\sum_{y=1}^{N}\sum_{i=1}^{U} Z^{y}_{lo,j\beta}t^{y}_{l,j} \leq sh, \quad \forall j. \tag{3.44}$$

- The sum of cycle times of all cycles performed by a truck y during the whole shift is less or equal to the shift duration.

$$\sum_{j=1}^{S}\left[\sum_{i=1}^{U} Z_{e,ij}^{y} t_{e,ij}^{y} + \sum_{\beta=1}^{U} Z_{lo,j\beta}^{y} t_{lo,j\beta}^{y} + \sum_{\beta=1}^{U} Z_{lo,j\beta}^{y}\left(t_{l,j}^{y} + t_{u}^{y}\right)\right] \leq sh, \quad \forall y. \tag{3.45}$$

- The number of trips that a truck y realizes to a shovel equals to the number of trips that the same truck leaves that shovel. Equation (3.46) shows how this requirement is considered:

$$\sum_{i=1}^{U} Z_{e,ij}^{y} = \sum_{\beta=1}^{U} Z_{lo,j\beta}^{y}, \quad \forall j,\ \forall y. \tag{3.46}$$

- The difference between the number of times a truck y dumps its load at an unloading point i and the number of times that truck travels empty from that unloading point to different shovels can not exceed one. This constraint is written as follows:

$$\sum_{j=1}^{S} Z_{e,ij}^{y} - \sum_{j=1}^{S} Z_{lo,j\beta}^{y} \leq 1, \quad \forall j,\ \forall y. \tag{3.47}$$

- The difference between the number of times an empty truck y travels from an unloading point i to different shovels and the number of time this truck dumps its load at that unloading point can not exceed one. This constraint is written as follows:

$$\sum_{j=1}^{S} Z_{lo,j\beta}^{y} - \sum_{j=1}^{S} Z_{e,ij}^{y} \leq 1, \quad \forall j,\ \forall y. \tag{3.48}$$

- The last constraint (3.49) ensures that the number of trips of trucks are positive and integer.

$$Z_{e,ij}^{y} \in \mathbb{N}^{+};\ Z_{lo,j\beta}^{y} \in \mathbb{N}^{+};\ i = 1,2,...,U;\ \beta = 1,2,...,U;\ j = 1,2,...,S;\ y = 1,2,...,N. \tag{3.49}$$

Constraints (3.46), (3.47) and (3.48) ensure that the continuity of loading and transportation is maintained.

3.10 SOLUTION PROCEDURE

This section describes the computational steps followed in order to solve the MILP model. The computational steps are summarized in the flowchart shown in Figure 3.4. The aim is to determine the optimal number of trips that each truck used in the haulage operations should realize on each path of the mine so that the fuel consumed by shovels and trucks will be minimized and all the handling demands are met. The first step in the computational procedure consists of the estimation of the fuel consumption of dump trucks from their operating data or design specifications. This step is followed by the determination of the loading time of trucks in function of the shovels capacities. Then the travel time of trucks on each route and the fuel consumption of shovels are estimated. The estimated loading time, travel time and fuel consumption of trucks, fuel consumption of shovels, the number of unloading points and the fleet size of trucks and shovels are saved in a dedicated database and used as input data of the MILP model. After that, the MILP model is solved using "*Intlinprog*" algorithm in Matlab to determine the optimum trips of each truck. This algorithm solves problems in the following form:

$$\min_{x} f^T x, \tag{3.50}$$

subject to:

$$\begin{cases} x\ (intcon),\ \text{are integers} \\ Ax \leq b,\ (\text{linear inequality constraint}) \\ A_{eq}x = b_{eq},\ (\text{linear equality constraint}) \\ lb \leq x \leq ub,\ (\text{lower and upper bounds}) \end{cases} \tag{3.51}$$

The vector x contains the number of trips that each truck loaded or empty has realized on each path of the mine during a shift. The linear inequality constraints (3.41), (3.42), (3.43) and (3.45) are integrated into matrix A and b. The linear equality constraint (3.46) written into matrix notation is incorporated into matrix A_{eq} and b_{eq}. The lower and upper bounds (3.49) are respectively integrated into the vector lb and ub.

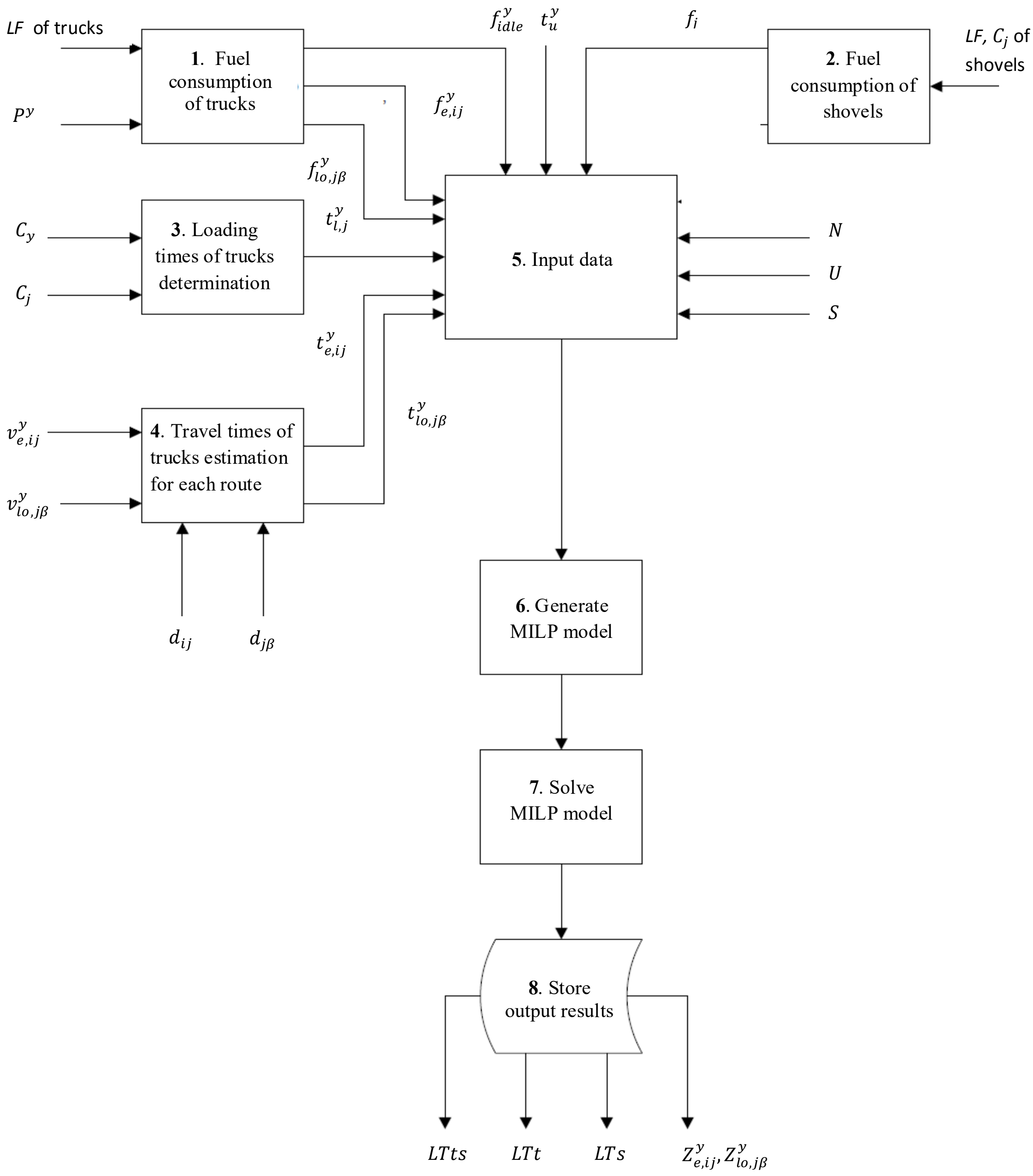


Figure 3.4. Information flow diagram for illustrating an overview of the optimization process

3.11 EVALUATION OF MODEL

To evaluate the energy performance of the MILP model, the fuel consumed per ton moved and fuel consumption per shift duration for trucks and both trucks and shovels obtained with the MILP are compared to those obtained with the fixed dispatch method. The fixed dispatch method is presented in the next section.

The percentage of improvement of the litres per ton for mixed capacity dump trucks, shovels and for both trucks and shovels will be calculated by equations (3.52),(3.53) and (3.54) respectively.

$$(LTt)_{\text{Improving}} = \frac{(LTt)_{\text{fixed dispatch}} - (LTt)_{MILP}}{(LTt)_{\text{fixed dispatch}}} \times 100\% \tag{3.52}$$

$$(LTs)_{\text{Improving}} = \frac{(LTs)_{\text{fixed dispatch}} - (LTs)_{MILP}}{(LTs)_{\text{fixed dispatch}}} \times 100\% \tag{3.53}$$

$$(LTts)_{\text{Improving}} = \frac{(LTts)_{\text{ fixed dispatch}} - (LTts)_{MILP}}{(LTts)_{\text{fixed dispatch}}} \times 100\% \tag{3.54}$$

The overall fuel saving will be estimated by the following equation:

$$\text{Fuel saving} = \frac{(F)_{\text{fixed dispatch}} - (F)_{MILP}}{(F)_{\text{fixed dispatch}}} \times 100\% \tag{3.55}$$

3.11.1 Fixed dispatch model for fuel minimization

In this section, a fixed dispatch model for fuel minimization was developed. This model is used in existing mines and will be used as a benchmark model. The fixed dispatch method consists of allocating a truck to a specified shovel. Each haul truck used in the haulage operations is assigned to follow a particular route. This assignation remains unchanged until the end of the shift. The number of trucks allocated to each shovel is fixed and does not change throughout the shift. [11, 8] and [46] are some studies that have addressed this method.

In the case of the fixed dispatch policy the objective function (3.40) is subjected to the following constraints:

$$Z^{y}_{e,ij} Z^{y}_{e,\beta,\gamma} = 0 \quad for \quad \{i,j\} \neq \{\beta,\gamma\} \tag{3.56}$$

$$Z^{y}_{lo,ji}Z^{y}_{lo,\gamma,\beta} = 0 \quad for \quad \{j,i\} \neq \{\gamma,\beta\} \tag{3.57}$$

With : β and γ, unloading point index and shovel index respectively, $Z^{y}_{lo,ji}$, the number of return trips that the truck y has realized to the unloading point i.

$$Z^{y}_{e,ij} = Z^{y}_{lo,ji}, \quad \forall j,\ \forall y,\ \forall i. \tag{3.58}$$

$$\sum_{j=1}^{S}\sum_{i=1}^{U} Z^{y}_{lo,ji}t^{y}_{cycle,ij\beta} \leq sh, \quad \forall y. \quad with \quad i=\beta. \tag{3.59}$$

$$\sum_{y=1}^{N}\sum_{j=1}^{S} Z^{y}_{lo,ji}C_y \geq D_i sh, \quad \forall i. \tag{3.60}$$

$$\sum_{y=1}^{N}\sum_{i=1}^{U} Z^{y}_{lo,ji}C_y \leq C_j sh, \quad \forall j. \tag{3.61}$$

$$\sum_{y=1}^{N}\sum_{i=1}^{U} Z^{y}_{lo,ji}t^{y}_{l,j} \leq sh, \quad \forall j. \tag{3.62}$$

$$Z^{y}_{e,ij} \in \mathbb{N}^{+};\ Z^{y}_{lo,ji} \in \mathbb{N}^{+};\ i=1,2,...,U;\ j=1,2,...,S;\ y=1,2,...,N \tag{3.63}$$

The constraints (3.56) and (3.57) ensure that each truck y is assigned only to one shovel and it can dump its load only at one unloading point during a shift. The continuity of loading and transportation is maintained by constraint (3.58). This constraint states that the number of trips an empty truck y travels from an unloading point i to a particular shovel j is equal to the return trips of this truck to the considered unloading point i. The sum of the duration times of all cycles performed by the truck y is constrained by the shift duration as specified by equation (3.59). Constraint (3.60) ensures that the handling demands of each unloading point are met. Constraint (3.61) ensures that the material transported by trucks from a loading point does not exceed the capacity of the shovel allocated at that loading point. The utilization time of shovels is constrained by the shift duration time as specified by constraint (3.62). The last constraint (3.63) ensures that the number of trips that each truck realizes on each road of the mine is positive and integer.

CHAPTER 4 CASE STUDY OF AN OPEN-PIT MINE

4.1 CHAPTER OVERVIEW

In this chapter, a case study of a hypothetical downgrade open-pit mine with two unloading points and three shovels located at three different pits is considered for optimization and simulation of the model. The handling demands of unloading points are 2325 t/h and 2375 t/h of materials. The design specification of dump trucks used in the haulage operations are given in Table 4.1[38, 47, 48, 49]. The haul roads between shovels and unloading points allow two-way traffic and the length of each road is given in Table 4.2. The operating speeds of loaded trucks are estimated using the Rimpull-Speed-Grade curves given in [47, 48] and [49]. The total resistance of the haul road is assumed to be equal to 4%. In order to answer the objective questions developed in Section 1.3, three problems are considered for simulation:

- Dispatch of a heterogeneous fleet of trucks and shovels

- Identification of the best shovel allocation

- Identification of the best fleet

The data used as input parameters of the MILP model in the simulation for each scenario are presented in the next section.

Table 4.1. Design specification of dump trucks

Parameters		Specifications	
Model	773D	775D	777D
Rated payload	56 t	65 t	96 t
Gross vehicle weight	92 530 kg	106 590 kg	161 030 kg
Bore x Stroke	137x152 mm	137x152 mm	170x190 mm
Displacement	27 $Litres$	27 $Litres$	34.5 $Litres$
Net power	485 kW	517 kW	699 kW
gross power	509 kW	541 kW	746 kW
Top speed (loaded)	66 km/h	66 km/h	60 km/h

Table 4.2. Mine topography and resources

Parameters	Mine operating condition
Mine topography	Downgrade mine
Distance between dumping points i	
and loading point j	$i_1 - j_1$ 1,5 km; $i_1 - j_2$ 2 km
	$i_1 - j_3$ 3 km; $i_2 - j_1$ 3.5 km
	$i_2 - j_2$ 2 km; $i_2 - j_3$ 1.5 km
Gradient	1:14 (4^o)
Optimal speed of empty dump truck	56 t - 50 km/h, 65 t - 50 km/h, 96 t - 50 km/h
Optimal speed of loaded dump truck	56 t - 39 km/h, 65 t - 35 km/h, 96 t - 36 km/h
Load factor	Loaded truck 35%
	Empty truck 20%
Load demand at each unloading point	$D_{i_1} = 2375t/h$ and $D_{i_2} = 2375t/h$

4.2 INPUT DATA

4.2.1 Problem 1: Dispatch of a heterogeneous fleet of trucks and shovels

In this problem, a heterogeneous fleet of ten trucks is used in the haulage. The fleet of trucks is made up of three trucks with a capacity of 56 t, three trucks with a capacity of 65 t and four with a capacity of 96 t. The operating speeds of loaded trucks are 39 km/h for trucks with capacity of 56 t, 35 km/h for trucks with capacity of 65 t and 36 km/h for trucks with capacity of 96 t. The mixed fleet of shovels consists of two shovels with a loading capacity of 1600 t/h and one shovel with a capacity of 2000 t/h. Figure 4.1 displays the allocation of shovels. The mine topography and operating parameters of the loading and haulage equipment used as input parameters of the model are shown in Table 4.2, Table 4.3, Table 4.4, Table 4.5 and Table 4.6.

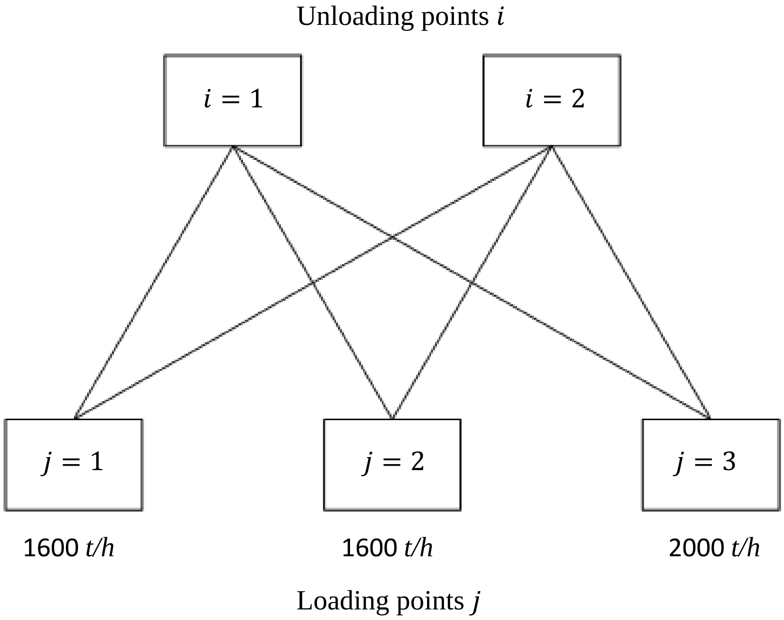


Figure 4.1. Shovel allocation

Table 4.3. Resources of trucks and shovels

Parameters	Resources		
	Trucks		
Truck capacity C_y	56 t	65 t	96 t
Number of trucks per capacity	3	3	4
Fleet size of trucks	10		
	Shovels		
Number of shovels N_j	3		
Capacity of shovels	1600 t/h	2000 t/h	
Number of shovels per capacity	2	1	
Fuel consumption of shovel during idle time $f_{j,idle}$	6.6 L/h	9.5 L/h	
Fuel consumption of shovel when the bucket is using f_j	117 L/h	130 L/h	

Table 4.4. Input data for heterogeneous fleet of dump trucks and shovels

Truck index	Fuel consumption				Loading time $t_{l,j}^y$ with shovel		
- Capacity	f_{ij}^y $[L/h]$	f_{ji}^y $[L/h]$	f_{idle}^y $[L/h]$	t_u^y $[h]$	j_1 $[h]$	j_2 $[h]$	j_3 $[h]$
$T_1 - 56\ t$	30.54	53.45	15.27	0.016	0.035	0.035	0.026
$T_2 - 56\ t$	30.54	53.45	15.27	0.016	0.035	0.035	0.026
$T_3 - 56\ t$	30.54	53.45	15.27	0.016	0.035	0.035	0.026
$T_4 - 65\ t$	32.46	56.81	16.23	0.016	0.041	0.041	0.031
$T_5 - 65t$	32.46	56.81	16.23	0.016	0.041	0.041	0.031
$T_6 - 65\ t$	32.46	56.81	16.23	0.016	0.041	0.041	0.031
$T_7 - 96\ t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_8 - 96\ t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_9 - 96\ t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_{10} - 96\ t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045

Table 4.5. Input data for heterogeneous fleet of dump trucks and shovels(travel times empty truck)

Truck index	From unloading point i to shovel j (empty truck)					
- Capacity	$i_1 - j_1$ $[h]$	$i_2 - j_1$ $[h]$	$i_1 - j_2$ $[h]$	$i_2 - j_2$ $[h]$	$i_1 - j_3$ $[h]$	$i_2 - j_3$ $[h]$
$T_1 - 56\ t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_2 - 56\ t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_3 - 56\ t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_4 - 65\ t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_5 - 65\ t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_6 - 65\ t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_7 - 96\ t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_8 - 96\ t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_9 - 96\ t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_{10} - 96\ t$	0.030	0.070	0.040	0.040	0.060	0.030

Table 4.6. Input data for heterogeneous fleet of dump trucks and shovels(travel times loaded truck)

Truck index	From shovel j to unloading point i (loaded truck)					
- Capacity	$j_1 - i_1$ $[h]$	$j_1 - i_2$ $[h]$	$j_2 - i_1$ $[h]$	$j_2 - i_2$ $[h]$	$j_3 - i_1$ $[h]$	$j_3 - i_2$ $[h]$
$T_1 - 56‘t$	0.031	0.0897	0.051	0.051	0.076	0.031
$T_2 - 56\ t$	0.031	0.0897	0.051	0.051	0.076	0.031
$T_3 - 56\ t$	0.031	0.0897	0.051	0.051	0.076	0.031
$T_4 - 65\ t$	0.043	0.100	0.057	0.057	0.086	0.043
$T_5 - 65\ t$	0.043	0.100	0.057	0.057	0.086	0.043
$T_6 - 65\ t$	0.043	0.100	0.057	0.057	0.086	0.043
$T_7 - 96\ t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_8 - 96t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_9 - 96\ t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_{10} - 96\ t$	0.042	0.097	0.056	0.056	0.083	0.042

4.2.2 Problem 2: Identification of the best shovel allocation

In this problem, a homogeneous fleet of ten trucks of capacity 96 t and a mixed fleet of three shovels are used in the haulage operations. The mixed fleet of shovels is made up of two shovels of capacity 1600 t/h and one shovel of 2000 t/h. There are three possible shovel allocations in different pits. Figure 4.2 gives the three possible shovel allocations in different loading points. To distinguish them, they are named allocation (a), allocation (b) and allocation (c). The allocation (a) allocates the shovel of capacity 2000 t/h at the third loading point. The same shovel is allocated at the second and first loading point with allocations (b) and (c) respectively.

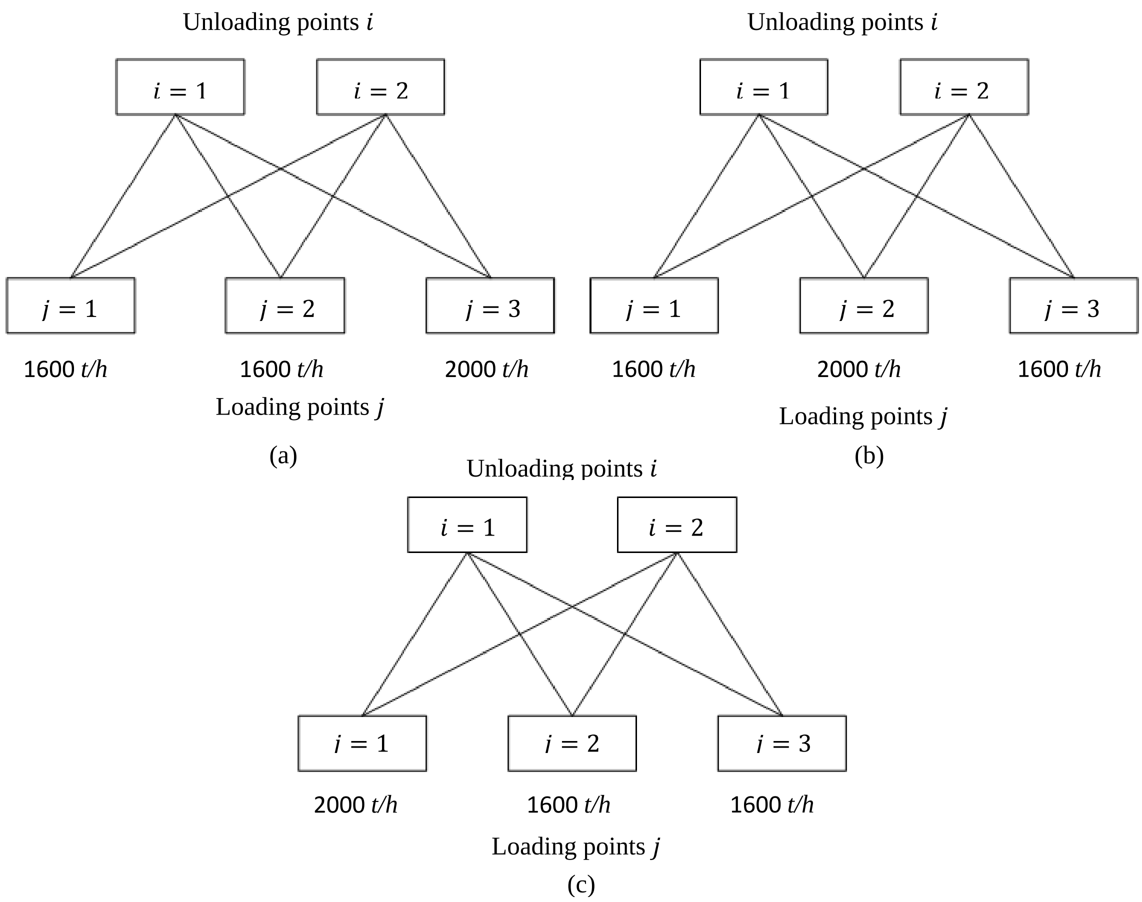


Figure 4.2. Possible shovel allocations

The total number of possible shovel allocation was determined by equation 4.1 as follows:

$$P_j = \frac{S!}{N_{C_1}! \times N_{C_2}! \times \ldots \times N_{C_{j=k}}!}, \tag{4.1}$$

$$P_j = \frac{3!}{2!1!} = 3$$

Where: S is the number of shovels, S_{C_1} , S_{C_2} ... $S_{C_{j=k}}$ are the numbers of shovels of capacity C_j and k the number of types of shovels.

The operating parameters of trucks and shovels are given in Table 4.7, Table 4.8, Table 4.9 and Table 4.10.

Table 4.7. Resources for problems 2 and 3

Parameters	Resources		
	Trucks		
Truck capacity C_y	96 t		
Fleet size of trucks	10		
	Shovels		
Number of shovels N_j	3		
Capacity of shovels	1600 t/h	2000 t/h	2300 t/h
Number of shovels per capacity	2	1	1
Fuel consumption of shovel during idle time $f_{j,idle}$	6.6 L/h	9.5 L/h	10.9 L/h
Fuel consumption of shovel when the bucket is using f_j	117 L/h	130 L/h	170 L/h

Table 4.8. Input data for problems 2 and 3 (fuel consumption and loading time of trucks)

Truck index	Fuel consumption				Loading time $t^y_{l,j}$ with shovel of capacity		
					$1600\,t/h$	$1600\,t/h$	$2000\,t/h$
- Capacity	f^y_{ij} $[L/h]$	f^y_{ji} $[L/h]$	f^y_{idle} $[L/h]$	t^y_u $[h]$	$[h]$	$[h]$	$[h]$
$T_1 - 96\,t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_2 - 96\,t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_3 - 96\,t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_4 - 96\,t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_5 - 96\,t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_6 - 96\,t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_7 - 96\,t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_8 - 96\,t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_9 - 96\,t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045
$T_{10} - 96\,t$	44.76	78.33	22.38	0.020	0.06	0.06	0.045

Table 4.9. Input data for problems 2 and 3 (travel times of empty trucks)

Truck index	From unloading point i to shovel j (empty truck)					
- Capacity	$i_1 - j_1$ $[h]$	$i_2 - j_1$ $[h]$	$i_1 - j_2$ $[h]$	$i_2 - j_2$ $[h]$	$i_1 - j_3$ $[h]$	$i_2 - j_3$ $[h]$
$T_1 - 96\,t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_2 - 96\,t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_3 - 96\,t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_4 - 96\,t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_5 - 96\,t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_6 - 96\,t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_7 - 96\,t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_8 - 96\,t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_9 - 96\,t$	0.030	0.070	0.040	0.040	0.060	0.030
$T_{10} - 96\,t$	0.030	0.070	0.040	0.040	0.060	0.030

Table 4.10. Input data for problems 2 and 3 (travel times of loaded trucks)

Truck index	From shovel j to unloading point i (loaded truck)					
- Capacity	$j_1 - i_1$ $[h]$	$j_1 - i_2$ $[h]$	$j_2 - i_1$ $[h]$	$j_2 - i_2$ $[h]$	$j_3 - i_1$ $[h]$	$j_3 - i_2$ $[h]$
$T_1 - 96\ t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_2 - 96t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_3 - 96\ t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_4 - 96\ t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_5 - 96t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_6 - 96\ t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_7 - 96\ t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_8 - 96t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_9 - 96\ t$	0.042	0.097	0.056	0.056	0.083	0.042
$T_{10} - 96\ t$	0.042	0.097	0.056	0.056	0.083	0.042

4.2.3 Problem 3: Identification of the best fleet

In the mining industry, project managers are continuously looking for methods to select the optimal fleet for a given operation. In this regard, the match factor ratio has been used to determine the best haulage and loading fleet [50]. The match factor is adopted as a productivity indicator for the truck-shovel system in the mining industry [16]. It is one of the most important indices indicating the efficiency of the truck-shovel dispatching systems [51]. In [16], a formula (4.2) for calculating the match factor in the case of a heterogeneous fleet of both trucks and shovels was developed.

$$MF = \frac{\sum_{C_j} \left[N_y \times \, lcm \left(\text{unique loading times} \right)_{C_j} \right]}{N_{C_j} \times \sum_{C_j} \left[\sum_{C_y} \frac{lcm \left(\text{unique loading times} \right)_{C_j}}{\left(\text{unique loading times} \right)_{C_y, C_j}} \right] \times t_{cycle}} \tag{4.2}$$

Where $lcm(\text{unique loading time})_{C_j}$ is the least common multiple of the unique loading time for each truck and shovel pair. The $(\text{unique loading times})_{C_y,C_j}$ is the cycle time of the shovel of capacity C_j when working with the truck of capacity C_y.

Equation (4.2) in the case of homogeneous fleet of both trucks and shovels is reduced to equation (4.3).

$$MF = \frac{N_y \times t_l^y}{N_j \times t_{cycle}} \tag{4.3}$$

This section deals with the analysis of the fuel consumed per ton of material moved with respect to the shovel size. Three fleets with different match factors are considered. All three fleets are made up with the same fleet of trucks, but different fleets of shovels. Table 4.11 outlines the equipment set of these three fleets. The operating parameters of dump trucks and shovels are given in Table 4.7, Table 4.8, Table 4.9 and Table 4.10.. The average truck cycle time for each fleet was determined from equation (3.7). The match factor of each fleet was estimated from equation (4.3) as shown below:

$$\begin{aligned} MF \text{ fleet A} &= \frac{10 \times 216}{3 \times 675.6} \\ &= 1.07 \\ MF \text{ fleet B} &= \frac{10 \times 162}{3 \times 621.6} \\ &= 0.87 \\ MF \text{ fleet B} &= \frac{10 \times 151.2}{3 \times 610.8} \\ &= 0.83 \end{aligned} \tag{4.4}$$

Table 4.11. Homogeneous fleet of trucks and shovels

Scenarios	Shovels		Trucks			Average truck	Match
	Number	capacity	Number	capacity	loading time	cycle time	factors
Fleet A	3	1600 t/h	10	96 t	216 s	675.6 s	1.07
Fleet B	3	2000 t/h	10	96 t	162 s	621.6 s	0.87
Fleet C	3	2300 t/h	10	96 t	151.2 s	610.8 s	0.83

CHAPTER 5 SIMULATION RESULTS AND ANALYSIS

5.1 CHAPTER OVERVIEW

In this chapter, the simulation results of the MILP model for the three dispatching problems formulated in Section 4.1 and those obtained with the fixed dispatch model in the case of heterogeneous fleet of dump trucks and shovels are presented and analysed.

5.2 DISPATCH OF A HETEROGENEOUS FLEET OF DUMP TRUCKS AND SHOVELS

5.2.1 MILP results

Considering a shift of 8 hours, solving the MILP model given in Section 3.9 with the operating data given in Table 4.2, Table 4.3, Table 4.4, Table 4.5 and Table 4.6, the number of trips that each truck has realized loaded or empty on each route of the mine, the number of time each truck y has been loaded by a specific shovel during a shift and the number of time that each truck has dumped its loaded at a specific unloading point i are determined. From this information, the fuel consumption per shift, the average specific fuel consumption, the litres per ton-kilometre of each truck and the distance travelled by each truck during the whole shift are estimated. The results obtained with the MILP model are described below and summarized in Table 5.1, Table 5.2, Table 5.3 and Table 5.4. The fuel consumption of trucks is displayed in Figure 5.1. The specific fuel consumption and the litres per ton-kilometre of trucks are shown on Figure 5.2 and Figure 5.3 respectively. The contribution of each shovel to the total handling demand during a shift is shown in Figure 5.4. For convenience, the specific fuel consumption and the litres per ton-kilometre are expressed in millilitres per ton and millilitres per ton-kilometre respectively.

Table 5.1. Problem 1: Optimum trip number of trucks (MILP)

Truck No - Capacity	Unloading Points	shovel 1		shovel 2		shovel 3	
		Empty	Loaded	Empty	Loaded	Empty	Loaded
$T_1 - 56t$	i_1	53	53	0	0	0	0
	i_2	0	0	0	0	20	20
$T_2 - 56t$	i_1	64	64	0	0	0	0
	i_2	0	0	0	0	8	8
$T_3 - 56t$	i_1	63	63	0	0	0	0
	i_2	0	0	0	0	8	8
$T_4 - 65t$	i_1	11	11	1	0	0	0
	i_2	0	0	0	1	19	19
$T_5 - 65t$	i_1	16	16	0	0	0	0
	i_2	0	0	18	18	4	4
$T_6 - 65t$	i_1	5	5	6	1	0	0
	i_2	0	0	0	5	9	9
$T_7 - 96t$	i_1	0	0	0	27	0	0
	i_2	0	0	33	6	15	15
$T_8 - 96t$	i_1	0	0	9	10	0	0
	i_2	0	0	6	5	38	38
$T_9 - 96t$	i_1	0	0	6	13	0	0
	i_2	0	0	9	2	37	37
$T_{10} - 96t$	i_1	0	0	1	10	0	0
	i_2	0	0	11	2	41	41

From Table 5.1, trucks have been dispatched as follows:

- Truck T_1 has travelled empty 53 times from the unloading point i_1 to the shovel j_1 and 20 times from the unloading point i_2 to the shovel j_3. After being loaded by, truck T_1 travelled from shovel j_1 to the unloading point i_1 53 times and 20 time from the shovel j_3 to the unloading point

i_2. The fuel consumption, the average specific fuel consumption and the litres per ton-kilometre of this truck were estimated to be 248.05 litres, 60,61 mL/t and 0.28 mL/tkm respectively. The total distance travelled by this truck was 219 km.

- Truck T_2 has travelled empty 64 times from the unloading point i_1 to the shovel j_1 and 8 times from the unloading point i_2 to the shovel j_3. After being loaded by, truck T_2 travelled from shovel j_1 to the unloading point i_1 64 times and 8 time from the shovel j_3 to the unloading point i_2. The fuel consumption, the average specific fuel consumption and the litres per ton-kilometre of this truck were estimated to be 248.05 litres, 59.58 mL/t and 0.28 mL/tkm respectively. The total distance travelled by this truck was 216 km.

- Truck T_3 has travelled empty 63 times from the unloading point i_1 to the shovel j_1 and 8 times from the unloading point i_2 to the shovel j_3. After being loaded by, truck T_1 travelled from shovel j_1 to the unloading point i_1 63 times and 8 time from the shovel j_3 to the unloading point i_2. The fuel consumption, the average specific fuel consumption and the litres per ton-kilometer of this truck were estimated to be 236.89 litres, 59.58 mL/t and 0.28 mL/tkm respectively. The total distance travelled by this truck was 213 km.

- Truck T_4 has travelled empty 11 times from the unloading point i_1 to the shovel j_1 , one time from the unloading point i_1 to the shovel j_2 and 19 times from the unloading point i_2 to the shovel j_3 . After being loaded, this truck travelled 11 times from the shovel j_1 to the unloading point i_1 , one time from the shovel j_2 to the unloading point i_2 and 19 times from the shovel j_3 to the unloading point i_2 . The fuel consumption, the average specific fuel consumption and the litres per ton kilometre of this truck were estimated to be 132.63 litres, 65.82 mL/t and 0.7 mL/tkm respectively. The total distance travelled by this truck was 94 km.

- Truck T_5 has travelled empty 16 times from the unloading point i_1 to the shovel j_1, 18 times from the unloading point i_2 to the shovel j_2 and 4 times from the unloading point i_2 to the shovel j_3. After being loaded, this truck travelled 16 times from the shovel j_1 to the unloading point i_1, 18 times from the shovel j_2 to the unloading point i_2 and 4 times from the shovel j_3 to the unloading point i_2. The fuel consumption, the average specific fuel consumption and the litres per ton-kilometer of this truck were estimated to be 174.72 litres, 70.73 mL/t and 0.54 mL/tkm

respectively. The total distance travelled by this truck was 132 *km*.

- Truck T_6 has travelled empty 5 times from the unloading point i_1 to the shovel j_1, 6 times from the unloading point i_1 to the shovel j_2 and 9 times from the unloading point i_2 to the shovel j_3. After being loaded, this truck travelled 5 times from the shovel j_1 to the unloading point i_1, one time from the shovel j_2 to the unloading point i_1, 5 times from the shovel j_2 to the unloading point i_2 and 9 times from the shovel j_3 to the unloading point i_2. The fuel consumption, the average specific fuel consumption and the litres per ton-kilometer of this truck were estimated to be 92.09 litres, 70.84 mL/t and 1.07 mL/tkm respectively. The total distance travelled by this truck was 66 *km*.

- Truck T_7 has travelled empty 33 times from the unloading point i_2 to the shovel j_2 and 15 times from the unloading point i_2 to the shovel j_3. After being loaded, this truck travelled 27 times from the shovel j_2 to the unloading point i_1, 6 times from the shovel j_2 to the unloading point i_2 and 15 times from the shovel j_3 to the unloading point i_2. The fuel consumption, the average specific fuel consumption and the litres per ton-kilometre of this truck were estimated to be 354.23 litres, 76.87 mL/t and 0.43 mL/tkm respectively. The total distance traveled by this truck was 177 *km*.

- Truck T_8 has travelled empty 9 times from the unloading point i_2 to the shovel j_2, 6 times from the unloading point i_2 to the shovel j_2 and 38 times from the unloading point i_2 to the shovel j_3. After being loaded, this truck travelled 10 times from the shovel j_2 to the unloading point i_1, 5 times from the shovel j_2 to the unloading point i_2 and 38 times from the shovel j_3 to the unloading point i_2. The fuel consumption, the average specific fuel consumption and the litres per ton-kilometre of this truck were estimated to be 350.83 litres, 68.97 mL/t and 0.39 mL/tkm respectively. The total distance travelled by this truck was 174 *km*.

- Truck T_9 has travelled empty 6 times from the unloading point i_1 to the shovel j_2, 9 times from the unloading point i_2 to the shovel j_2 and 37 times from the unloading point i_2 to the shovel j_3. After being loaded, this truck travelled 13 times from the shovel j_2 to the unloading point i_1, 2 times from the shovel j_2 to the unloading point i_2 and 37 times from the shovel j_3 to the unloading point i_2. The fuel consumption, the average specific fuel consumption and the litres per ton-kilometre of this truck were estimated to be 344.74 litres, 69.06 mL/t and 0.40 mL/tkm respectively. The total distance travelled by this truck was 171 km.

- Truck T_{10} has travelled empty one time from the unloading point i_1 to the shovel j_2, 11 times from the unloading point i_2 to the shovel j_2 and 47 times from the unloading point i_2 to the shovel j_3. After being loaded, this truck travelled 10 times from the shovel j_2 to the unloading point i_1, 2 times from the shovel j_2 to the unloading point i_2 and 41 times from the shovel j_3 to the unloading point i_2. The fuel consumption, the average specific fuel consumption and the litres per ton-kilometre of this truck were estimated to be 345.19 litres, 67.84 mL/t and 0.40 mL/tkm respectively. The total distance travelled by this truck was 171 km.

The results obtained with the MILP model show that for the entire fleet (truck and shovels) used in the haulage operations, the energy efficiency indicator is 13.47 mL/t. 5070.67 litres of fuel are consumed for the whole haulage operations (loading and transport) during a shift. The energy efficiency indicators for trucks and shovels are 63.18 mL/t and 67.77 L/t respectively.

Table 5.2. Problem 1: Performance indicators of trucks (MILP)

Trucks					
Index	Ft^y [L]	LTt^y [mL/t]	$LTkm^y$ [mL/tkm]	Tons [t]	d^y [km]
T_1	241.94	59.18	0.27	4088	219
T_2	240.24	59.58	0.27	4032	216
T_3	236.89	59.58	0.28	3976	213
T_4	132.63	65.82	0.70	2015	94
T_5	184.50	74.70	0.57	2470	132
T_6	87.52	67.32	0.10	1300	66
T_7	354.23	76.87	0.43	4608	177
T_8	350.83	68.95	0.40	5088	174
T_9	344.74	69.06	0.40	4992	171
T_{10}	345.19	67.84	0.40	5088	171

Table 5.3. Problem 1: Performance indicators of shovels (MILP)

Shovels			
Index	Fs_j $[L]$	LTs_j $[mL/t]$	Tons $[t]$
$j_1 = 1600$	870.53	71.59	12160
$j_2 = 1600$	662.76	75.10	8825
$j_3 = 2000$	1018.67	61.10	16672

Table 5.4. Problem 1: Performance indicators of the all fleet (MILP)

Trucks		Shovels			Trucks & shovels	
LTt $[mL/t]$	Ft $[L]$	LTs $[mL/t]$	Fs $[L]$	F $[L]$	$LTts$ $[mL/t]$	Tons $[t]$
66.89	2518.70	67.77	2551.96	5070.67	134.65	37657

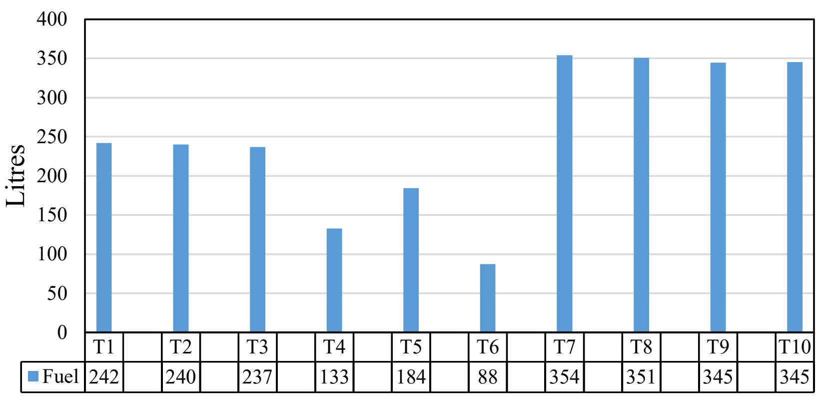


Figure 5.1. Problem 1: Fuel consumed by trucks (MILP)

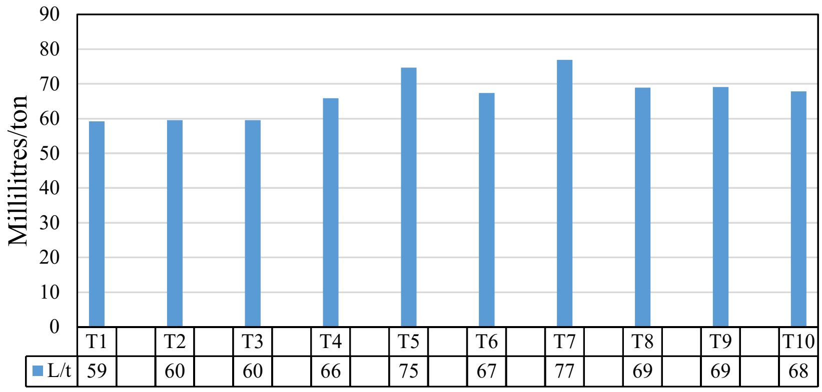


Figure 5.2. Problem 1: Litres per ton of trucks (MILP)

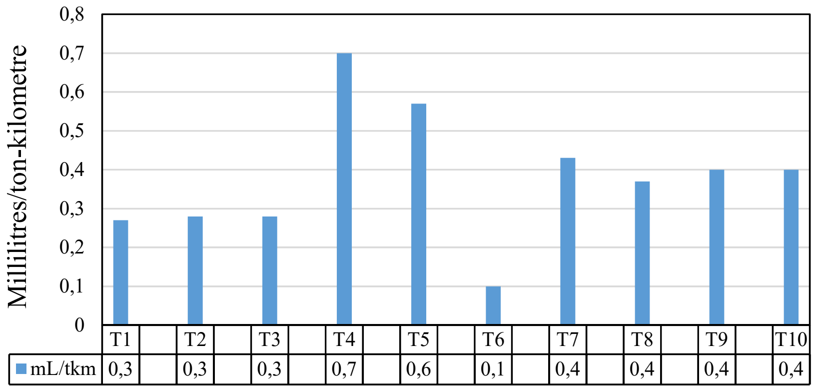


Figure 5.3. Problem 1: Litres per ton-kilometre of trucks (MILP)

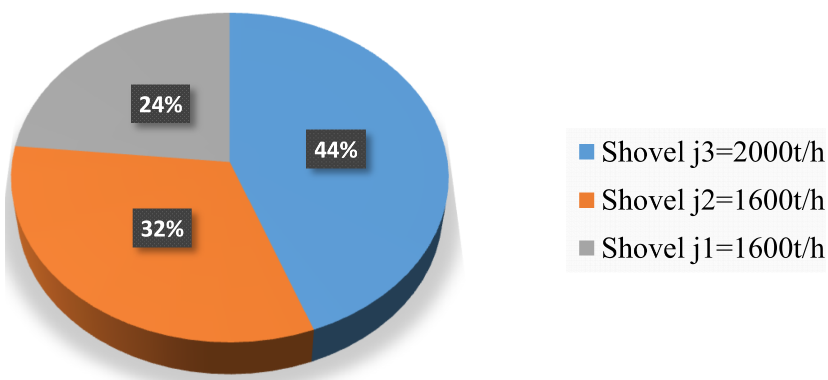


Figure 5.4. Problem 1: Contribution of each shovel to the total handling demand (MILP)

5.2.2 Fixed dispatch results

In this section, the same dispatch problem is solved with the fixed dispatch model developed in section 3.11.1. The results obtained with this model are described below and summarized in Table 5.5, Table 5.6, Table 5.7 and Table 5.8. The fuel consumption of trucks is displayed in Figure 5.5. The specific fuel consumption and the litres per ton-kilometre of trucks are shown in Figure 5.6 and Figure 5.7 respectively. The contribution of each shovel to the total handling demand during a shift is shown in Figure 5.8. For convenience, the specific fuel consumption and the litres per ton-kilometre are expressed in millilitres per ton and millilitres per ton-kilometre respectively.

From Table 5.5, trucks have been dispatched as follows:

- Trucks T_1 and T_3 were assigned to the route $i_1 - j_2$. On this route, T_1 has realized 27 cycles and consumed 127.61 litres of fuel. Its specific fuel consumption and litres per ton-kilometre were 84.40 mL/t and 0.78 mL/tkm respectively. The total distance travelled by T_1 during the shift was 108 km. T_3 has realized 37 cycles on the route $i_2 - j_2$ and consumed 174.87 litres. Its specific fuel consumption and litres per ton-kilometre were 84.40 mL/t and 0.57 mL/tkm respectively. The total distance travelled by T_3 during the shift was 148 km.

- Trucks T_2, T_7 and T_8 were assigned to the route $i_2 - j_3$. On this route, T_2 has realized 77 cycles and consumed 247.52 litres of fuel. Its specific fuel consumption and litres per ton-kilometre were 57.40 mL/t and 0.25 mL/tkm respectively. The total distance that T_2 travelled during the shift was 231 km. T_7 and T_8 have realized 58 cycles and consumed 353.07 litres of fuel each of one. These trucks have the same specifications. Their specific fuel consumption and litres per ton-kilometre were 63.41 mL/t and 0.36 mL/tkm respectively. T_7 and T_8 travelled the same total distance, 174 km.

- Trucks T_4, T_5 and T_6 were assigned to the route $i_1 - j_1$. These trucks have the same specifications, they have realized the same number of cycles, 61 cycles, and each of them has consumed 264.85 litres of fuel. Their specific fuel consumption and litres per ton-kilometre were 66.80 mL/t and 0.37 mL/tkm respectively. The total distance that each of these trucks travelled during a shift were 183 km.

- Trucks T_9 and T_10 were assigned to the route $i_1 - j_2$. These trucks have the same specifications, they have realized the same number of cycles, 35 cycles, and consumed 278.85 litres of fuel each. Their specific fuel consumption and litres per ton-kilometre were 82.99 mL/t and 0.59 mL/tkm. The total distance that each of these trucks travelled during the shift was 140 km

Table 5.5. Problem 1: Optimum trip number of trucks (Fixed Dispatch)

Truck No - Capacity	Unloading Points	shovel 1		shovel 2		shovel 3	
		Empty	Loaded	Empty	Loaded	Empty	Loaded
$T_1 - 56t$	i_1	0	0	0	0	0	0
	i_2	0	0	27	27	0	0
$T_2 - 56t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	77	77
$T_3 - 56t$	i_1	0	0	0	0	0	0
	i_2	0	0	37	37	0	0
$T_4 - 65t$	i_1	61	61	0	0	0	0
	i_2	0	0	0	0	0	0
$T_5 - 65t$	i_1	61	61	0	0	0	0
	i_2	0	0	0	0	0	0
$T_6 - 65t$	i_1	61	61	0	0	0	0
	i_2	0	0	0	0	0	0
$T_7 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	58	58
$T_8 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	58	58
$T_9 - 96t$	i_1	0	0	35	35	0	0
	i_2	0	0	0	0	0	0
$T_{10} - 96t$	i_1	0	0	35	35	0	0
	i_2	0	0	0	0	0	0

The results obtained with the fixed dispatch model show that for the entire fleet (truck and shovel) used in the haulage operations the energy efficiency indicator was 13.97 mL/t. 5260.76 litres of fuel were consumed for the whole haulage operations (loading and transport) during a shift. The energy indicators for trucks and shovels are 69.29 mL/t and 67.62 mL/t respectively.

Table 5.6. Problem 1: Performance indicators of trucks (Fixed Dispatch)

Trucks					
Index	Ft^y	LTt^y	$LTkm^y$	Tons	d^y
	$[L]$	$[mL/t]$	$[mL/tkm]$	$[t]$	$[km]$
T_1	127.61	84.40	0.78	1512	108
T_2	247.52	57.40	0.25	4312	231
T_3	174.87	84.40	0.57	2072	148
T_4	264.85	66.79	0.37	3965	183
T_5	264.85	66.79	0.37	3965	183
T_6	264.85	66.79	0.37	3965	183
T_7	353.07	63.41	0.36	5568	174
T_8	353.07	63.41	0.36	5568	174
T_9	278.85	82.99	0.59	3360	140
T_{10}	278.85	82.99	0.59	3360	140

Table 5.7. Problem 1: Performance indicators of shovels (Fixed Dispatch)

Shovels			
Index	Fs_j	LTs_j	Tons
$[t/h]$	$[L]$	$[mL/t]$	$[t]$
$j_1 = 1600$	881,13	74.08	11895
$j_2 = 1600$	763,78	74.12	10304
$j_3 = 2000$	1007,47	65.22	15448

Table 5.8. Problem 1: Performance indicators of the all fleet (Fixed Dispatch)

Trucks		Shovels			Trucks & shovels	
LTt $[mL/t]$	Ft $[L]$	LTs $[mL/t]$	Fs $[L]$	F $[L]$	$LTts$ $[mL/t]$	Tons $[t]$
69.29	2608,38	70.45	2652,38	5260.76	139.74	37647

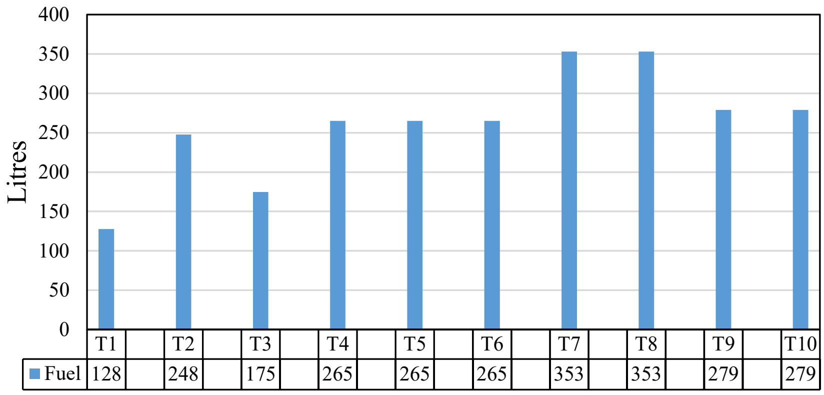


Figure 5.5. Problem 1: Fuel consumed by trucks (Fixed dispatch model)

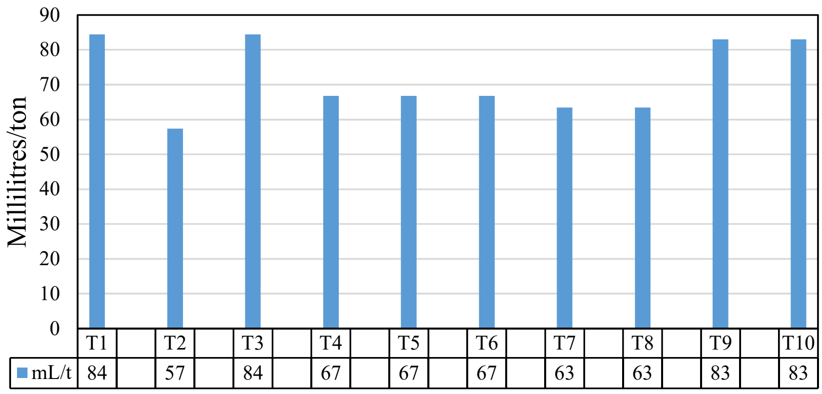


Figure 5.6. Problem 1: Specific fuel of trucks (Fixed dispatch model)

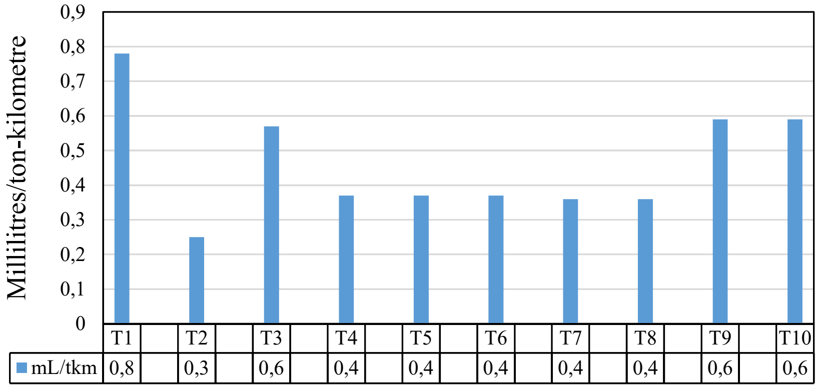


Figure 5.7. Problem 1: Litres per ton-kilometre of trucks (Fixed dispatch model)

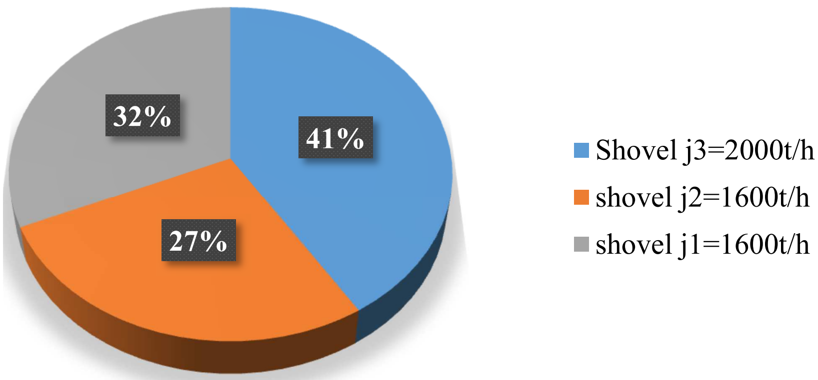


Figure 5.8. Problem 1: Contribution of each shovel to the total handling demand (fixed dispatch)

5.3 IDENTIFICATION OF THE BEST ALLOCATION RESULTS

Considering a shift of 8 hours, solving the MILP model for different allocations of shovels, the following results were found. The first allocation (a), with the shovel of capacity 2000 t/h allocated at the third loading point, results in 136,98 millilitres per ton and 5154,94 litres of fuel consumed for the whole haulage operation. 37632 tons of material were transported during the entire shift. Trucks and shovels have consumed 2578,76 and 2576,18 litres of fuel respectively. The energy indicator of trucks was found to be 68,46 and that for shovels 68,52 millilitres per ton. The total distance travelled by empty trucks was 634.5 km. The same distance was travelled by trucks after being loaded. Table 5.9, Table 5.10 and Table 5.11 summarise the results obtained with the MILP model for this shovel allocation.

Table 5.9. Problem 2: Performance indicators of trucks (Allocation (a))

Trucks					
Index	Ft^y	LTt^y	Tons	d_e^y	d_{lo}^y
	$[L]$	$[mL/t]$	$[t]$	$[km]$	$[km]$
T_1	239.24	65.58	3648	65	65
T_2	348.99	63.77	5472	85,5	85,5
T_3	0	0	0	0	0
T_4	333.99	66.91	4992	78	78
T_5	0	0	0	0	0
T_6	333.99	66.91	4992	78	78
T_7	354.94	63.75	5568	87,5	87,5
T_8	353.07	63.41	5568	87	87
T_9	253.41	82.49	3072	63,5	63,5
T_{10}	358.53	82.99	4320	90	90

Table 5.10. Problem 2: Performance indicators of shovels (Allocation (a))

Shovels			
Index	Fs_j	LTs_j	Tons
$[t/h]$	$[L]$	$[mL/t]$	$[t]$
$j_1 = 1600$	933.79	73.13	12768
$j_2 = 1600$	668.83	74.91	8928
$j_3 = 2000$	976.13	61.25	15936

Table 5.11. Problem 2: Performance indicators of the all fleet (allocation (a))

Trucks				Shovels			Trucks & shovels	
$d_{e,tot}$	$d_{lo,tot}$	LTt	Ft	LTs	Fs	F	$LTts$	Tons
$[km]$	$[km]$	$[mL/t]$	$[L]$	$[mL/t]$	$[L]$	$[L]$	$[mL/t]$	$[t]$
634.5	634.5	68.46	2576,18	68.52	2578.76	5154.94	136.98	37632

The second shovel allocation (b), with the shovel of capacity 2000 t/h allocated in the second loading point, results in 140,76 millilitres per ton and 5296.93 litres of fuel consumed by trucks and shovels for the whole haulage operation. 37632 tons of material were transported by trucks during the entire shift. Trucks and shovels have consumed 2670,11 and 2626,82 litres of fuel respectively. The energy indicator of trucks were found to be 70,95 and that for shovel 69,80 millilitres per ton. The total distance traveled by empty trucks was 627 km and that travelled by trucks after being loaded 651 km. Table 5.12, Table 5.13 and Table 5.14 summarise the results obtained with the MILP model for this shovel allocation.

Table 5.12. Problem 2: Performance indicators of trucks (allocation (b))

Trucks					
Index	Ft^y	LTt^y	Tons	d_e^y (empty)	d_{lo}^y
	$[L]$	$[mL/t]$	$[t]$	$[km]$	$[km]$
T_1	83.94	79.49	1056	22	22
T_2	333.99	66.91	4992	78	78
T_3	333.99	66.91	4992	78	78
T_4	374.32	77.98	4800	97	97
T_5	333.99	66.91	4992	78	78
T_6	333.99	66.91	4992	78	78
T_7	7.63	79.49	96	2	2
T_8	333.99	66.91	4992	78	78
T_9	160.26	79.49	2016	42	42
T_{10}	373.94	79.49	4704	74	98

Table 5.13. Problem 2: Performance indicators of shovels (allocation (b))

Shovels			
Index	Fs_j	LTs_j	Tons
$[t/h]$	$[L]$	$[mL/t]$	$[t]$
$j_1 = 1600$	933.79	73.13	12768
$j_2 = 2000$	759.23	62.78	12096
$j_3 = 1600$	933.79	73.13	12768

Table 5.14. Problem 2: Performance indicators of the all fleet (allocation (b))

Trucks				Shovels			Trucks & shovels	
$d_{e,tot}$ [km]	$d_{lo,tot}$ [km]	LTt [mL/t]	Ft [L]	LTs [mL/t]	Fs [L]	F [L]	$LTts$ [mL/t]	Tons [t]
627	651	70.95	2626,82	69.8	2626.82	5296.93	140.76	37632

The last shovel allocation (c), with the shovel of capacity 2000 t/h allocated at the first loading point, results in 138,80 millilitres per ton and 5223,46 litres of fuel consumed by trucks and shovels. 37632 tons of material were transported by trucks during the entire shift. Trucks and shovels have consumed 2644,67 and 2578,76 litres of fuel respectively. The energy indicator of trucks were found to be 70,28 and for shovels 69,80 millilitres per ton. The total distance travelled by empty trucks was 634.5 km. The same distance was travelled by trucks after being loaded. Table 5.15, Table 5.16 and Table 5.17 summarise the results obtained with the MILP model for this allocation.

Table 5.15. Problem 2: Performance indicators of trucks (allocation (c))

Trucks					
Index	Ft^y [L]	LTt^y [mL/t]	Tons [t]	d_e^y (empty) [km]	d_{lo}^y [km]
T_1	7.97	82.99	96	2	2
T_2	383.48	72.63	5280	82.5	82.5
T_3	333.99	66.91	4992	78	78
T_4	353.24	73.59	4800	88	88
T_5	333.99	66.91	4992	78	78
T_6	353.07	63.41	5568	87	87
T_7	7.97	82.99	96	2	2
T_8	353.07	63.41	5568	87	87
T_9	302.76	82.99	3648	76	76
$T-10$	215.12	82.99	2592	54	54

Table 5.16. Problem 2: Performance indicators of shovels (allocation (c))

Shovels			
Index	Fs_j	LTs_j	Tons
$[t/h]$	$[L]$	$[mL/t]$	$[t]$
$j_1 = 2000$	976.14	61.25	15936
$j_2 = 1600$	668.83	74.91	8928
$j_3 = 1600$	933.79	73.13	12768

Table 5.17. Problem 2: Performance indicators of the all fleet (allocation (c))

Trucks				Shovels		Trucks & shovels		
$d_{e,tot}$	$d_{lo,tot}$	LTt	Ft	LTs	Fs	F	$LTts$	Tons
$[km]$	$[km]$	$[mL/t]$	$[L]$	$[mL/t]$	$[L]$	$[L]$	$[mL/t]$	$[t]$
634.5	634.5	70.28	5223.42	68.52	2578.76	5223.42	138.80	37632

The optimum number of trips that each truck has realized on each route of the mine during a shift of 8 hours for the three possible shovel allocations are given in Table 5.18, Table 5.19 and Table 5.20,

Table 5.18. Problem 2: Optimum trip number of trucks (allocation (c))

Truck No - Capacity	Unloading Points	shovel 1		shovel 2		shovel 3	
		Empty	Loaded	Empty	Loaded	Empty	Loaded
$T_1 - 96t$	i_1	0	0	1	0	0	0
	i_2	0	0	0	1	0	0
$T_2 - 96t$	i_1	26	26	0	0	0	0
	i_2	0	0	0	0	29	29
$T_3 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	52	52
$T_4 - 96t$	i_1	24	24	0	0	0	0
	i_2	0	0	26	26	0	0
$T_5 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	52	52
$T_6 - 96t$	i_1	58	58	0	0	0	0
	i_2	0	0	0	0	0	0
$T_7 - 96t$	i_1	0	0	0	1	0	0
	i_2	0	0	1	0	0	0
$T_8 - 96t$	i_1	58	58	0	0	0	0
	i_2	0	0	0	0		0
$T_9 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	38	38	0	0
$T_{10} - 96t$	i_1	0	0	26	27	0	0
	i_2	0	0	1	0	0	0

Table 5.19. Problem 2: Optimum trip number of trucks (allocation (b))

Truck No - Capacity	Unloading Points	shovel 1		shovel 2		shovel 3	
		Empty	Loaded	Empty	Loaded	Empty	Loaded
$T_1 - 96t$	i_1	0	0	11	10	0	0
	i_2	0	0	0	1	0	0
$T_2 - 96t$	i_1	29	29	0	0	0	0
	i_2	0	0	0	0	23	23
$T_3 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	52	52
$T_4 - 96t$	i_1	0	0	0	1	0	0
	i_2	0	0	44	43	6	6
$T_5 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	52	52
$T_6 - 96t$	i_1	52	52	0	0	0	0
	i_2	0	0	0	0	0	0
$T_7 - 96t$	i_1	0	0	0	1	0	0
	i_2	0	0	1	0	0	0
$T_8 - 96t$	i_1	52	52	0	0	0	0
	i_2	0	0	0	0		0
$T_9 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	21	21	0	0
$T_{10} - 96t$	i_1	0	0	48	49	0	0
	i_2	0	0	1	0	0	0

Table 5.20. Problem 2: Optimum trip number of trucks (allocation (a))

Truck No - Capacity	Unloading Points	shovel 1		shovel 2		shovel 3	
		Empty	Loaded	Empty	Loaded	Empty	Loaded
$T_1 - 96t$	i_1	22	22	16	15	0	0
	i_2	0	0	0	1	0	0
$T_2 - 96t$	i_1	6	6	0	0	0	0
	i_2	0	0	0	0	51	51
$T_3 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	0	0
$T_4 - 96t$	i_1	0	0	0	0	0	0
	i_2	52	52	0	0	0	0
$T_5 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	0	0
$T_6 - 96t$	i_1	52	52	0	0	0	0
	i_2	0	0	0	0	0	0
$T_7 - 96t$	i_1	0	0	0	1	0	0
	i_2	0	0	1	0	57	57
$T_8 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	58	58
$T_9 - 96t$	i_1	1	1	0	0	0	0
	i_2	0	0	31	31	0	0
$T_{10} - 96t$	i_1	0	0	44	45	0	0
	i_2	0	0	1	0	0	0

5.4 IDENTIFICATION OF THE BEST FLEET RESULTS

In solving the MILP model proposed for the three fleets, the following results were found. For fleet A with shovels of 1600 t/h capacity, 5427.67 litres of fuel were consumed by trucks and shovels. The energy efficiency achieved by this fleet was 144.23 litres per ton moved for the entire haulage operation. Trucks and shovels have consumed 2712.41 and 2715.26 litres of fuel respectively. The energy indicator for trucks alone was found to be 72.08 mL/t and that for shovels 72.15 mL/t. The total distance travelled by empty trucks during the whole shift was 651 km. The same distance was travelled by trucks after being loaded. Table 5.21, Table 5.22 and Table 5.23 summarize the results achieved with this fleet.

Table 5.21. Problem 3: Performance indicators of trucks (Fleet A)

Trucks					
Index	Ft^y	LTt^y	Tons	d_e^y	d_{lo}^y
	$[L]$	$[mL/t]$	$[t]$	$[km]$	$[km]$
T_1	127.48	82.99	1536	32	32
T_2	333.99	66.91	4992	78	78
T_3	333.99	66.901	4992	78	78
T_4	358.53	82.99	4320	90	90
T_5	333.99	66.91	4992	78	78
T_6	333.99	66.91	4992	78	78
T_7	46.51	69.20	672	11	11
T_8	333.99	66.91	4992	78	78
T_9	151.38	82.99	1824	38	38
T_10	358.53	82.99	4320	90	90

Table 5.22. Problem 3: Performance indicators of shovels (Fleet A)

Shovels			
Index	Fs_j	LTs_j	Tons
$[t/h]$	$[L]$	$[mL/t]$	$[t]$
$j_1 = 1600$	933.79	73.14	12768
$j_1 = 1600$	887.42	73.36	12096
$j_1 = 1600$	894.05	70.02	12768

Table 5.23. Problem 3: Performance indicators of (Fleet A)

Trucks				Shovels			Trucks & shovels	
$d_{e,tot}$ $[km]$	$d_{lo,tot}$ $[km]$	LTt $[mL/t]$	Ft $[L]$	LTs $[mL/t]$	Fs $[L]$	F $[L]$	$LTts$ $[mL/t]$	Tons $[t]$
651	651	72.08	2712.41	72.15	2715,26	5427.67	144.23	37632

For the second fleet B with shovels of capacity 2000 t/h, 4833.86 litres of fuel were consumed in the haulage operation. The energy efficiency of this fleet was 128.45 mL/t moved for the whole haulage operation. Trucks and shovels consumed 2480.24 and 2353.62 litres of fuel respectively. The energy indicator of trucks alone was 65.90 mL/t and that for shovels 62.54 mL/t. The total distance travelled by empty trucks was 618 km. The same distance was travelled by trucks after being loaded. Table 5.24, Table 5.25 and Table 5.26 summarize the results obtained with this fleet.

Table 5.24. Problem 3: Performance indicators of trucks (Fleet B)

Trucks					
Index	Ft^y $[L]$	LTt^y $[mL/t]$	Tons $[t]$	d_e^y $[km]$	d_{lo}^y $[km]$
T_1	7.63	79.49	96	2	2
T_2	355.95	63.92	5568	87.5	87.5
T_3	353.06	63.41	5568	87	87
T_4	368.95	72.51	5088	94.5	94.5
T_5	353.06	63.41	5568	87	87
T_6	353.06	63.41	5568	87	87
T_7	129.38	64.17	2016	32	32
T_8	353.06	63.41	5568	87	87
T_9	0	0	0	0	0
T_10	206.05	79.49	2592	54	54

Table 5.25. Problem 3: Performance indicators of shovels (Fleet B)

Shovels			
Index	Fs_j	LTs_j	Tons
$[t/h]$	$[L]$	$[mL/t]$	$[t]$
$j_1 = 2000$	976.13	61.25	15936
$j_1 = 2000$	401.35	69.68	5760
$j_1 = 2000$	976.13	61.25	15936

Table 5.26. Problem 3: Performance indicators of Fleet B

Trucks				Shovels			Trucks & shovels	
$d_{e,tot}$	$d_{lo,tot}$	LTt	Ft	LTs	Fs	F	$LTts$	Tons
$[km]$	$[km]$	$[mL/t]$	$[L]$	$[mL/t]$	$[L]$	$[L]$	$[mL/t]$	$[t]$
618	618	65.9	2480.24	62.54	2353.62	4833.86	128.45	37632

The last fleet C leads to 139.76 litres per ton and 5259.45 litres of fuel consumed for the whole haulage. Trucks and shovels have consumed 2378.45 and 2881 litres of fuel. The energy efficiency of trucks alone was found to be 63.2 mL/t and that for shovels 74 mL/t. The total distance travelled by empty trucks was 618 km. The same distance was travelled by trucks after being loaded. Table 5.27, Table 5.28 and Table 5.29 summarize the results obtained with this fleet.

Table 5.27. Problem 3: Performance indicators of trucks (Fleet C)

Trucks					
Index	Ft^y	LTt^y	Tons	d_e^y	d_{lo}^y
	$[L]$	$[mL/t]$	$[t]$	$[km]$	$[km]$
T_1	7.56	78.79	96	2	2
T_2	355.19	62.71	5664	88.5	88.5
T_3	355.19	62.71	5664	88.5	88.5
T_4	156.52	62.71	2496	39	39
T_5	355.19	62.71	5664	88.5	88.5
T_6	355.19	62.71	5664	88.5	88.5
T_7	355.19	62.71	5664	88.5	88.5
T_8	355.19	62.71	5664	88.5	88.5
T_9	52.95	78.79	672	14	14
T_{10}	30.26	78.79	384	8	8

Table 5.28. Problem 3: Performance indicators of shovels (Fleet C)

Shovels			
Index	Fs_j	LTs_j	Tons
$[t/h]$	$[L]$	$[mL/t]$	$[t]$
$j_1 = 2300$	1356.81	74.38	18240
$j_1 = 2300$	167.38	145.3	1152
$j_1 = 2300$	1356.81	74.38	18240

Table 5.29. Problem 3: Performance indicators of (Fleet C

Trucks				Shovels			Trucks & shovels	
$d_{e,tot}$	$d_{lo,tot}$	LTt	Ft	LTs	Fs	F	$LTts$	Tons
$[km]$	$[km]$	$[mL/t]$	$[L]$	$[mL/t]$	$[L]$	$[L]$	$[mL/t]$	$[t]$
594	594	63.2	2378.45	74.38	2881	5259.45	139.76	37632

The optimum number of trips that each truck has realized on each route of the mine during a shift of 8 hours for the three fleets are given in Table 5.30, Table 5.31 and Table 5.32. Figure 5.9 and Figure 5.10 display the fuel consumed for the whole haulage operations and the energy efficiency achieved by each fleet respectively.

Table 5.30. Problem 3: Optimum trip number of trucks with Fleet A

Truck No - Capacity	Unloading Points	shovel 1		shovel 2		shovel 3	
		Empty	Loaded	Empty	Loaded	Empty	Loaded
$T_1 - 96t$	i_1	0	0	16	15	0	0
	i_2	0	0	0	1	0	0
$T_2 - 96t$	i_1	29	29	0	0	0	0
	i_2	0	0	0	0	23	23
$T_3 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	52	52
$T_4 - 96t$	i_1	52	52	0	0	0	0
	i_2	0	0	0	0	0	0
$T_5 - 96t$	i_1	0	0	0	1	0	0
	i_2	0	0	1	0	6	6
$T_6 - 96t$	i_1	52	52	0	0	0	0
	i_2	0	0	0	0	0	0
$T_7 - 96t$	i_1	0	0	0	1	0	0
	i_2	0	0	1	0	6	6
$T_8 - 96t$	i_1	52	52	0	0	0	0
	i_2	0	0	0	0	0	0
$T_9 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	19	19	0	0
$T_{10} - 96t$	i_1	0	0	44	45	0	0
	i_2	0	0	1	0	0	0

Table 5.31. Problem 3: Optimum trip number of trucks with Fleet B

Truck No - Capacity	Unloading Points	shovel 1		shovel 2		shovel 3	
		Empty	Loaded	Empty	Loaded	Empty	Loaded
$T_1 - 96t$	i_1	0	0	1	0	0	0
	i_2	0	0	0	1	0	0
$T_2 - 96t$	i_1	50	50	0	0	0	0
	i_2	0	0	1	1	7	7
$T_3 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	58	58
$T_4 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	30	30	23	23
$T_5 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	58	58
$T_6 - 96t$	i_1	58	58	0	0	0	0
	i_2	0	0	0	0	0	0
$T_7 - 96t$	i_1	0	0	0	1	0	0
	i_2	0	0	1	0	20	20
$T_8 - 96t$	i_1	58	58	0	0	0	0
	i_2	0	0	0	0	0	0
$T_9 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	0	0
$T_{10} - 96t$	i_1	0	0	26	27	0	0
	i_2	0	0	1	0	0	0

Table 5.32. Problem 3: Optimum trip number of trucks with Fleet C

Truck No - Capacity	Unloading Points	shovel 1		shovel 2		shovel 3	
		Empty	Loaded	Empty	Loaded	Empty	Loaded
$T_1 - 96t$	i_1	0	0	1	0	0	0
	i_2	0	0	0	1	0	0
$T_2 - 96t$	i_1	59	59	0	0	0	0
	i_2	0	0	0	0	0	0
$T_3 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	59	59
$T_4 - 96t$	i_1	13	13	0	0	0	0
	i_2	0	0	0	0	13	13
$T_5 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	59	59
$T_6 - 96t$	i_1	59	59	0	0	0	0
	i_2	0	0	0	0	0	0
$T_7 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	0	0	59	59
$T_8 - 96t$	i_1	59	59	0	0	0	0
	i_2	0	0	0	0	0	0
$T_9 - 96t$	i_1	0	0	0	0	0	0
	i_2	0	0	7	7	0	0
$T_{10} - 96t$	i_1	0	0	3	4	0	0
	i_2	0	0	1	0	0	0

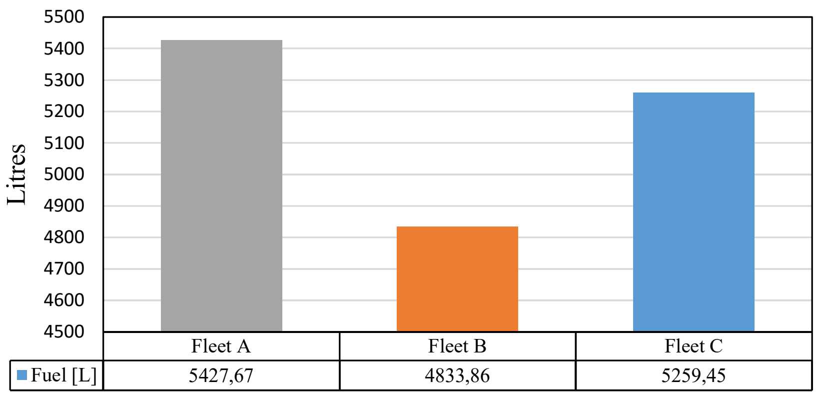


Figure 5.9. Fuel consumed by trucks and shovels

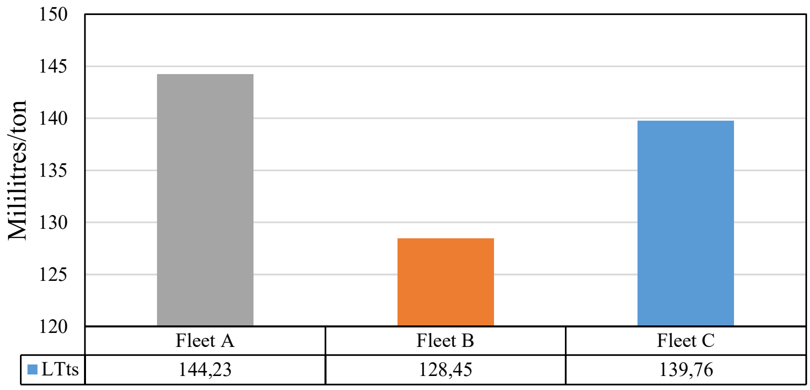


Figure 5.10. Litres per ton of trucks and shovels

CHAPTER 6   DISCUSSION OF RESULTS

6.1   CHAPTER OVERVIEW

In this chapter, a discussion of the results presented in the previous chapter is conducted in order to show the effectiveness of the MILP model and to address the research questions provided in Section 1.3.

6.2   MILP MODEL VS FIXED DISPATCH MODEL

In order to address the first research question provided in Section 1.3, a conclusive analysis of the results presented in the previous sections is discussed in this section. A comparison of the results obtained with both the MILP mode, and fixed dispatch model, resulted in the observations described below.

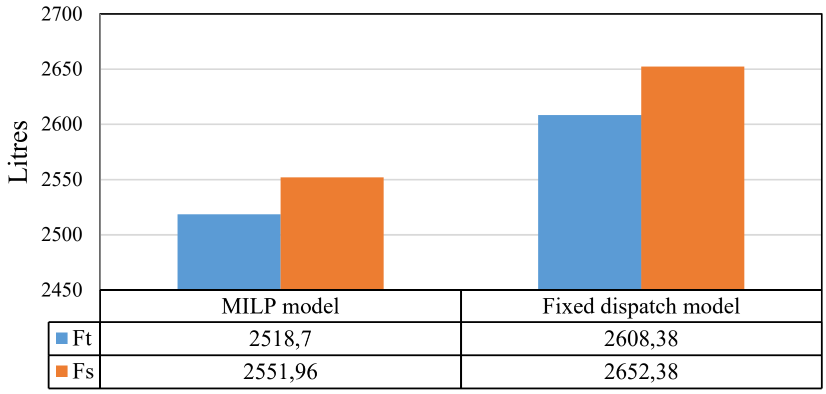
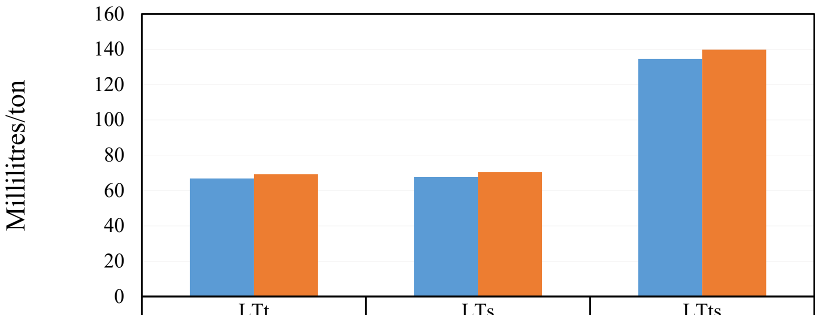


Figure 6.1. Fuel consumed (MILP model vs Fixed dispatch model)

The fuel consumption of trucks is reduced with the MILP model. This is shown in Figure 6.1. Indeed, with the MILP model, 89.68 litres of fuel are consumed less and the LTt is improved by 3.46 %. The explanation of this observation is that, with the MILP model, trucks are dispatched using the flexible dispatching strategy. That strategy results in a better optimization of the route choice of empty and loaded trucks.

The overall fuel consumption of shovels is reduced with the MILP model. Indeed, 100.42 litres of fuel are consumed less in the loading operations with the MILP model. The LTs is also improved by 3.80 %. The explanation for this is that, the shovel j_3 that has the highest capacity is more utilized with the MILP model than with the fixed dispatch model. This could be seen by comparing the contribution of this shovel to the total handling demand displays on Figure 5.4and Figure 5.8. With the MILP model, 44 % of the total handling demand is loaded into the trucks by the shovel j_3, whereas only 41 % of the total handling demand is loaded into the trucks by this shovel with the fixed dispatch model. Yet, the shovel j_3 compared to the two others shovels used in the loading operations is the most efficient with regards to the fuel consumption per ton during the working times. Its fuel consumption per ton during working times is 65 $mL/ton - hour$ while for the two others shovels is 73 $mL/ton - hour$. Consequently, a small amount of fuel was consumed to load 44 % of the total handling demand with the MILP model than what was consumed to load the same amount of material with the fixed dispatch model; which resulted in less overall fuel consumption in the loading operations with the MILP model.



	LTt	LTs	LTts
MILP model	66,88	67,76	134,65
FD model	69,28	70,45	139,73

Figure 6.2. Litres per ton (MILP model vs Fixed dispatch model)

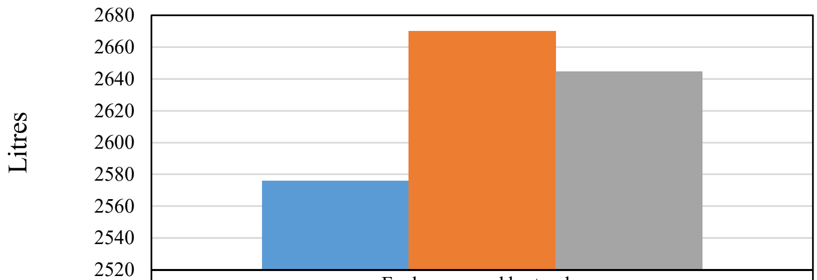
The energy efficiency indicators LTs_j of shovel j_1 and j_3 obtained with the MILP model are smaller than those obtained with the fixed dispatch model. The explanation for this is that, these shovels are more utilized with the MILP model, which means that the amounts of material loaded by these shovels during a shift are large with the MILP model (this is displayed in Figure 5.4 and Figure 5.8). The idling periods of these shovels and their fuel consumption during these periods are also small. Hence, the LTs_j of these shovels is reduced with the MILP.

The litres per ton of both trucks and shovels ($LTts$) are reduced by 3.58 %. Roughly 190.10 litres of fuel is consumed less with the MILP, this represents an overall 3.61 % saving of fuel.

6.3 IDENTIFICATION OF THE BEST ALLOCATION DISCUSSION

In this section, the results presented in section 5.3 are analyzed to address the second research question formulated in section1.3. A comparison of the results obtained with the three possible shovel allocations results in the observations described below.

From the obtained results it is clear that the second allocation is less efficient than the two others. Indeed, by allocating the shovel with the highest capacity at the second loading point and for the same amount of material transported, roughly 141.99 litres and 73.51 litres of fuel are additionally consumed in the haulage operations with this allocation compared to the allocations (a) and (c) respectively. The explanation of this observation is that, with the allocation (b), the total travel distance of loaded trucks is 651.5 *km* while for the two other allocations it is 634.5 *km*. Hence, trucks consume more fuel with the allocation (b). This is shown in the Figure 6.3.



	Fuel consumed by trucks
Allocation (a)	2576,18
Allocation (b)	2670,11
Allocation (c)	2644,66

Figure 6.3. Fuel consumed by trucks

Another explanation of this observation is that the shovel of capacity 2000 t/h is less utilized with the allocation (b) with respect to the two other allocations. This is seen by comparing the contributions of this shovel to the handling demand displayed in Figure 6.4, Figure 6.5 and Figure 6.6. Indeed, with the allocation (b), only 32% of materials moved in the haulage are loaded into the trucks by this shovel; whereas for the two other allocations 42% of materials are loaded into the trucks by the shovel with the capacity of 2000 t/h. However, this shovel is the most efficient regarding the fuel consumption per ton during the working time.

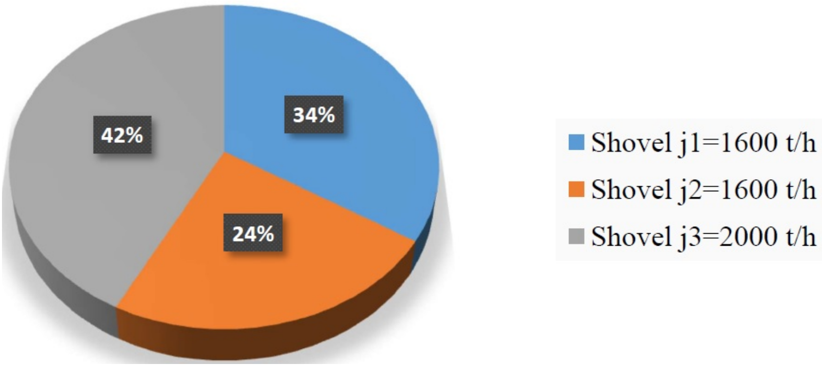


Figure 6.4. Contribution of each shovel to the total handling demand (Allocation (a))

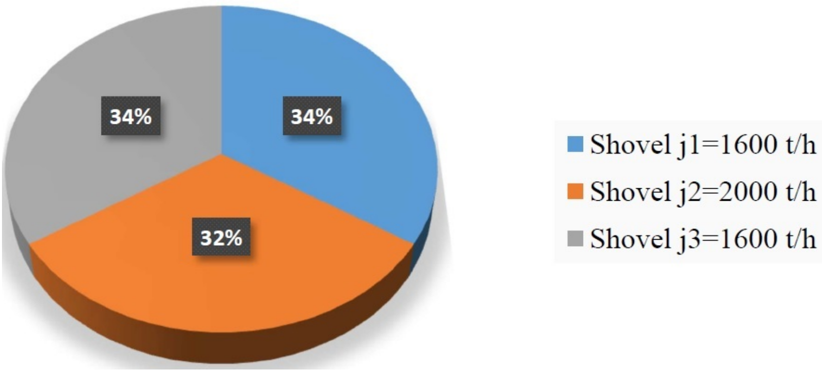


Figure 6.5. Contribution of each shovel to the total handling demand (Allocation (b))

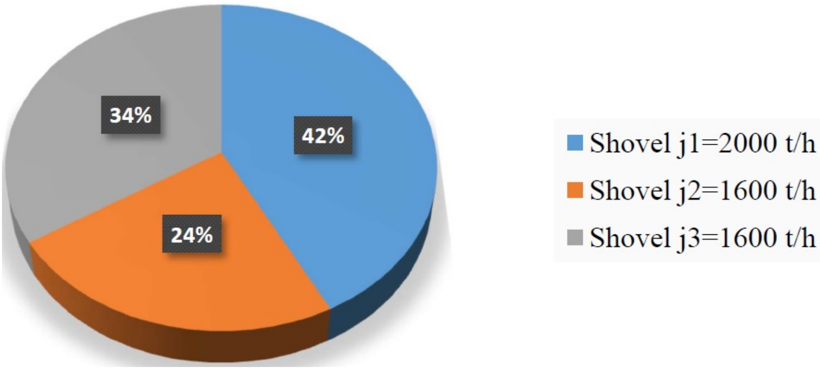


Figure 6.6. Contribution of each shovel to the total handling demand (Allocation (c))

Hence, as a consequence of this, a small amount of fuel is consumed for the loading operations with allocations (a) and (c) than what is consumed with the allocation (b). This is shown in Figure 6.7.

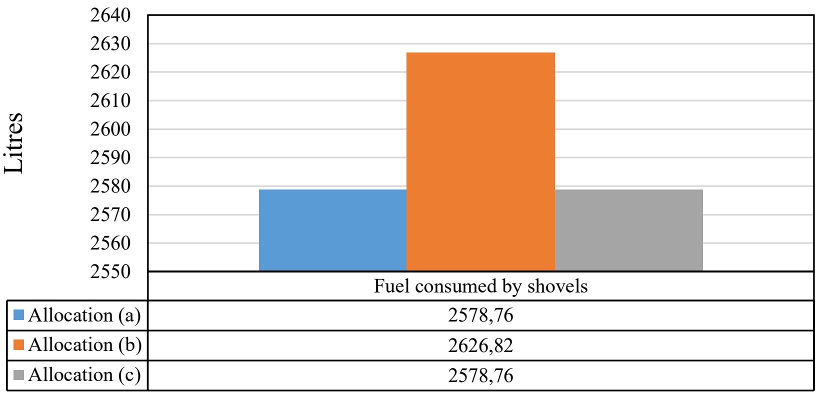


Figure 6.7. Fuel consumed by shovels

In conclusion, the best shovel allocation is the allocation (a) which has the shovel of capacity 2000 t/h allocated at the loading point $j = 3$. Indeed, with this shovel allocation, savings of 2.68 and 1.31 % of fuel is achieved in the haulage operations with respect to the allocation (b) and (c) respectively. The litres per ton of trucks is decreased by 3.52 % and 2.59 % with respect to the allocation (b) and (c) respectively. This allocation decreases the litres per ton of shovels by 1.83 % compared to the allocation (b). It has the same energy indicator of shovels with the allocation (c). Indeed, the same amount of fuel is consumed by the shovels to load the same amount of material into the trucks during the whole shift. The $LTts$ of the truck-shovel dispatch system is decreased by 2.68 % and 1.31 % with respect to the allocations (b) and (c) respectively.

6.4 IDENTIFICATION OF THE BEST FLEET DISCUSSION

In this section, the results presented in section 5.4 are analysed to address the third and fourth research questions. In a comparison of the energy performance of the three fleets, it is seen that fleet A with shovels with a capacity of 1600 t/h is the most inefficient. But in terms of the overall efficiency and productivity, fleet A is the best as its match factor is close to the theoretical perfect match factor of 1.0. Fleet B with shovels with a capacity of 2000 t/h is the most efficient fleet. Indeed, 593,81 litres of fuel are saved with fleet B with respect to fleet A. The $LTts$ and the LTt are respectively decreased by 13.25 % and 8.55 % with this fleet compared to fleet A.

The results obtained with fleet B when compared to those obtained with fleet C show that a saving of 425,59 litres of fuel and a decrease of 7.83 % of the litres per ton are realized with fleet B. Thus, from the obtained results, we can assert that the best haulage and loading fleet with regards to productivity is not necessarily the best fleet with regards to fuel consumption.

CHAPTER 7 CONCLUSION AND FUTURE WORK

7.1 SUMMARY

In this study, a mixed integer linear programming (MILP) model for fuel minimization of trucks and shovels in open-pit mines is developed. The design specifications of each equipment used in the haulage operations are directly considered in the formulation of the proposed model. The model determines the optimal number of trips that each truck should realize on each route of the mine during a shift. The advantage of this model is that it is applicable to homogeneous and heterogeneous fleets of trucks and shovels. To illustrate the applicability of the proposed model, a case study of an under-trucked mine with two unloading points, a mixed fleet of trucks and shovels was considered. The simulation results obtained with the MILP model when compared to a fixed dispatch show that the developed MILP model decreased the litres per ton of fuel consumption of trucks by 3.46 %, of shovels by 3.80 % and that of both trucks and shovels by 3.58 %.Overall, 3.61 % saving of fuel is achieved. The fact that fuel saving is realized, vehicle emission is reduced and air quality is improved.

In the case of a heterogeneous fleet of shovels, it has been shown that the proposed MILP model can help the decision makers to identify the best allocation of each shovel. That allocation will result in minimum fuel consumption in the haulage operations, therefore minimizing diesel emission.

The present study has also established that the match factor can not be considered as the unique criteria for determining the best fleet of equipment to use in the haulage of transportation. Other parameters such as fuel consumption and the litres per ton expected must be analysed in order to determine the best fleet of equipment. The MILP presented in this study can help project managers to do such an analysis.

For an operational open-pit mine with certain topography and resources, the litres per ton obtained from the proposed MILP model can be used as a reference for evaluating the efficiency of its truck-shovel dispatching system.

7.2 FUTURE WORK

The following directions are addressed for further research.

- The optimization model developed in this study can be modified to include the waiting time of trucks at loading and unloading points. so that it can be applicable in the case of an over-trucked mine.

- The optimization model can be modified to consider the case of a real time dispatching system.

- This optimization model can be modified so that in the case of a heterogeneous fleet of shovels, the best allocation of shovels that leads to minimum fuel consumption in the haulage operation can be directly determined from this model.

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